Potential Productivity, Yield Gap, and Water Balance of Soybean-Chickpea Sequential Systematic Selected Benchmark Sites in India

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Executive summary

Before any improvements to crop management practices are made, it is useful to know the potential yield of crops in the region of interest, and the gap between the potential yield and the actual yield obtained by the growers. This analysis helps to know the major factors causing the difference between the actual and the attainable yield for a given site. Under the Asian Development Bank (ADB)-supported project on integrated watershed management we carried out such analysis for soybean-chickpea sequential system for the regions where the project is operational. We used CROPGRO models of soybean and chickpea to determine the yield potential (water-limited yields) and yield gap of the two crops for several sites within the soybean production zones of India.

The simulation study showed that the average potential productivity of the soybean-chickpea sequential system under rainfed situation ranged from 1390 to 4590 kg ha^{-1} across sites. The current level of productivity of the system across sites ranges from 970 to 1780 kg ha^{-1}. The yield gap of 200 to 3300 kg ha^{-1} for the system indicates the potential to increase productivity with improved management under rainfed situation. However, higher increases in yields would be possible in good rainfall years or with supplemental irrigation.

Water balance analysis showed that 35 to 70% of rainfall was used by the crop as evapotranspiration, whereas 25 to 40% was lost as surface runoff indicating the need for water harvesting for supplemental irrigation or to recharge the groundwater in the target region.

Various constraints limiting crop yields in these regions have been highlighted. It is suggested that location-specific integrated approaches would be needed to bridge the yield gap of the predominant crops grown in the target regions.

Introduction

Assessment of potential yield and the yield gap between potential and actual yield is essential before any strategy/investment for improving crop production for a location is made. Potential yield is determined by solar radiation, temperature, photoperiod, atmospheric concentration of carbon dioxide, and genotype characteristics assuming water, nutrients, pests, and diseases are not limiting crop growth. This is also called water non-limiting potential yield. Under rainfed situation where the water supply for crop production is not fully under the control of the grower, water-limiting yield may be considered as the maximum attainable yield for yield gap analysis assuming other factors are not limiting crop production. However, there may be season-to-season variability in potential yield caused by weather variability, particularly rainfall. Once the yield gap between water-limiting yield and actual yield is determined, then the relative contribution of other major constraints and limitations causing yield gap can be assessed so as to focus on the priority research or crop management needs to bridge the yield gap.

Water-limiting potential yield for a site could be determined by growing crops without any growth constraints, except water availability. Alternatively, crop simulation models could be used to estimate the potential yields provided the required soils and climatic input data for the site are available for model execution. Using CROPGRO-soybean model, we estimated the potential yield and yield gap of soybean for the 11 selected sites within the soybean production zone of India (Piara Singh et al. 2001). At these sites, land degradation caused by water erosion, soil fertility depletion, and waterlogging are the major constraints limiting crop yields and sustainability on relatively high water-holding capacity soils. The production problems are further amplified by the existence of biotic and socioeconomic constraints in these regions. This study was further extended to 24 sites as more soils and weather data became available. This report presents the current productivity levels, potential yields, yield gaps, and water balance of the soybean-chickpea sequential system for the soybean production zone using CROPGRO models of soybean and chickpea. Suggestions are also made for bridging the yield gap through crop management and conservation and use of natural resources of the target region.

Section 1: Area, production, and productivity of soybean in India

India ranks third after Argentina and Brazil to have registered a phenomenal growth in the production of soybean. Soybean cultivation in India has steadily increased. It was a minor crop during the early 1970s but at present, it occupies third place in the oilseed production in India. The area under soybean in India has rapidly increased from 0.03 million ha in 1970 to 2.6 million ha in 1990 and to 5.7 million ha in 2000 (Directorate of Economics and Statistics, Government of India 1970–92, Directorate of Economics and Statistics, Government of India 1993–2000, FAO 2002).

Increased soybean production is mainly driven by increased area sown to the crop. In 2000, the soybean production was 5.4 million t. The progress in soybean production is most impressive, however, these growth figures belie the fact that the productivity continues to remain low and major steps are required to enhance production by increasing productivity rather than increasing area under the crop. The average soybean productivity for India has hovered around 1 t ha^{-1} during 1983–2000 (Fig. 1).

The study of long-term growth trend does not indicate any appreciable contribution towards productivity gains by improved agricultural technologies in soybean cultivation except the maintenance of yield. Despite the release of short-duration and high-yielding varieties in recent years, there is no evidence of yield increase in the state of Madhya Pradesh, which is the heartland of soybean production in India. Thus, the growth in production is primarily led by an increased area sown under the crop.

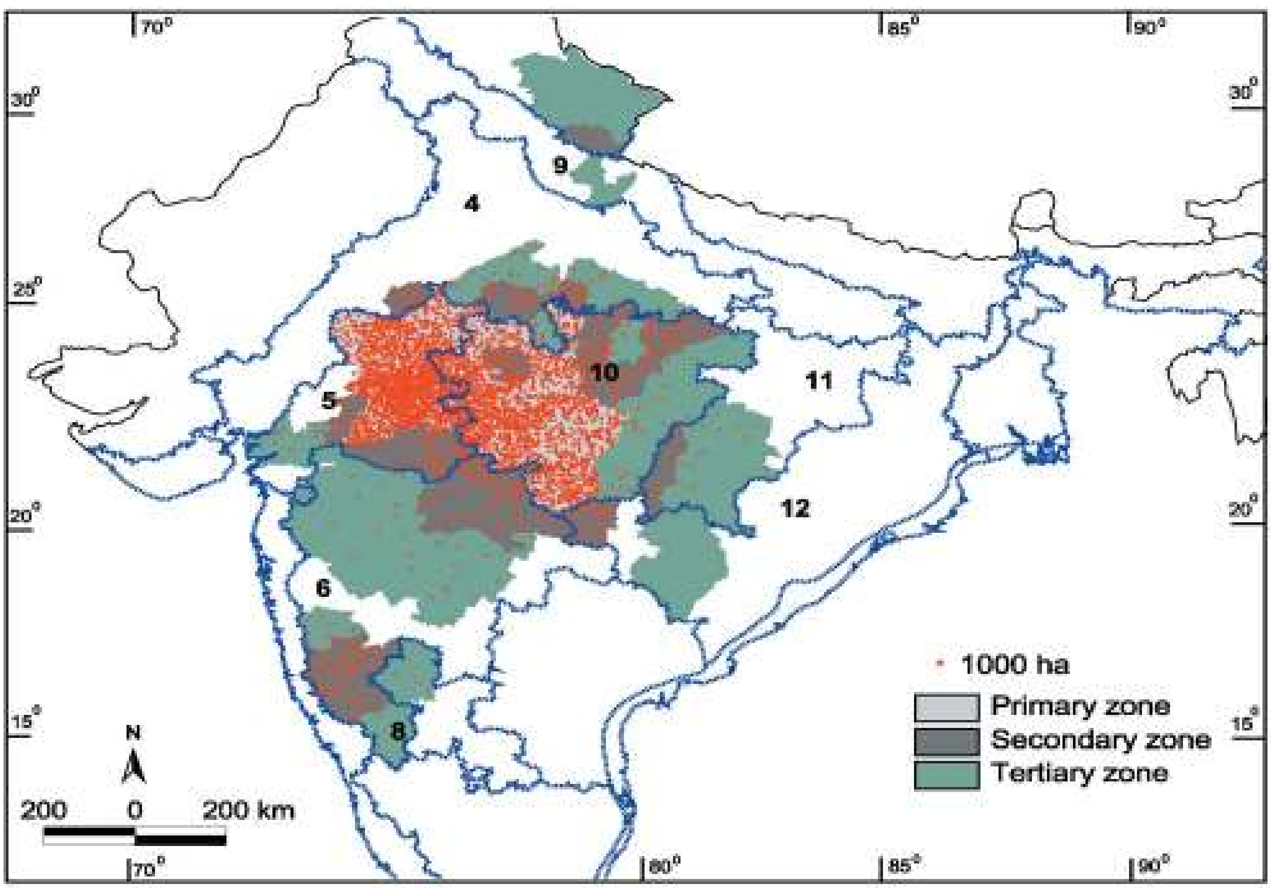


Figure 1. Trends of soybean area, production, and productivity in India.

Major soybean-producing states of India

In India, soybean crop is primarily cultivated in the states of Madhya Pradesh, Rajasthan, Maharashtra, and Uttar Pradesh. Figure 2 shows the distribution of the crop in two epochs: 1985 and 1997. Efforts to grow soybean in the submontane plains of India commenced in the early 1960s. The crop was promising in Madhya Pradesh, Maharashtra, and Uttar Pradesh but not in Gujarat. Currently Madhya Pradesh accounts for nearly 87% of the area under the crop in the country and contributes about 83% of the total national production. In Uttar Pradesh, the area under soybean increased until mid-1980s, but a sharp decline was noted in 1987. This is clearly seen in comparing the area distribution pattern maps for 1985 and 1997. As in Gujarat, the crop did not hold ground initially in Maharashtra as well. However, by 1990, Maharashtra regained the position of the second largest soybean-producing state in India.

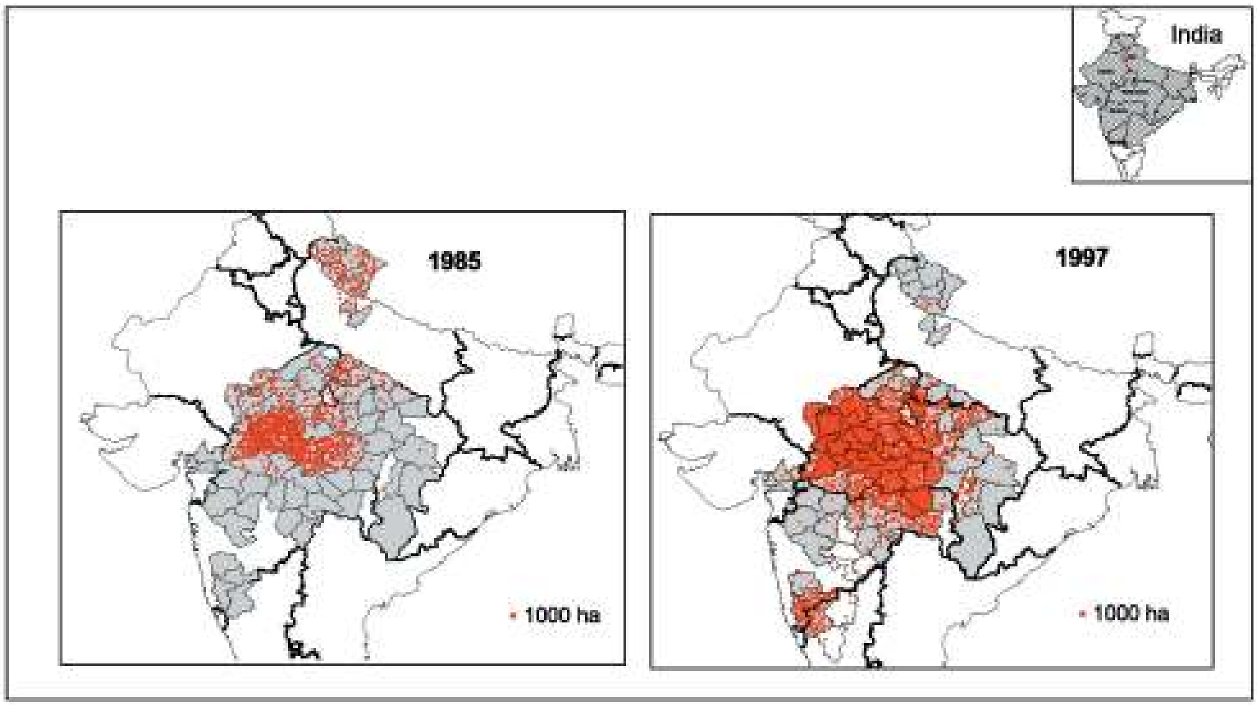
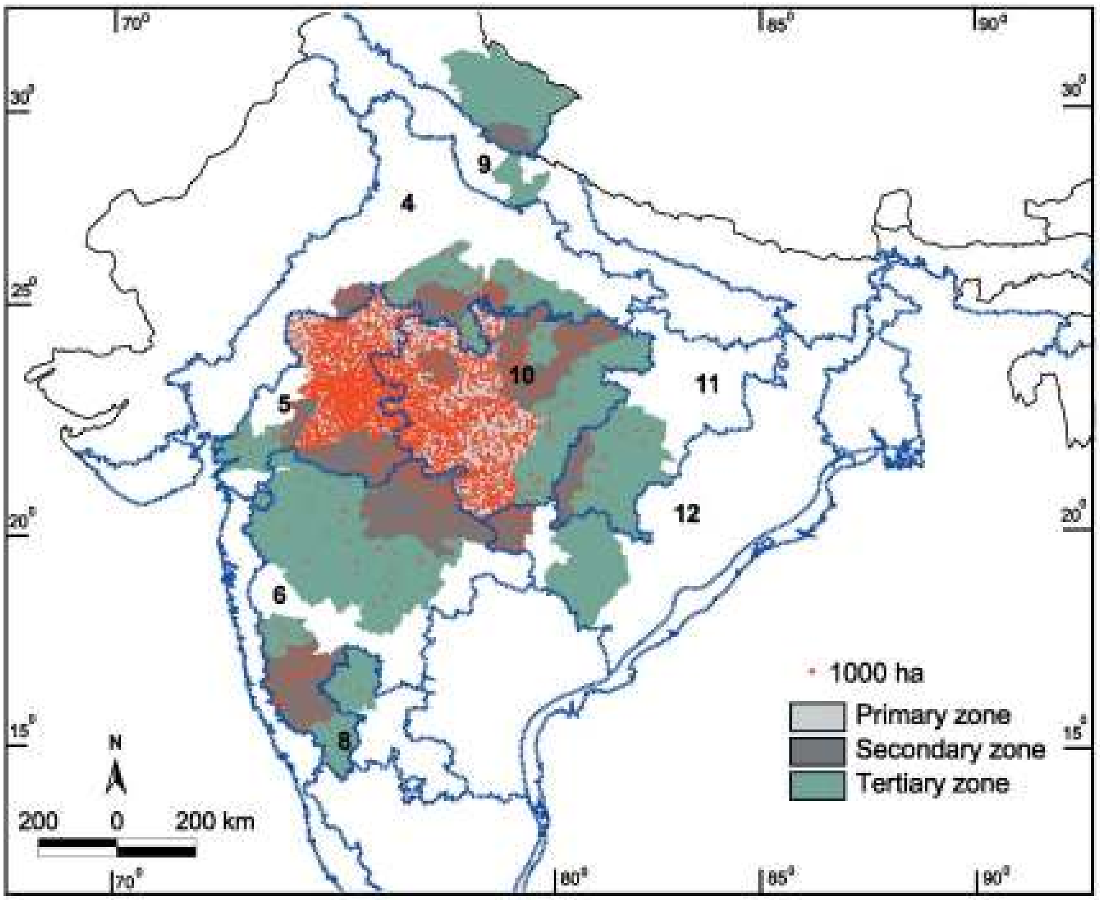


Figure 2. Soybean distribution in India during 1985 and 1997.

Classification of soybean-producing districts

The soybean area distribution presented in Figure 2 reveals a selective, concentrated adaptation of the crop in India. This is more clearly evident in the area and production data of 1997 which show that only 14 districts in Madhya Pradesh account for 58% of national area under the crop and contribute as much as 55% to the total national soybean production. Such a development pattern raises an important question: In what ways are these (high spread) districts different in terms of their natural resource endowments and socioeconomic infrastructure compared to the other districts that show a low soybean crop spread? The resources could be defined in terms of regional soil type, annual or seasonal rainfall, irrigation facilities, use of fertilizers, adoption of high-yielding varieties, cropping patterns, location of soybean processing industries, etc. To provide an answer to the above question, it is necessary to identify those factors of production that render some districts high-density soybean producers and some as low-density producers. Based on soybean productivity levels and contribution of soybean area in the districts to their gross cropped area (GCA) and to total soybean area in India, we grouped soybean-producing districts of India into three zones: primary, secondary, and tertiary. For this purpose the available data of the last three seasons (1994/95, 1995/96, and 1996/97) were used. A district was considered primary if it had at least

15% of GCA under soybean, at least 1% of total soybean area in the country, and soybean productivity levels more than the national average (0.95 t ha^{-1}). The districts meeting all the three conditions in any one season were grouped under the primary zone. After separating the primary districts, the secondary districts were identified from the remaining districts. The secondary zone constituted those districts which had at least 5% of GCA under soybean, at least 0.5% of total soybean area in the country, and soybean productivity levels more than 0.5 t ha^{-1}. The remaining districts which grew soybean but did not fall in the above two categories were grouped under the tertiary zone. The map of these zones was overlayed on the map of agroecological zones (AEZs) of India (Sehgal et al. 1995). The AEZs of interest from soybean production point of view are AEZs 4, 5, 6, 9, 10, 11, 12, and 14 (Fig. 3).



Soybean area, production, and productivity in different zones

Soybean area, production, and productivity of primary, secondary, and tertiary zones during the 1996/97 cropping season are presented in Table 1. Twenty-four of the soybean-producing districts are included in the primary zone. The primary zone is located predominantly in Madhya Pradesh and also in two districts in Maharashtra (Nagpur and Wardha) and three districts in Rajasthan (Chittorgarh, Jhalawar, and Kota) (Table 2). The primary production zone corresponds to AEZs 5 and 10. AEZ 5 constitutes central highlands having Vertic Inceptisols and Vertisols; the climate is semi-arid (moist) and length of growing season varies from 120 to 150 days. AEZ 10 consists of central highlands and Maharashtra plateau having Vertisols and Vertic Inceptisols. The climate is semi-arid (dry and moist) and length of growing season varies from 120 to 180 days.

Table 1. Soybean area, production, and productivity in primary, secondary, and tertiary zones of India during 1996/97.

	Area ('000 ha)			Production ('000 t)			Productivity (t ha^{-1})		
Zone[1]	Total	SD[2]	CV[3]	Total	SD	CV	Total	SD	CV
Primary (24)	4233	86	2	4216	79	2	1.04	0.2	19
Secondary (22)	996	21	2	987	29	3	0.96	0.5	48
Tertiary (42)	158	4	2	166	4	3	0.95	0.4	40

1. Figures in parentheses represent number of districts.
2. SD = Standard deviation.
3. CV = Coefficient of variation (expressed in %).

Table 2. Area and production of soybean in the primary soybean production zone of India during 1996/97.

District	State	Area ('000 ha)	Production ('000 t)	Productivity (t ha^{-1})	GCA[1] ('000 ha)	Soybean area (% of GCA)
Ujjain	Madhya Pradesh	401.5	357.3	0.89	760.0	52.8
Hoshangabad	Madhya Pradesh	330.2	382.7	1.16	734.0	45.0
Shajapur	Madhya Pradesh	286.3	217.9	0.76	658.0	43.5
Mandsaur	Madhya Pradesh	271.3	226.9	0.84	831.0	32.6
Dewas	Madhya Pradesh	231.1	232.9	1.01	548.0	42.2
Sehore	Madhya Pradesh	219.3	196.0	0.89	552.0	39.7
Dhar	Madhya Pradesh	214.6	199.5	0.93	701.0	30.0
Nagpur	Maharashtra	212.3	213.8	1.01	590.0	36.0
Rajgarh	Madhya Pradesh	207.7	142.9	0.69	565.0	36.8
Indore	Madhya Pradesh	203.3	218.0	1.07	443.0	45.9
Betul	Madhya Pradesh	181.1	189.3	1.05	529.0	34.2
Ratlam	Madhya Pradesh	173.5	176.5	1.02	476.0	36.4
Kota[2]	Rajasthan	167.8	200.7	1.20	752.5	22.3
Sagar	Madhya Pradesh	149.2	144.0	0.97	655.0	22.8
Chhindwara	Madhya Pradesh	130.1	148.4	1.14	594.0	21.9
Guna	Madhya Pradesh	126.4	103.5	0.82	734.0	17.2
Jhalawar[2]	Rajasthan	118.0	135.9	1.15	453.8	26.0
Narsinghpur	Madhya Pradesh	113.3	183.0	1.62	402.0	28.2
Raisen	Madhya Pradesh	109.9	112.5	1.02	532.0	20.7
Seoni	Madhya Pradesh	91.0	103.1	1.13	465.0	19.6
Wardha	Maharashtra	83.9	108.4	1.29	385.0	21.8
Chittorgarh[2]	Rajasthan	81.0	74.6	0.92	594.3	13.6
Bhopal	Madhya Pradesh	65.2	63.3	0.97	210.0	31.0
Tikamgarh	Madhya Pradesh	64.5	85.1	1.32	383.0	16.8
Total		4232.6	4216.1	1.04		
SD		86.4	78.9	0.20		
CV (%)		2	2	19		

1. GCA = Gross cropped area.
2. Data for 1994/95.

We have identified 22 districts under the secondary zone. Of these, 10 districts are in Madhya Pradesh, 7 in Maharashtra, 1 in Uttar Pradesh, 1 in Chattisgarh, 1 in Uttaranchal, 1 in Karnataka, and 1 in Rajasthan (Table 3). The secondary soybean production zone overlaps parts of AEZs 4, 5, 6, 10, 11, 12, and 14. AEZs 4, 5, and 6 have Vertisols and Vertic Inceptisols, and semi-arid to sub-humid climate; the length of growing season varies from 120 to 180 days. In AEZs 10, 11, and 12 comprising central highlands, Maharashtra plateau, and eastern plateau, the climate is sub-humid (dry), soils are Vertisols, Vertic Inceptisols, and Alfisols, and length of growing season varies from 150 to 210 days. AEZ 14 comprises the Terai region of Uttar Pradesh (now in Uttaranchal). It has perhumid climate with length of growing season varying from 270 to 300 days. The tertiary zone includes 42 districts with 18 districts of Madhya Pradesh, 13 of Maharashtra, 7 of Uttar Pradesh, 5 of Uttaranchal, 3 of Gujarat, and 2 of Karnataka (Table 4). Tertiary soybean production zone overlaps parts of AEZs 4, 5, 6, 9, 10, 11, 12, and 14. The characteristics of these zones, except AEZ 9, have been described above. AEZ 9 comprises the northern plain, having alluvial derived soils and semi-arid climate; the length of growing season varies from 120 to 150 days.

Table 3. Area and production of soybean in the secondary soybean production zone of India during 1996/97.

District	State	Area ('000 ha)	Production ('000 t)	Productivity (t ha^{-1})	GCA[1] ('000 ha)	Soybean area (% of GCA)
Amravati	Maharasthra	94.0	100.4	1.07	1011.0	9.3
Vidisha	Madhya Pradesh	83.3	80.2	0.96	606.0	13.7
Khandwa	Madhya Pradesh	77.7	43.0	0.55	524.0	14.8
Damoh	Madhya Pradesh	67.9	60.1	0.89	378.0	18.0
Chandrapur	Maharashtra	58.4	69.0	1.18	556.7	10.5
Shivpuri	Madhya Pradesh	49.7	34.9	0.70	516.0	9.6
Sangli	Maharashtra	49.3	110.0	2.23	658.8	7.5
Kolhapur	Maharashtra	48.2	98.4	2.04	615.2	7.8
Jhansi	Uttar Pradesh	46.7	36.5	0.78	401.4	11.6
Satna	Madhya Pradesh	46.0	27.8	0.60	473.0	9.7
Jabalpur	Madhya Pradesh	42.7	41.7	0.98	630.0	6.8
Belgaum	Karnataka	41.7	33.0	0.79	999.9	4.2
Chhatarpur	Madhya Pradesh	37.5	26.3	0.70	467.0	8.0
Rajnandgaon	Chhattisgarh	37.1	26.2	0.71	626.0	5.9
Yeotmal	Maharashtra	35.4	53.0	1.50	971.6	3.6
Khargone	Madhya Pradesh	34.1	23.3	0.68	742.0	4.6
Bundi[2]	Rajasthan	31.2	27.9	0.89	334.2	9.3
Rewa	Madhya Pradesh	29.4	17.2	0.59	492.0	6.0
Jhabua	Madhya Pradesh	27.5	16.3	0.59	459.0	6.0
Buldhana	Maharashtra	24.4	28.8	1.18	814.1	3.0
Akola	Maharashtra	24.2	28.9	1.19	1049.3	2.3
Nainital	Uttaranchal	9.5	4.0	4.42	85.2	11.1
Total		995.9	986.9	0.96		
SD		20.6	29.4	0.46		
CV (%)		2	3	48		

1. GCA = Gross cropped area.
2. Data for 1994/95.

Table 4. Area and production of soybean in the tertiary soybean production zone of India during 1996/97.

District	State	Area ('000 ha)	Production ('000 t)	Productivity (t ha^{-1})	GCA[1] ('000 ha)	Soybean area (% of GCA)
Morena	Madhya Pradesh	14.0	17.9	1.28	484.0	2.9
Mandla	Madhya Pradesh	12.1	10.8	0.89	574.0	2.1
Lalitpur	Uttar Pradesh	11.5	12.1	1.05	306.1	3.8
Bhandara	Maharashtra	11.2	12.9	1.15	416.0	2.7
Satara	Maharashtra	9.8	14.8	1.51	685.0	1.4
Durg	Chhatisgarh	7.9	4.8	0.61	804.0	1.0
Vadodara[2]	Gujarat	7.6	10.6	1.40	567.1	1.3
Jalaun	Uttar Pradesh	6.6	5.1	0.77	388.7	1.7
Gwalior	Madhya Pradesh	6.6	10.9	1.65	307.0	2.1
Bilaspur	Chhatisgarh	5.9	4.8	0.81	1072.0	0.6
Shahdol	Madhya Pradesh	5.7	3.2	0.56	576.0	1.0
Panna	Madhya Pradesh	5.6	3.7	0.66	280.0	2.0
Parbhani	Maharashtra	5.2	6.6	1.27	1285.1	0.4
Bijapur	Karnataka	4.3	3.0	0.69	1554.0	0.3
Latur	Maharashtra	4.2	4.6	1.10	69.3	0.6
Jalna	Maharashtra	4.0	3.3	0.83	722.7	0.6
Jalgaon	Maharashtra	3.6	5.5	1.53	1172.0	0.3
Aurangabad	Maharashtra	3.5	4.5	1.29	941.0	0.4
Datia	Madhya Pradesh	3.0	2.8	0.93	147.0	2.0
Banda	Uttar Pradesh	2.7	2.1	0.77	600.9	0.4
Hamirpur	Uttar Pradesh	2.6	2.0	0.77	357.0	0.7
Dharwad	Karnataka	2.5	2.0	0.78	1355.7	0.2
Broach[2]	Gujarat	2.2	1.5	0.68	431.1	0.5
Dhule	Maharashtra	2.0	3.4	1.70	804.9	0.2
Nasik	Maharashtra	1.9	2.6	1.37	977.9	0.2
Nanded	Maharashtra	1.8	3.0	1.67	816.0	0.2
Pithorgarh	Uttaranchal	1.4	0.7	0.47	117.9	1.2
Osmanabad	Maharashtra	1.4	1.5	1.07	718.3	0.2
Garhwal	Uttar Pradesh	0.9	0.4	0.40	135.8	0.7
Beed	Maharashtra	0.9	1.0	1.11	913.4	0.1
Raipur	Chhatisgarh	0.8	0.8	1.00	1188.0	0.1
Ahmednagar	Maharashtra	0.8	1.1	1.38	1441.4	0.1
Sidhi	Madhya Pradesh	0.7	0.4	0.57	483.0	0.1
Dangs[2]	Gujarat	0.7	0.3	0.43	56.7	1.2
Almorah	Uttaranchal	0.4	0.2	0.47	174.1	0.2
Bareilly	Uttar Pradesh	0.4	0.3	0.76	522.4	0.1
Shajahanpur	Uttar Pradesh	0.3	0.3	0.74	585.0	0.1
Tehri Garhwal	Uttaranchal	0.3	0.2	0.47	107.4	0.3
Balaghat	Madhya Pradesh	0.3	0.4	1.33	353.0	0.1
Bastar	Chhatisgarh	0.3	0.3	1.00	906.0	0.0
Chamoli	Uttaranchal	0.1	0.1	0.48	66.7	0.2
Uttar Kashi	Uttaranchal	0.1	0.0	0.47	46.6	0.2
Total		158.0	166.5	0.95		
SD		3.7	4.5	0.38		
CV (%)		2	3	40		

1. GCA = Gross cropped area.
2. Data for 1994/95.

The development of soybean crop in the primary zone is characterized by an exponential increase in area and production (Fig. 4). While the area under the crop and production were negligible in 1983/84, this zone produced 4.2 million t of soybean from an area of 4.2 million ha during 1996/97 (Table 1 and Fig. 4). The inset table in Figure 4 shows the compound growth rate (CGR) of soybean area, production, and productivity of the primary zone during the periods 1983–90, 1990–97, and 1983–97. The CGRs of soybean area and production in the zone during 1990–97 are lower compared to those during 1983–90. This implies that the development of the soybean crop in this zone has been relatively slower during 1990–97. However, the productivity growth rate during 1990–97 is about 30% higher than that attained during 1983–90. This suggests that soybean development in the primary zone was predominantly extensive during 1983–90 and relatively more intensive during the later period. However, crop intensification measures adopted to increase the productivity of the zone (as indicated by higher CGR) do not seem to have achieved the desired effect. The average productivity of the primary zone during 1983–90 was 0.76 t ha^{-1}. Despite efforts to enhance the productivity levels, the productivity increased marginally to 1.04 t ha^{-1} during 1990–97. The coefficient of variation (CV) for the primary zone productivity is 19%, indicating that efforts are needed to increase the productivity of soybean while maintaining low CV in productivity in the primary zone.

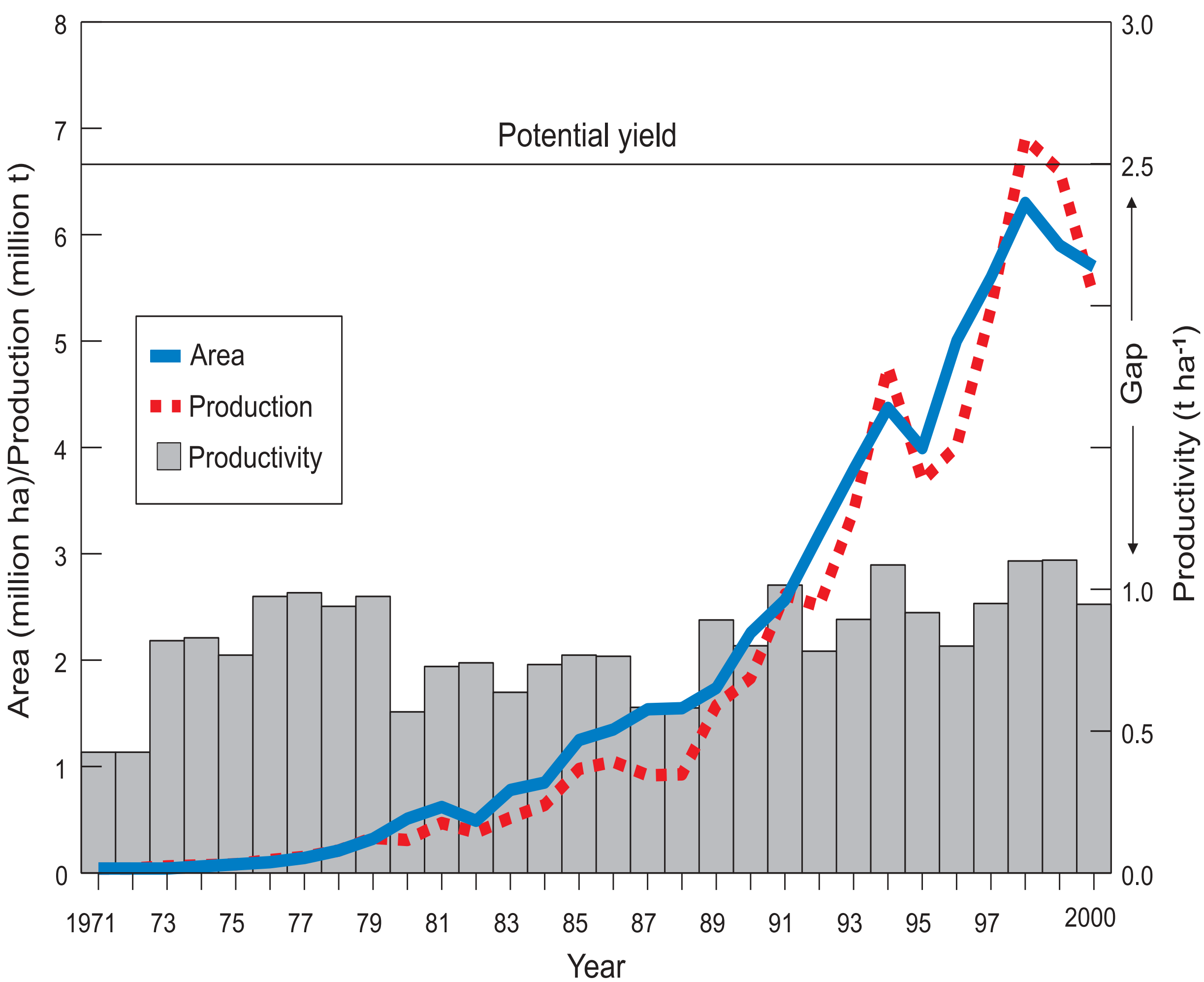


Figure 4. Soybean area, production, and productivity in the primary zone in India.

The soybean development pattern in the secondary zone is generally similar to that in the primary zone during 1983–97 (Fig. 5). Area and production showed an increasing trend until 1993–94 and these declined during 1994–95. The data on CGRs of area and production in the secondary zone reveal that the area under the crop increased at a slower rate during 1983–90 and later increased at a higher rate compared to that in the primary soybean zone. The productivity of this zone is marginally lower (0.96 t ha^{-1}) compared to that of the primary zone (1.04 t ha^{-1}) (Table 1). High CV in productivity (48%) indicates that high productivity levels need to be achieved along with reduction in CV.

In the tertiary zone, soybean area and production peaked in 1985 (Fig. 6). Subsequently, there was a gradual decline until 1987 and a sharp decline in 1988. Only after 1992, the soybean crop has begun to spread again in this zone. Nevertheless, area and production values were lower in 1995 compared to those in 1985, and started increasing again after 1995. The area and production CGRs during 1983–90 were negative. The average productivity of the zone during this period was about 0.75 t ha^{-1}.

During 1990–97, average soybean productivity in the tertiary zone was higher than that of the secondary zone and comparable to that of the primary zone. Although the average productivity levels of primary and tertiary production zones are similar, the variability associated with soybean yields in the tertiary zone is about twice that in the primary zone (Table 1), indicating that productivity gains are needed along with reduction in variability in yields in this zone.

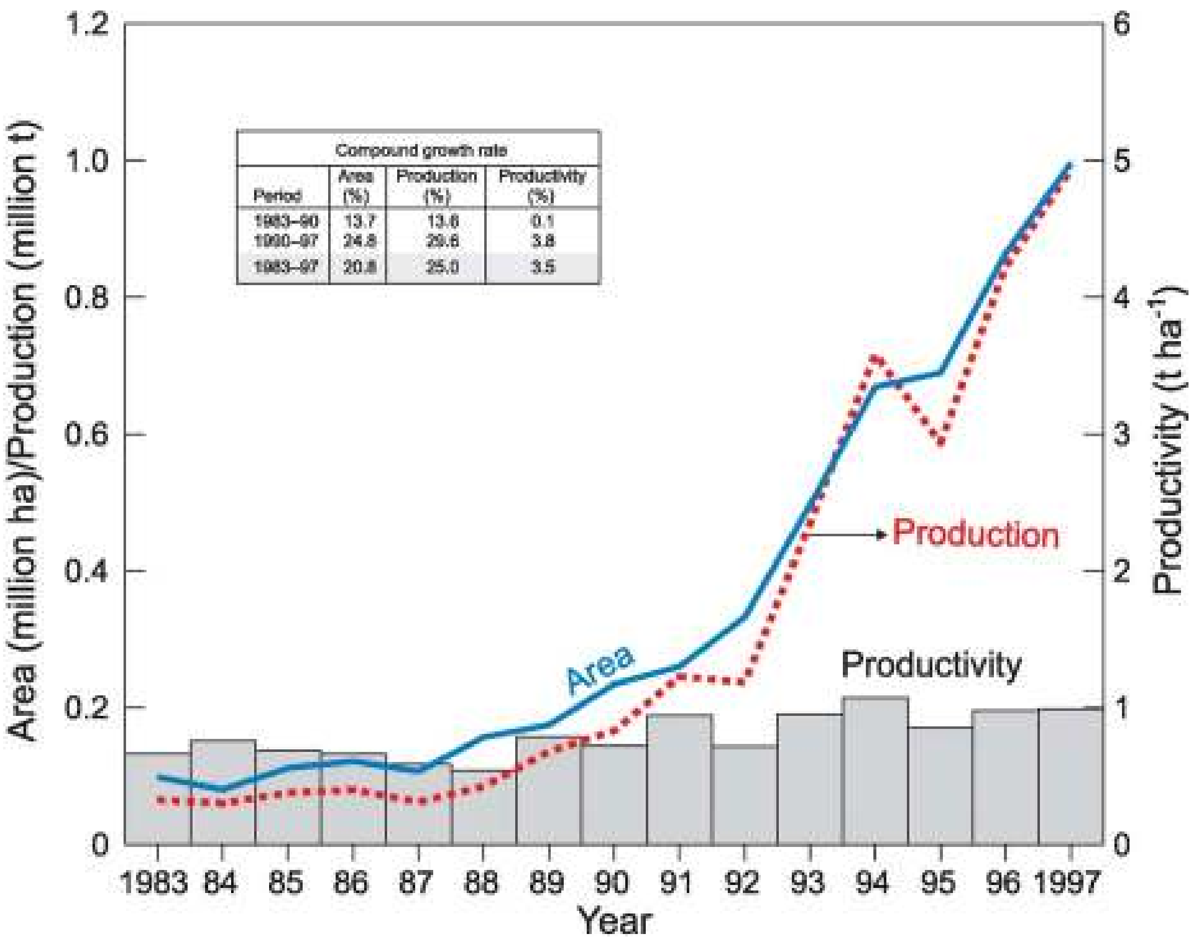
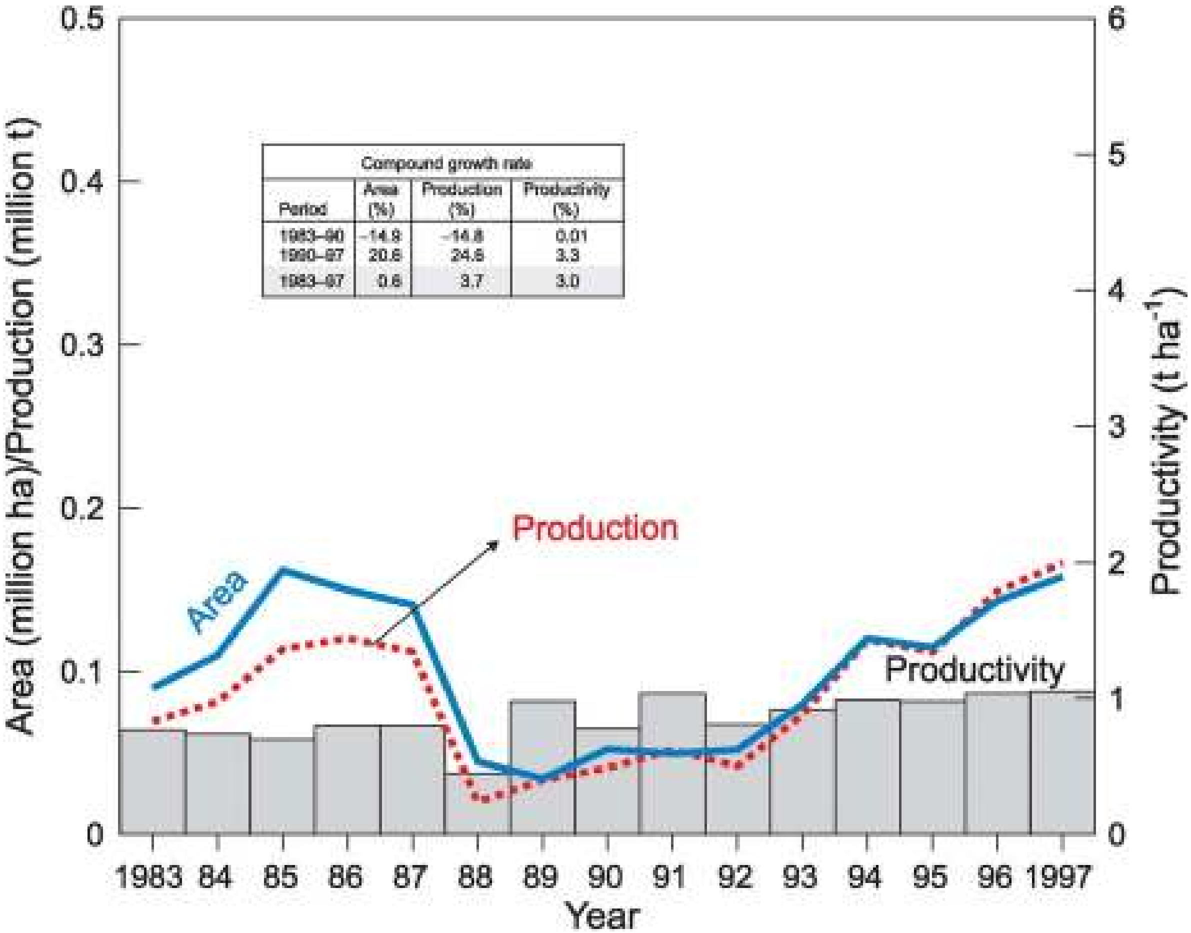


Figure 5. Soybean area, production, and productivity in the secondary zone in India.



Soybean in the primary zone

As seen in Table 2, the primary production zone accounted for 4.2 million ha (78% of the total soybean area) and produced 4.2 million t (78% of the annual production) of soybean in 1996–97. In contrast, negligible area was under soybean cultivation during 1983/84. Within a span of a decade or so, the primary zone has attained the status of a leading soybean producer in the country. This raises a few questions: How was such an impressive rate of growth in soybean cultivation achieved? Was it at the cost of other crops in the zone? To answer these questions, we analyzed the cropping pattern in the primary zone during 1983–95. Based on this analysis, the following observations have been noted.

Trends in area and production of important crops and land area left fallow in the primary zone during 1983–95 are shown in Figures 7 and 8 and Table 5. The primary zone produced 1.6 million t of sorghum from an area of 2.1 million ha during 1983/84. However, by 1994/95, the area under this crop was drastically reduced to 0.81 million ha with a production of 0.53 million t. As is clearly seen in Figure 7, sorghum cultivation declined linearly during 1983–95. This is also evident from the negative CGRs of sorghum crop (see the inset table in Fig. 7). Initially, the rate of decline in sorghum area was slow (2.6% yr^{-1} during 1983–90). However, there was a pronounced decline (10.3% yr^{-1}) during 1990–95 (with an overall rate of decline of 5.5% yr^{-1} during 1983–95). Other important crops of the primary zone such as rice and

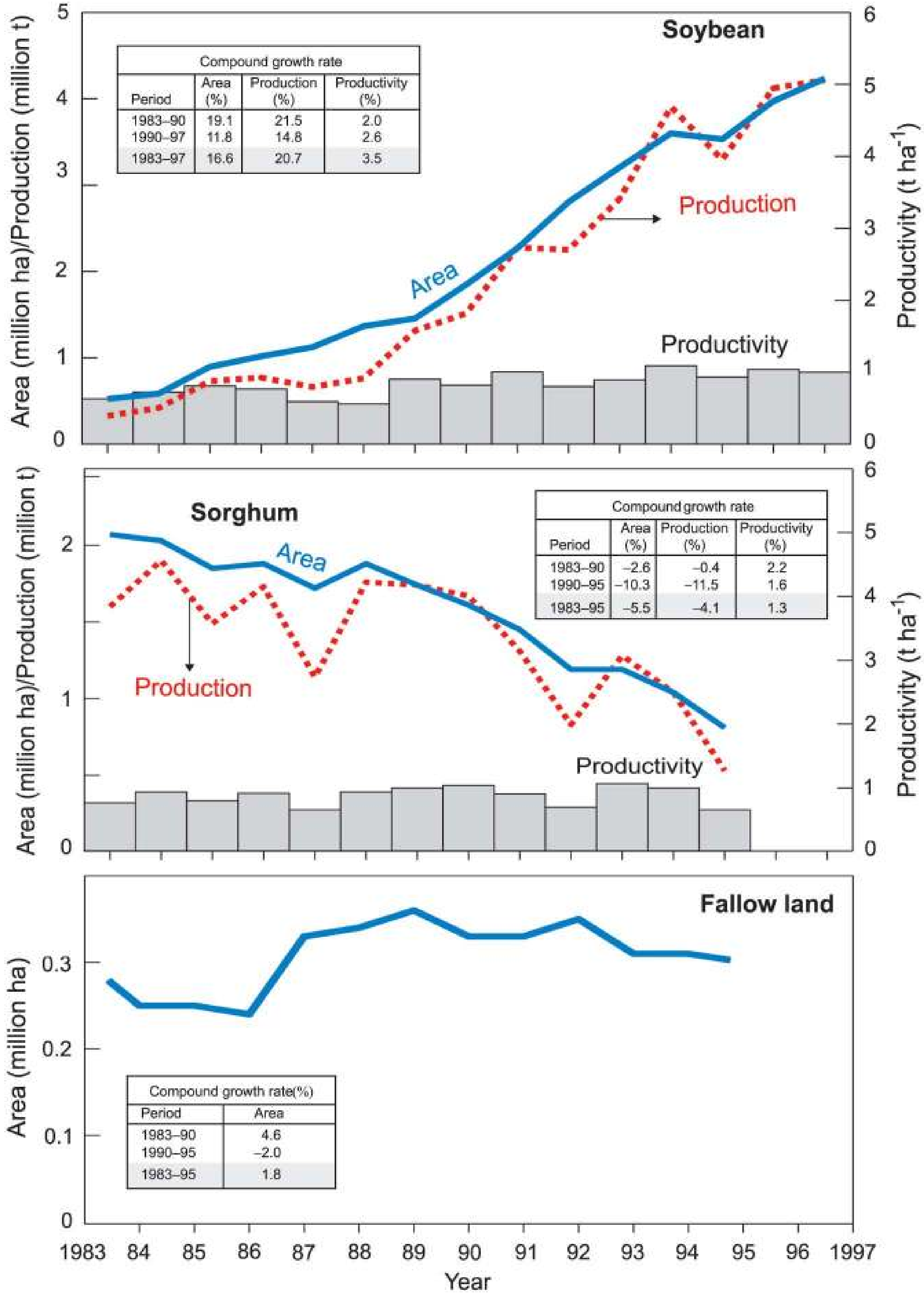


Figure 7. Land use for soybean, sorghum, and fallow in the primary zone of soybean in India.

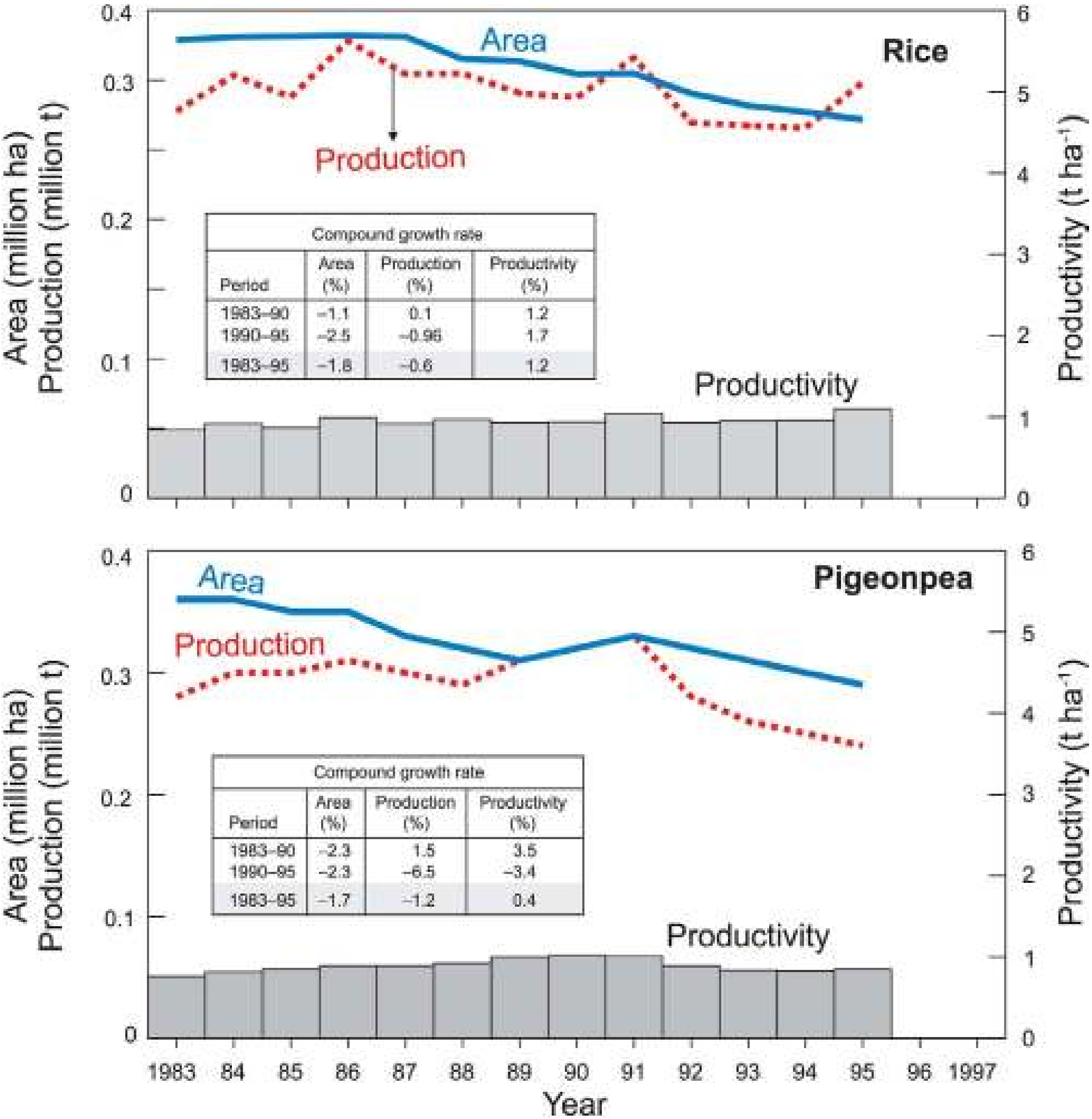


Figure 8. Land use for rice and pigeonpea in the primary zone of soybean in India.

pigeonpea also showed a similar trend during 1983–95. The rates of decline in area under rice and pigeonpea during this period were 1.8% and 1.7% respectively. However, these rates of decline were lower than that of sorghum. The trend in the annual fallow land shows an increase in the area until 1991/92 and a subsequent decrease. In recent years, the fallow land declined at the rate of 3.6% per year.

While area under sorghum, rice, pigeonpea, and fallow land have declined during 1983–95 in the primary zone, the area under soybean has continuously increased. Area sown to other minor crops in the zone also decreased from 1983 to 1995 (Table 5). Thus, we can conclude that soybean area has been expanding in the primary zone in the areas that were previously sown to sorghum, rice, pigeonpea, and other crops or left as cultivated fallow during the rainy cropping season (Fig. 8 and Table 5).

Table 5. Area, production, and productivity of rainy season crops in relation to gross cropped area (GCA) of soybean primary zone in India during 1983 and 1995.

Crop	Area ('000 ha)	Production ('000 t)	Productivity (t ha^{-1})	% of GCA
1983 (GCA = 11.887 million ha)				
Soybean	525	329	0.62	4.40
Sorghum	2069	1602	0.77	17.40
Rice	329	278	0.84	2.77
Pigeonpea	363	277	0.76	3.05
Groundnut	261	149	0.57	2.19
Linseed	257	78	0.30	2.16
Sesame	199	31	0.16	1.67
Minor pulses	890			7.48
Fallow	246			2.07
1995 (GCA = 13.547 million ha)				
Soybean	3532	3296	0.92	26.07
Sorghum	806	532	0.66	5.95
Rice	267	314	1.18	1.97
Pigeonpea	250	187	0.75	1.85
Groundnut	166	156	0.94	1.23
Linseed	147	61	0.42	1.09
Sesame	67	16	0.24	0.50
Minor pulses	603			4.45
Fallow	336			2.48

Section 2: Analysis of potential yield, yield gap, and water balance of soybean and chickpea crops

Crop growth is a result of various complex and interrelated physical and physiological plant processes operating during the life cycle of a crop. Crop growth simulation models, which integrate these processes, provide the opportunity to simulate crop yields in a given climate-soil environment. These models can also be used to optimize agronomic management in response to single or multiple inputs to achieve a given level of crop yields. When coupled with historical weather data and related soil series, these models could also be used to determine potential productivity, both water non-limiting and water limiting yields, and the yield variations caused by variable weather. In this study, we have quantified the water limiting potential yields and yield variability caused by weather variability of sole soybean and soybean-chickpea sequential system for the 24-benchmark sites within the soybean-growing region of India (Table 6).

Table 6. Geographical location and climate of the benchmark sites in soybean production zones in India.

Site	Latitude (N)	Longitude (E)	Elevation (m)	Annual rainfall (mm)	PET[1] (mm)
PRIMARY ZONE					
Low rainfall					
Kota	25°11'	75°51'	257	734	1523
Medium rainfall					
Nimuch[2]	24°28'	74°54'	496	764	1601
Ujjain	23°00'	75°12'	489	949	1699
Dhar	22°60'	75°60'	583	969	1814
Kannod[2]	22°24'	76°26'	353	867	
Rajgarh	24°00'	76°26'	302	979	1492
High rainfall					
Guna	24°39'	77°19'	478	1032	1511
Nagpur	21°60'	79°30'	310	1110	2051
Shajapur	23°24'	76°00'	427	1001	
Wardha	20°36'	78°12'	–	1113	1460
Indore	22°43'	75°48'	567	1068	1814
Ratlam	23°19'	75°30'	486	1069	1521
Raisen	23°24'	78°12'	–	1141	1553
Betul	21°55'	77°54'	658	1223	1370
Bhopal	23°17'	77°21'	523	1139	1554
Sagar	23°51'	78°45'	551	1249	1464
SECONDARY ZONE					
Medium rainfall					
Akola	20°42'	77°20'	282	787	1730
Amravati	20°56'	77°47'	–	856	1770
Jhabua	22°47'	74°35'	530	820	
High rainfall					
Vidisha	24°60'	78°00'	592	1004	1511
Belgaum	15°51'	74°32'	753	1112	1482
Jabalpur	23°10'	79°57'	393	1548	1401
TERTIARY ZONE					
Medium rainfall					
Patancheru	17°27'	75°54'	540	909	1758
Nanded	19°60'	77°12'	358	849	1606

1. PET = Potential evapotranspiration.
2. Nimuch is in district Mandsaur and Kannod in district Dewas.

Materials and methods

To simulate the potential yields of sole soybean and soybean-chickpea sequential system, we used the crop growth simulation models available in the Decision Support Systems for Agro-technology Transfer (DSSAT) v 3.0 (Tsuji et al. 1994). These models need inputs of daily weather data, soil data, and the cultivar-specific parameters (genetic coefficients) to simulate plant growth and resource use by these systems. Past weather data were obtained either from the India Meteorology Department (IMD) (Pune) or directly from the agricultural research stations that operate the meteorological stations (Table 7). Annual rainfall at the selected locations ranged from 734 mm at Kota to 1548 mm at Jabalpur and potential evapotranspiration (PET) from 1370 mm at Betul to 2051 mm at Nagpur (Table 6). Simulations were performed for the period ranging from 17 to 30 years depending upon the availability of data for the benchmark sites (Table 7). Solar radiation data were available for Patancheru but not for other locations. These were derived from the maximum and minimum temperatures using Bristow and Campbell (1984) method. Whenever the weather data were missing it was either substituted with normal values or deleted.

Table 7. Weather databases used for simulation studies for benchmark sites in India.

Site	Weather period	Weather years
PRIMARY ZONE		
Low rainfall		
Kota[1]	1962, 1965–91,1993–96	30
Medium rainfall		
Nimuch	1969–96	28
Ujjain	1969–96	28
Dhar	1973–96	24
Kannod	1969–83, 1986–89, 1992–95	21
Rajgarh	1969–93	25
High rainfall		
Guna	1975–95	21
Nagpur	1969–96	28
Shajapur	1969–93	25
Wardha	1975–92	18
Indore	1975–99	25
Ratlam	1969–95	27
Raisen[1]	1975–91	17
Betul[1]	1975–96	22
Bhopal	1969–96	28
Sagar	1969–96	28
SECONDARY ZONE		
Medium rainfall		
Akola	1969–96	28
Amravati	1975–94	19
Jhabua	1969–80, 1993–96	15
High rainfall		
Vidisha	1970–75, 1977, 1979–81, 1983–96	23
Belgaum	1975–92	18
Jabalpur[1]	1975–82, 1988–96	17
TERTIARY ZONE		
Medium rainfall		
Patancheru	1975–99	25
Nanded	1969–95	27

1. Complete weather data set was available from 1981–91 and 1993–96 for Kota, 1988–91 for Raisen, and 1988–96 for Betul and Jabalpur. Daily rainfall was the only weather element available for the remaining weather years for the four locations. Long-term mean values were substituted for solar radiation and maximum and minimum temperatures for years when the required data were not available.

The soils in the soybean-growing regions in India are mainly Vertisols and associated soils. The soils data were obtained from the soil survey reports published by the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), Nagpur (Lal et al. 1994). For a given benchmark site the data of the nearest soil series were used for this analysis (Table 8). Except Sukali series, which came under Inceptisol, all others belonged to Vertisols. The soils data file needed to execute the soybean model was created by using the soil parameters estimator program available in DSSAT by inputting soil characteristics of a location, except for the Patancheru site for which we had the soil parameters either measured or calibrated. This program estimated soil water contents at saturation (SSAT), upper and lower limits of soil water availability (SDUL and SLLL), surface runoff curve number (SLRO), deep drainage coefficient (SLDR), soil albedo (SALB), and stage-1 evaporation limit (SLU1). The depth of soils at different locations varied from 45 cm at Kamiliakheri to 240 cm at Jambha. The extractable soil water-holding capacities (SDUL minus SLLL) ranged from 54 to 283 mm for the whole soil profile (Table 8). Root growth factor (SRGF) was adjusted so that the value of SRGF is 1.0 for the top layer and decreased exponentially with soil depth. A mean value of SLRO (SLRO = 82.0) that was calibrated for the Patancheru site was used for all soil series of the benchmark sites. Based on soil properties and the description of the drainage class, the soil parameters estimator program estimated SLDR equal to 0.40 for most of the soil series. The calibrated SLDR for Patancheru location was 0.9 for the shallow soil and 0.7 for the medium deep soil. A soil fertility factor (SLPF) of 1.0 was used for all sites indicating that the simulations were performed assuming soil fertility was not a limiting factor for crop growth and yield.

The initial conditions estimated by the soil parameters estimator program were organic carbon content, mineral nitrogen (N) content, and soil water at the start of simulation. The mineral N content for the whole profile was around 50 ppm for all the soil series. However, the NO_3-N estimated during the initial conditions was only 17 ppm for Jambha series, between 30 and 40 ppm for Achmatti, Linga, Sarol, Kheri, Chambal, and Jamra series, and above 40 ppm for the remaining series. Low NO_3-N indicates waterlogging during the initial conditions.

Sole soybean system

Crop yields and water balance of the sole soybean system were simulated using the seasonal analysis program of DSSAT. In the seasonal analysis program there is no carryover effects of water or nutrient balance from one season to another. Each year the model starts with the same initial conditions at the defined starting date. For this analysis the simulations were performed for the cultivar PK 472 which is widely grown in the target region. The genetic coefficients for this cultivar were determined using crop growth and development data collected at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India. This cultivar matures in about 100–110 days. A plant population of 35 plants m^{-2} at 30-cm row spacing was considered throughout the simulation study. The model simulations were initiated on 15 May each year and the soil profile was considered to be at the lower limit of water availability (SLLL) on that day. The sowing window assumed was 1 June to 30 July considering the spatial and temporal variations in the onset of rainy season in the target region. The simulated crop was sown on the day when the soil moisture content in the top 30-cm soil depth reached at least 40% of the extractable water-holding capacity during the sowing window. Sowing was not done until this condition was satisfied. The model outputs for each year were: sowing and harvest dates, biomass and seed yields, and water balance components of soybean. The mean, standard deviation (SD), and the minimum and maximum values were also determined.

Table 8. Soil type and characteristics of benchmark sites used for simulation.

Site	Soil series	Soil type	Soil depth (cm)	Maximum extractable water (mm)
PRIMARY ZONE				
Low rainfall				
Kota	Chambal	Vertisol	188	224
Medium rainfall				
Nimuch	Jamra	Vertisol	140	166
Ujjain	Sarol	Vertisol	160	195
Dhar	Sarol	Vertisol	160	195
Kannod	Sarol	Vertisol	160	195
Rajgarh	Jamra	Vertisol	140	166
	Saunther	Vertisol	77	91
High rainfall				
Guna	Jamra	Vertisol	140	166
	Saunther	Vertisol	77	91
Nagpur	Linga	Vertisol	140	160
Shajapur	Sarol	Vertisol	160	195
	Saunther	Vertisol	77	91
Wardha	Sukali	Inceptisol	150	179
Indore	Sarol	Vertisol	160	195
	Kamiliakheri	Inceptisol	45	54
Ratlam	Sarol	Vertisol	160	195
Raisen	Sarol	Vertisol	160	195
	Jamra	Vertisol	140	166
Betul	Jambha	Vertisol	240	283
Bhopal	Jamra	Vertisol	140	166
	Saunther	Vertisol	77	91
Sagar	Jamra	Vertisol	140	166
SECONDARY ZONE				
Medium rainfall				
Akola	Jambha	Vertisol	240	283
Amravati	Jambha	Vertisol	240	283
Jhabua	Sarol	Vertisol	160	195
High rainfall				
Vidisha	Jamra	Vertisol	140	166
Belgaum	Achmatti	Vertisol	170	189
Jabalpur	Kheri	Vertisol	150	177
TERTIARY ZONE				
Medium rainfall				
Patancheru	Kasireddipalli	Vertisol (shallow)	112	153
	Kasireddipalli	Vertisol (deep)	127	184
Nanded	Jambha	Vertisol	240	283

Soybean-chickpea sequential system

Crop yields and water balance of the soybean-chickpea sequential system were simulated using the sequential analysis program of DSSAT. The Sequence Analysis program allows the user to carry out simulations of crop rotations or crop sequences. In this analysis soybean was sown in the rainy season followed by the chickpea crop in the postrainy season. This cropping system is often recommended and followed by many farmers in the region in addition to other systems. Weather and soil data used for this analysis were the same as for the seasonal analysis. Initial conditions assumed in the sequential analysis applied only to the first year of simulation as the soil-water and nutrient status effects are carried over from one season or crop to the subsequent season or crop. The management data for soybean were also the same as for seasonal analysis. For the simulation of chickpea crop, we used the cultivar ICCC 37 for which the genetic coefficients were determined using the crop growth and development data sets from ICRISAT, Patancheru, India. This cultivar matures in about 95–130 days. A plant population of 30 plants m^{-2} at 30-cm row spacing was considered throughout the simulation study. The sowing window assumed for chickpea was 10 October to 30 November. The simulated crop was sown on the day when the soil moisture content of the top 30-cm soil depth reached at least 40% of extractable water-holding capacity (EWHC). Chickpea could not get sown in many years with this condition at Sagar, Vidisha, and Nimuch, so the criterion was relaxed to at least 20% of EWHC for these three locations. Acceptable level of yields were obtained for these three locations during extra number of years with the relaxation of the sowing criterion.

Results and discussion

The soil and climatic characteristics of the locations determined potential productivity that could be obtained for each cropping system at a given level of management. The year-to-year variability in weather influenced the productivity as well as the resource use of these systems at each site. The simulated results obtained on sowing date, harvest dates, crop yields, and water balance components were categorized into primary, secondary, and tertiary production zones of soybean and also into high and low rainfall categories. Among the 24 locations selected, 16 belonged to primary, 6 to secondary, and remaining 2 to tertiary zones. The results obtained on various outputs of the model are discussed in terms of their mean value and variability (SD or CV) caused by weather at each site.

Sole soybean system

Sowing and harvest dates of soybean. It is not possible to manipulate the time of sowing in rainfed system as it mainly depends on the onset of monsoon. A negative correlation (r = –0.4) between the mean seed yields and the mean sowing dates indicated that those sites where early sowing was not feasible it might have a negative effect on the yield of soybean. Soybean was sown every year at all the sites selected for simulation. The mean sowing date was after 23 June at Kota, Guna, Nimuch, Kannod, Shajapur, Rajgarh, and Jhabua and for the remaining sites it was before this date (Table 9). As the sowing date was determined by the threshold value of the soil moisture content of the top soil layer during the sowing window, the delayed sowing at some of the sites may be due to their geographical location in the western part of India where the monsoon arrives late compared to the other sites. The mean sowing date ranged between 16 June and 2 July across sites. Mean value of sowing dates showed that early sowing was feasible at nearly 80% of the sites. Variation in sowing date was more for the sites where soybean was sown late.

Date of final harvest is determined by the sowing date as well as the thermal regime of the site during the crop growth period. Generally early sowing resulted in early harvest of the crop (Table 9). At some sites such as Belgaum early sowing resulted in early harvest compared to the sites where sowing was done almost at the same time. Variability in the harvest dates at a given location was less compared to the variability in the sowing dates. The mean duration of the crop ranged from 105 days (Belgaum) to 115 days (Bhopal).

Table 9. Sowing and harvest dates of simulated soybean in seasonal analysis for various sites in India.

	Sowing date				Harvest date			
Site	Early	Late	Mean	SD	Early	Late	Mean	SD
PRIMARY ZONE								
Low rainfall								
Kota	6 Jun	24 Jul	2 Jul	11	8 Oct	7 Nov	18 Oct	6
Medium rainfall								
Nimuch	4 Jun	28 Jul	29 Jun	15	6 Oct	28 Oct	14 Oct	6
Ujjain	5 Jun	23 Jul	21 Jun	11	4 Oct	1 Nov	10 Oct	6
Dhar	1 Jun	13 Jul	22 Jun	12	1 Oct	22 Oct	11 Oct	6
Kannod	4 Jun	4 Aug	27 Jun	15	2 Oct	3 Nov	12 Oct	7
Rajgarh (Saunther)	9 Jun	16 Jul	26 Jun	10	6 Oct	23 Oct	13 Oct	4
High rainfall								
Guna (Saunther)	9 Jun	22 Jul	30 Jun	11	8 Oct	23 Oct	13 Oct	5
Nagpur	5 Jun	7 Jul	20 Jun	9	29 Sep	16 Oct	7 Oct	5
Shajapur (Saunther)	7 Jun	24 Jul	25 Jun	14	4 Oct	28 Oct	12 Oct	6
Wardha	1 Jun	12 Jul	17 Jun	10	29 Sep	18 Oct	5 Oct	5
Indore (Kamiliakheri)	7 Jun	25 Jul	21 Jun	12	2 Oct	27 Oct	9 Oct	6
Indore (Sarol)	7 Jun	18 Jul	20 Jun	10	3 Oct	29 Oct	9 Oct	7
Ratlam	1 Jun	29 Jul	18 Jun	14	1 Oct	2 Nov	10 Oct	6
Raisen (Jamra)	1 Jun	8 Jul	22 Jun	8	5 Oct	18 Oct	10 Oct	3
Betul	1 Jun	3 Jul	19 Jun	7	30 Sep	14 Oct	7 Oct	3
Bhopal (Saunther)	1 Jun	7 Jul	17 Jun	9	2 Oct	19 Oct	9 Oct	4
Bhopal (Jamra)	1 Jun	7 Jul	16 Jun	10	2 Oct	19 Oct	8 Oct	4
Sagar	1 Jun	15 Jul	22 Jun	13	3 Oct	26 Oct	12 Oct	6
SECONDARY ZONE								
Medium rainfall								
Akola	1 Jun	10 Jul	18 Jun	12	28 Sep	19 Oct	7 Oct	6
Amravati	5 Jun	10 Jul	18 Jun	11	1 Oct	19 Oct	7 Oct	5
Jhabua	1 Jun	20 Jul	29 Jun	13	1 Oct	1 Nov	13 Oct	7
High rainfall								
Vidisha	1 Jun	16 Jul	24 Jun	12	6 Oct	22 Oct	13 Oct	4
Belgaum	1 Jun	12 Jul	17 Jun	10	22 Sep	15 Oct	29 Sep	6
Jabalpur	8 Jun	8 Jul	23 Jun	7	5 Oct	17 Oct	9 Oct	3
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	3 Jun	12 Jul	20 Jun	9	25 Sep	18 Oct	4 Oct	5
Patancheru (shallow soil)	3 Jun	12 Jul	20 Jun	9	25 Sep	18 Oct	4 Oct	5
Nanded	1 Jun	26 Jul	23 Jun	14	27 Sep	28 Oct	9 Oct	7

Soybean yields. Considering the simulated mean seed yield of soybean, the primary, secondary, and tertiary locations were respectively categorized into low (<1500 kg ha^{-1}), medium (1500–2000 kg ha^{-1}), and high seed yield potential (>2000 kg ha^{-1}). Indore (Kamiliakheri), Kota, and Rajgarh (Saunther) of the primary zone, Akola of secondary zone, and Nanded of tertiary zone fell under low potential yield category while Betul, Indore (Sarol), Bhopal (Jamra), Dhar, Raisen, and Wardha of primary zone, Jabalpur and Vidisha of secondary zone, and Patancheru of tertiary zone fell under high yield potential category (Table 10). The remaining sites fell under medium yield potential category. The simulated results of seasonal analysis showed that 50, 33, and 17% sites of the primary and secondary zones were categorized under medium, high, and low yield potential, respectively. More than 80% of sites selected for simulation from the soybean-growing regions of India had medium to high mean yield potential. From this, it can be implied that a good potential for growing soybean exists at majority of the sites in India. There was a large difference between maximum obtainable yield and minimum yields for the selected locations (Table 10). The threshold value for economic yield of soybean was tentatively fixed at 500 kg ha^{-1} (because farmers consider as crop failure when the yields are less than 500 kg ha^{-1}). The minimum simulated yields revealed that the potential was less than this threshold value for locations having low mean potential and also in some other medium and high potential sites like Bhopal (Saunther), Guna, Rajgarh (Saunther), Nimuch, Ratlam, Raisen, Amravati, and Jhabua; whereas at the remaining sites the minimum yield was more than 500 kg ha^{-1}.

Table 10. Seed yield and total dry matter of simulated soybean in seasonal analysis for various benchmark sites in India[1].

	Seed yield				Total dry matter			
Site	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
PRIMARY ZONE								
Low rainfall								
Kota	80	3188	1205	77	463	6014	2414	66
Medium rainfall								
Nimuch	188	2951	1595	51	380	5279	3154	41
Ujjain	704	2919	1867	39	1223	5024	3416	34
Dhar	533	4246	2385	41	1119	6953	4146	35
Kannod	506	3305	1642	55	878	5602	3087	45
Rajgarh (Saunther)	328	2687	1259	52	591	4403	2396	42
High rainfall								
Guna (Saunther)	342	2916	1633	56	1050	5332	3211	44
Nagpur	1062	2673	1941	25	1738	4798	3339	23
Shajapur (Saunther)	566	3293	1639	50	930	5511	2952	44
Wardha	1824	3955	3040	21	3225	6702	5351	20
Indore (Kamiliakheri)	175	2758	1301	61	685	5517	2575	53
Indore (Sarol)	760	4588	2273	41	1353	7999	4134	37
Ratlam	474	3043	1848	45	846	5206	3357	41
Raisen (Jamra)	393	4670	2882	44	1859	8312	5576	31
Betul	924	3296	2141	28	1665	5258	3793	22
Bhopal (Saunther)	361	2678	1807	35	1422	4580	3273	29
Bhopal (Jamra)	805	3064	2310	27	2486	5445	4278	22
Sagar	610	3198	1965	35	1850	5339	3652	30
SECONDARY ZONE								
Medium rainfall								
Akola	133	2537	1360	57	176	4093	2279	55
Amravati	440	2624	1552	46	775	4672	2772	41
Jhabua	117	2716	1939	38	487	5026	3363	34
High rainfall								
Vidisha	911	3250	2224	25	2168	6344	4200	23
Belgaum	858	2943	1844	34	1542	4727	3100	30
Jabalpur	1132	2477	2079	18	2249	4149	3637	15
TERITIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	700	3396	2664	26	1636	5504	4433	24
Patancheru (shallow soil)	752	3370	2700	26	1750	5460	4489	23
Nanded	293	3872	1662	63	517	6150	2672	60

1. Minimum, maximum, and mean values are given in kg ha^{-1}.

Year-to-year variation in seed yield expressed as CV ranged from 18 to 77% across sites and production zones. The variation in yields could be classified as low, medium, and high when the CV is <30, 30–50, and >50%, respectively. All sites with low yield potential had CV >50%. Hence these locations are prone to high climatic risk. Sites with high yield potential like Jabalpur, Wardha, Vidisha, Patancheru, Bhopal (Jamra), and Betul had CV <30%; therefore these sites are more stable compared to other high-yielding sites with CV between 30 and 50%. All sites with medium yield potential had CV between 30 and 50%, except Nagpur with low and Nimuch, Kannod, and Guna with high variation.

Based on the total biomass all the locations were categorized into low (<3000 kg ha^{-1}), medium (3000–4000 kg ha^{-1}), and high (>5000 kg ha^{-1}). All locations with low total biomass had low seed yield potential except Shajapur and Amravati, which had medium seed yield potential, whereas all locations with high total biomass had high seed yield potential. Betul and Jabalpur with medium total biomass had high seed yield (see Appendices I and II).

Water balance of sole soybean

Rainfall. Considering the mean annual rainfall of the selected sites, all the 24 sites selected for simulation were classified into low (<750 mm), medium (750–1000 mm), and high (>1000 mm) rainfall areas within each soybean production zone (Table 6). The same criteria were used for classifying seasonal rainfall during soybean growing period since more than 90% rainfall occurred during this period. Mean seasonal rainfall at each site did not satisfy the categorization based on annual rainfall. Sites having CV of 30% or more were considered as having high variability, whereas those with <30% were considered as having low variability. The CV in rainfall to some extent also depended upon the quality as well as the number of years of weather data available. Kota and Nimuch of primary zone, Akola of secondary zone, and Patancheru of tertiary zone had low rainfall (<750 mm). All these low rainfall sites showed high variation. Ratlam, Raisen, Bhopal, Betul, and Sagar of the primary zone, and Jabalpur of the secondary zone had seasonal rainfall >1000 mm (Table 11). Of these high rainfall sites Bhopal, Ratlam, and Sagar had high CV and hence less dependable compared to other sites. More than 50% sites of the primary and tertiary zone and 67% sites of the secondary zone had medium rainfall (750–1000 mm). Among such sites, Ujjain, Kannod, Nimuch, Guna, Jhabua, and Rajgarh had high CV compared to others. The mean rainfall of all primary, secondary, and tertiary centers was 965, 903, and 752 mm respectively. Based on the mean rainfall, 58% of the sites were categorized under medium rainfall category (750–1000 mm), 17% under low rainfall (<750 mm), and 25% under high rainfall (>1500 mm) groups. From this, it can be said that most of the soybean cultivation in India is concentrated in medium rainfall zones. The minimum and maximum values indicated that all sites had rainfall below 600 mm (low group) and above 1000 mm (high group) respectively. A poor but positive correlation (r = 0.24) existed between rainfall and seed yield, which may be due to poor distribution of rainfall to meet the crop water needs.

Surface runoff. Across locations mean rainfall and mean runoff were highly correlated (r = 0.90). All the locations with kharif (rainy season) rainfall of <800 mm and Dhar and Vidisha which had 900 and 950 mm of kharif rainfall, respectively, had low mean runoff potential (<275 mm). Locations with kharif rainfall between 800 and 1000 mm, and Raisen with 1050 mm rainfall had medium runoff potential (275–350 mm). Other locations with rainfall of >1000 mm had high runoff potential (>350 mm) (Table 11). The CV ranged from 49% (Akola) to 95% (Jhabua) at low runoff potential sites and from 41% (Betul) to 64% (Raisen) at medium runoff potential sites.

The simulation results showed that on an average 34, 31, and 29% of seasonal rainfall was lost as runoff from high, medium, and low rainfall regimes, respectively. The runoff varied from 26% (Patancheru) to 31% (Nimuch and Kota) for low rainfall sites, from 22% (Jhabua) to 36% (Rajgarh and Ujjain) for medium rainfall sites, and from 30% (Raisen and Jabalpur) to 37% (Bhopal and Ratlam) for high rainfall sites. A higher runoff from high rainfall sites explains to some extent the poor correlation between rainfall and seed yield. For example, low runoff values at Patancheru favor high yields in spite of low mean rainfall.

Table 11. Water balance components (mm) of simulated sole soybean in seasonal analysis for various sites in India (values of extractable water are at soybean harvest).

	Rainfall				Surface runoff				Deep drainage				Evapotranspiration				Extractable water			
Site	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
PRIMARY ZONE																				
Low rainfall																				
Kota	300	1475	683	40	25	655	212	70	0	185	38	149	119	481	327	25	12	222	106	61
Medium rainfall																				
Nimuch	306	1467	747	32	28	688	234	63	0	423	80	113	184	469	329	20	20	149	103	30
Ujjain	454	1839	897	33	100	936	324	55	0	397	84	126	247	448	357	14	63	182	132	22
Dhar	596	1492	907	24	75	647	255	56	0	314	81	118	307	609	436	19	48	188	135	26
Kannod	426	1716	892	36	35	774	299	61	0	395	93	103	287	485	373	16	42	191	127	32
Rajgarh (Saunther)	424	1701	949	30	81	841	338	54	39	501	221	48	230	469	346	18	22	81	44	36
High rainfall																				
Guna (Saunther)	330	1775	963	33	65	931	334	58	1	341	213	45	234	500	375	19	14	91	40	43
Nagpur	553	1463	956	23	83	676	300	44	0	318	130	66	292	473	400	11	90	160	126	16
Shajapur (Saunther)	589	1769	953	25	80	848	322	54	42	547	214	47	238	513	366	19	28	76	51	26
Wardha	569	1579	974	23	91	731	302	47	0	310	109	85	347	544	458	11	51	177	105	41
Indore (Kamiliakheri)	555	1447	970	23	99	826	335	47	27	303	185	44	273	562	430	20	1	47	20	65
Indore (Sarol)	555	1447	968	23	99	825	336	47	0	159	49	118	315	616	471	19	22	181	112	36
Ratlam	582	1851	1020	30	148	890	379	48	11	394	150	75	226	451	339	17	112	204	152	16
Raisen (Jamra)	444	1612	1055	28	72	682	308	64	0	209	111	68	356	648	530	16	16	149	106	28
Betul	574	1544	1099	22	139	692	372	41	0	303	116	79	283	459	371	12	151	288	240	12
Bhopal (Saunther)	462	1846	1099	30	75	920	403	50	72	518	288	43	248	430	354	12	15	92	54	33
Bhopal (Jamra)	462	1846	1099	30	71	909	391	51	0	455	221	57	281	443	370	10	58	171	117	21
Sagar	442	2047	1144	31	85	896	400	53	0	584	260	54	245	521	363	16	62	166	121	19
SECONDARY ZONE																				
Medium rainfall																				
Akola	278	1191	705	30	37	448	201	49	0	103	6	350	225	470	360	18	15	299	138	51
Amravati	496	1151	771	26	42	454	214	54	0	47	8	200	267	554	393	19	25	267	156	50
Jhabua	293	1421	794	33	61	554	175	95	0	361	71	125	217	523	417	24	5	184	131	140
High rainfall																				
Vidisha	562	1627	951	25	93	684	246	65	0	437	144	73	289	567	447	21	38	156	113	21
Belgaum	558	1561	957	23	98	741	310	46	0	287	103	83	320	496	390	13	121	191	154	14
Jabalpur	592	1989	1241	24	126	1002	369	63	0	572	341	45	276	442	387	13	104	164	144	10
TERTIARY ZONE																				
Medium rainfall																				
Patancheru (deep soil)	469	1293	734	31	51	706	200	69	0	200	31	181	315	454	397	9	13	202	105	55
Patancheru (shallow soil)	469	1293	734	31	49	698	198	68	0	232	48	146	318	455	398	9	13	152	90	49
Nanded	309	1515	787	31	33	599	192	70	0	95	6	358	247	650	443	25	19	282	146	55

In general, the mean runoff potential was more than 25% of seasonal rainfall for all the soybean-growing sites simulated except Jhabua. The high runoff values indicate the need for various conservation measures to control soil erosion and harvest excess runoff water, especially at sites having high rainfall.

Deep drainage. Imperfect drainage is a problem since many of the soybean-growing sites in India are on Vertisols. Deep drainage is primarily determined by the water-holding capacity of the soil profile and the amount and distribution of rainfall in addition to other factors such as soil porosity, infiltration capacity, and slope of the land. Like runoff, a positive correlation ($r = 0.85$) existed between rainfall and deep drainage. On an average 6, 12, and 19% of rainfall was lost as deep drainage from the low, medium, and high rainfall sites, respectively. Deep drainage was low (<50 mm) at sites with low rainfall except Nimuch, where it showed medium drainage (50–200 mm). Deep drainage was high (>200 mm) for high rainfall sites, except Raisen, Betul, and Ratlam, which showed medium drainage (Table 11). Sites with medium rainfall, i.e., Amravati, Nanded, and Indore (Sarol) had low deep drainage and Guna, Shajapur, and Rajgarh had high drainage and the remaining sites had medium drainage. High drainage at Guna, Shajapur, and Rajgarh may be because these locations were simulated with shallow Saunther series. From the above, it can be inferred that sites like Raisen, Betul, Ratlam, Amravati, Nanded, and Indore (Sarol), where rainfall is high but the deep drainage is low or medium, could be prone to waterlogging compared to other sites. Also, the estimated initial NO_3-N content of the soil series associated with these sites is low. The CV for deep drainage is much larger than that for surface runoff as the deep drainage at some sites did not occur every year.

Evapotranspiration. As expected, seed yield and evapotranspiration (ET) were well correlated ($r = 0.60$). ET was more than 400 mm at Indore, Dhar, Wardha, and Raisen of primary zone, Jhabua and Vidisha of secondary zone, and Nanded of tertiary zone (Table 11). Yield potential was medium to high at these locations. At the locations which had low yield potential, the ET was between 325 and 400 mm. The CV ranged from 11% (Wardha) to 25% (Nanded). In general, with the increase in the amount of rainfall greater proportion of rainfall was used as ET by the soybean crop. At the low rainfall site of Kota, an average 47.9% of rainfall was used as ET. At the medium-rainfall sites in all the three zones, ET ranged from 36.5% to 56.3% of seasonal rainfall, whereas at the high rainfall sites of the primary and secondary zones, ET ranged from 31.2% to 50.2% of seasonal rainfall. The remaining rainfall was either lost as surface runoff and deep drainage or retained in the soil profile for the next crop.

Extractable soil water. Extractable water left in the soil profile at harvest of the soybean crop is determined by the extractable water-holding capacity of the soil and the amount of rainfall received prior to the harvest of the soybean crop. The sites differed significantly in the amount of water retained in the soil at soybean harvest indicating the potential to grow the next season crop at different sites (Table 11). There was also year-to-year variability in the amount of water retained in the soil. Generally, the sites in the low and medium rainfall regime had less variability in extractable soil water retained compared to those in the high rainfall regime.

Soybean-chickpea sequential system

Sowing and harvest dates of soybean. The mean sowing date for soybean was after 23 June at Kota, Guna, Nimuch, and Kannod and in the remaining locations it was before this date (Table 12). The mean sowing date across soybean production zones ranged from 12 June and 29 June. Due to the carryover effect of soil moisture, the sowing dates simulated were slightly earlier than those simulated for the seasonal analysis. Generally, the variation in sowing date was more for locations where soybean was sown late. Harvest date for soybean ranged from 29 September at Belgaum to 16

October at Kota. The variation in harvest date was less than that observed for the sowing date. The duration of soybean crop was slightly more than that in seasonal analysis. It ranged from 108 days at Belgaum to 118 days at Sagar.

Table 12. Sowing and harvest dates of simulated soybean in sequential analysis for various sites in India.

	Sowing date				Harvest date			
Site	Early	Late	Mean	SD	Early	Late	Mean	SD
PRIMARY ZONE								
Low rainfall								
Kota	9 Jun	28 Jul	29 Jun	12	8 Oct	27 Oct	16 Oct	5
Medium rainfall								
Nimuch	2 Jun	5 Aug	25 Jun	15	5 Oct	28 Oct	13 Oct	6
Ujjain	1 Jun	12 Jul	17 Jun	9	3 Oct	17 Oct	9 Oct	4
Dhar	1 Jun	21 Jul	19 Jun	11	1 Oct	21 Oct	11 Oct	6
Kannod	4 Jun	31 Jul	23 Jun	13	2 Oct	25 Oct	11 Oct	6
Rajgarh (Saunther)	1 Jun	18 Jul	18 Jun	12	5 Oct	18 Oct	11 Oct	3
Rajgarh (Jamra)	1 Jun	18 Jul	19 Jun	12	4 Oct	18 Oct	11 Oct	4
High rainfall								
Guna (Saunther)	1 Jun	30 Jul	26 Jun	13	6 Oct	23 Oct	13 Oct	5
Guna (Jamra)	1 Jun	27 Jul	25 Jun	13	6 Oct	22 Oct	13 Oct	5
Nagpur	1 Jun	12 Jul	14 Jun	11	27 Sep	16 Oct	6 Oct	5
Shajapur (Saunther)	1 Jun	1 Aug	20 Jun	12	3 Oct	28 Oct	10 Oct	6
Shajapur (Sarol)	1 Jun	1 Aug	20 Jun	13	3 Oct	28 Oct	11 Oct	6
Wardha	1 Jun	20 Jul	14 Jun	11	29 Sep	18 Oct	5 Oct	5
Indore (Kamiliakheri)	7 Jun	12 Jul	18 Jun	8	2 Oct	18 Oct	9 Oct	4
Indore (Sarol)	1 Jun	12 Jul	17 Jun	9	2 Oct	18 Oct	9 Oct	4
Ratlam	1 Jun	6 Aug	17 Jun	14	1 Oct	2 Nov	10 Oct	6
Raisen (Jamra)	1 Jun	16 Jul	19 Jun	9	3 Oct	18 Oct	10 Oct	3
Raisen (Sarol)	1 Jun	16 Jul	19 Jun	9	4 Oct	19 Oct	10 Oct	3
Betul	1 Jun	5 Jul	13 Jun	9	1 Oct	12 Oct	6 Oct	4
Bhopal (Saunther)	1 Jun	15 Jul	15 Jun	10	2 Oct	19 Oct	9 Oct	4
Bhopal (Jamra)	1 Jun	15 Jul	15 Jun	10	2 Oct	19 Oct	9 Oct	4
Sagar	1 Jun	17 Jul	14 Jun	11	3 Oct	26 Oct	10 Oct	5
SECONDARY ZONE								
Medium rainfall								
Akola	1 Jun	11 Jul	16 Jun	9	26 Sep	17 Oct	6 Oct	5
Amravati	1 Jun	17 Jul	12 Jun	10	30 Sep	18 Oct	5 Oct	5
Jhabua	1 Jun	27 Jul	18 Jun	13	30 Sep	31 Oct	9 Oct	8
High rainfall								
Vidisha	1 Jun	14 Jul	16 Jun	11	4 Oct	17 Oct	10 Oct	4
Belgaum	1 Jun	20 Jul	13 Jun	11	22 Sep	15 Oct	29 Sep	6
Jabalpur	1 Jun	16 Jul	19 Jun	8	5 Oct	16 Oct	9 Oct	3
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	1 Jun	11 Jul	17 Jun	9	23 Sep	13 Oct	3 Oct	5
Patancheru (shallow soil)	1 Jun	11 Jul	17 Jun	9	23 Sep	13 Oct	3 Oct	6
Nanded	1 Jun	18 Jul	17 Jun	12	24 Sep	20 Oct	7 Oct	6

Soybean yields. Because of the carryover effects of soil moisture from one season to another in the sequential analysis, the soybean yields were relatively higher in sequential analysis compared to the seasonal analysis. Therefore, few locations that were classified under lower yield potential with seasonal analysis shifted to high yield potential category. Indore (Kamiliakheri), Kota, and Rajgarh (Saunther) of the primary zone had low yield potential (<1500 kg ha^{-1}) (Table 13). Guna, Shajapur, and Bhopal (all simulated with shallow Saunther series) and Nimuch, Kannod, and Rajgarh (Jamra series) of the primary zone; Akola, Amravati, Jhabua, and Belgaum of the secondary zone; and Nanded of the tertiary zone had medium yield potential (1500 to 2000 kg ha^{-1}). All other sites had high yield potential (>2000 kg ha^{-1}). Simulations for some locations (Guna, Shajapur, Rajgarh, Indore, and Bhopal) were done with two separate soil series because of their proximity to the sites and as expected deeper soil series showed higher yield potential (Table 13). However, yield difference was not obtained when the Patancheru station was analyzed with deep and shallow soils of the Kasireddipalli series. This may be because the soil moisture during the rainy season was not a limiting factor at Patancheru. The simulated results showed that 57, 29, and 14% of the sites in the primary zone were categorized under high, medium, and low yield potential, respectively; and 67 and 33% of the secondary zone under high and medium yield potential, respectively. Of the two tertiary centers studied, one had high and the other medium potential. Considering all the soybean zones, about 90% of the sites selected for simulation studies had medium to high mean yield potential. Thus, it can be inferred that a good potential for growing soybean exists at most of the sites in India.

The minimum yields showed that the potential was less than half a ton for sites having low mean yield potential and also for other medium and high potential sites like Bhopal (Saunther), Guna (Saunther), Akola, and Nanded. When compared to the seasonal analysis only few locations showed minimum yields below the economic threshold, i.e., less than half a ton. The variation in the yields due to weather was similar to that obtained with seasonal analysis.

Potential of sites for total biomass production, generally followed the same trend as for the mean seed yield, i.e., the locations which had higher biomass had higher seed yields and vice-versa (Appendices III and IV).

Yield gap of soybean. The mean observed yields of soybean ranged from 540 kg ha^{-1} at Belgaum to 1000 kg ha^{-1} at Kota while the simulated yields ranged from 1220 kg ha^{-1} at Indore to 3100 kg ha^{-1} (Kamiliakheri series) at Wardha (Table 13). Based on the mean observed yields, Belgaum, Rajgarh, Jhabua, and Guna were classified as low (<700 kg ha^{-1}); Jabalpur, Betul, Nimuch, Sagar, Nagpur, Shajapur, Amravati, Vidisha, Raisen, Kannod, and Ratlam as medium (700–850 kg ha^{-1}); and Bhopal, Dhar, Ujjain, Wardha, Indore, Nanded, Akola, and Kota as high (>850 kg ha^{-1}) yield potential sites. Except Kota, Akola, and Nanded, all the centers where the district average yields were high, the simulated potential yields were also high. The total mismatch between simulated and observed yields in case of Kota indicates that the area could be under irrigation. For the sites with low and medium observed yields, the corresponding simulated yields ranged from low to medium and medium to high yield, respectively. From this, it can be said that concurrence existed between simulated and observed yields. It is not logical to correlate simulated yields with the observed yields because the simulated yields are from point area, whereas observed yields are district averages where many constraints such as pests and diseases, waterlogging, and nutrient deficiencies might have been affecting the yield in addition to spatial variability in weather. Inspite of this, a good correlation ranging from 0.4 to 0.8 was observed for Rajgarh, Guna, Ujjain, Jhabua, Ratlam, Nagpur, Shajapur, Jabalpur, and Amravati, and from 0.1 to 0.4 for Bhopal (Saunther), Dhar, Nanded, Indore (Sarol), Wardha, Sagar, Betul, Nimuch, Kannod, and Vidisha. A poor correlation of less than 0.1 was noted for Belgaum, Raisen, Indore (Kamiliakheri), and Bhopal (Jamra). A strong correlation indicated that yield variation was primarily caused by weather variability, whereas a weak correlation indicated that factors other than weather were affecting the crop yields or it can even be a wrongly matched soil series or poor quality weather data.

October at Kota. The variation in harvest date was less than that observed for the sowing date. The duration of soybean crop was slightly more than that in seasonal analysis. It ranged from 108 days at Belgaum to 118 days at Sagar.

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PRIMARY ZONE								
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Kota	9 Jun	28 Jul	29 Jun	12	8 Oct	27 Oct	16 Oct	5
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Dhar	1 Jun	21 Jul	19 Jun	11	1 Oct	21 Oct	11 Oct	6
Kannod	4 Jun	31 Jul	23 Jun	13	2 Oct	25 Oct	11 Oct	6
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Rajgarh (Jamra)	1 Jun	18 Jul	19 Jun	12	4 Oct	18 Oct	11 Oct	4
High rainfall								
Guna (Saunther)	1 Jun	30 Jul	26 Jun	13	6 Oct	23 Oct	13 Oct	5
Guna (Jamra)	1 Jun	27 Jul	25 Jun	13	6 Oct	22 Oct	13 Oct	5
Nagpur	1 Jun	12 Jul	14 Jun	11	27 Sep	16 Oct	6 Oct	5
Shajapur (Saunther)	1 Jun	1 Aug	20 Jun	12	3 Oct	28 Oct	10 Oct	6
Shajapur (Sarol)	1 Jun	1 Aug	20 Jun	13	3 Oct	28 Oct	11 Oct	6
Wardha	1 Jun	20 Jul	14 Jun	11	29 Sep	18 Oct	5 Oct	5
Indore (Kamiliakheri)	7 Jun	12 Jul	18 Jun	8	2 Oct	18 Oct	9 Oct	4
Indore (Sarol)	1 Jun	12 Jul	17 Jun	9	2 Oct	18 Oct	9 Oct	4
Ratlam	1 Jun	6 Aug	17 Jun	14	1 Oct	2 Nov	10 Oct	6
Raisen (Jamra)	1 Jun	16 Jul	19 Jun	9	3 Oct	18 Oct	10 Oct	3
Raisen (Sarol)	1 Jun	16 Jul	19 Jun	9	4 Oct	19 Oct	10 Oct	3
Betul	1 Jun	5 Jul	13 Jun	9	1 Oct	12 Oct	6 Oct	4
Bhopal (Saunther)	1 Jun	15 Jul	15 Jun	10	2 Oct	19 Oct	9 Oct	4
Bhopal (Jamra)	1 Jun	15 Jul	15 Jun	10	2 Oct	19 Oct	9 Oct	4
Sagar	1 Jun	17 Jul	14 Jun	11	3 Oct	26 Oct	10 Oct	5
SECONDARY ZONE								
Medium rainfall								
Akola	1 Jun	11 Jul	16 Jun	9	26 Sep	17 Oct	6 Oct	5
Amravati	1 Jun	17 Jul	12 Jun	10	30 Sep	18 Oct	5 Oct	5
Jhabua	1 Jun	27 Jul	18 Jun	13	30 Sep	31 Oct	9 Oct	8
High rainfall								
Vidisha	1 Jun	14 Jul	16 Jun	11	4 Oct	17 Oct	10 Oct	4
Belgaum	1 Jun	20 Jul	13 Jun	11	22 Sep	15 Oct	29 Sep	6
Jabalpur	1 Jun	16 Jul	19 Jun	8	5 Oct	16 Oct	9 Oct	3
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	1 Jun	11 Jul	17 Jun	9	23 Sep	13 Oct	3 Oct	5
Patancheru (shallow soil)	1 Jun	11 Jul	17 Jun	9	23 Sep	13 Oct	3 Oct	6
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Table 13. Simulated seed yield, observed mean yield, and yield gap of soybean in sequential analysis for various sites in India[1].

Site	Simulated yield					Observed mean yield	Yield gap with mean	Yield gap with maximum
	Min	25 percentile	Max	Mean	CV (%)			
PRIMARY ZONE								
Low rainfall								
Kota	350	575	2896	1315	58	1004	311	1892
Medium rainfall								
Nimuch	653	1203	3021	1842	41	769	1073	2252
Ujjain	899	1530	3011	2158	31	883	1275	2128
Dhar	708	2031	4249	2722	34	866	1856	3383
Kannod	639	1102	3325	1893	44	836	1056	2489
Rajgarh (Saunther)	348	810	2385	1338	46	624	713	1761
Rajgarh (Jamra)	787	997	3023	1903	39	624	1279	2399
High rainfall								
Guna (Saunther)	301	1041	3061	1755	52	660	1095	2401
Guna (Jamra)	532	1403	3698	2209	46	660	1549	3038
Nagpur	1230	1688	2871	2099	26	787	1312	2084
Shajapur (Saunther)	726	919	3316	1759	45	791	968	2525
Shajapur (Sarol)	953	1338	3694	2110	35	791	1319	2903
Wardha	1904	2442	4026	3108	20	907	2201	3119
Indore (Kamiliakheri)	158	542	2855	1220	67	932	288	1923
Indore (Sarol)	796	1542	4180	2308	36	932	1376	3248
Ratlam	623	1115	3530	2016	42	830	1186	2700
Raisen (Jamra)	594	1880	4744	2949	40	836	2113	3908
Raisen (Sarol)	713	2041	4543	3024	37	836	2189	3707
Betul	1520	1870	3253	2297	20	747	1550	2506
Bhopal (Saunther)	375	1473	2818	1892	34	856	1036	1962
Bhopal (Jamra)	732	2134	3339	2402	27	856	1545	2483
Sagar	1218	1767	3244	2291	24	772	1519	2472
SECONDARY ZONE								
Medium rainfall								
Akola	137	844	2730	1515	48	990	525	1740
Amravati	966	1246	2609	1740	31	798	942	1811
Jhabua	450	1420	2782	1919	35	629	1290	2153
High rainfall								
Vidisha	1691	2162	3599	2646	20	820	1826	2779
Belgaum	960	1200	2882	1922	32	541	1381	2341
Jabalpur	1184	2046	2566	2133	18	734	1399	1832
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	983	2598	3557	2873	24	-	-	-
Patancheru (shallow soil)	943	2564	3578	2865	24	-	-	-
Nanded	433	1204	3950	1902	51	995	907	2955

1. All values (except CV) are given in kg ha^{-1}.

Mean simulated yield obtained for a location was compared with the mean observed yield (from 1983 to 1995 or available data) to calculate the yield gap. In general, the sites having greater yield potential had larger yield gap. On an average, the yield gap was around 550 kg ha^{-1} for sites having low, 1000 kg ha^{-1} for medium, and 1600 kg ha^{-1} for high soybean yield potential (Table 13). The yield gap ranged from 300 (Indore-Kamiliakheri) to 900 kg ha^{-1} (Nanded) for low, from 950 (Amravati) to 1500 kg ha^{-1} (Akola) for medium, and from 1200 (Ratlam) to 2200 kg ha^{-1} (Wardha) for high potential areas. The sites where the yield gap was more indicated greater opportunity for increasing the yield provided the yield constraints could be economically managed. Hence, it will be very useful to study the constraints causing yield gap at each site. Maximum obtainable yield at each site was considered as water non-limiting yield. Based on the maximum yield, the yield gap ranged from 1800 to 4000 kg ha^{-1}. The average yield gap was 2130 kg ha^{-1} for low potential areas, 2250 kg ha^{-1} for medium potential areas, and 2750 kg ha^{-1} for high potential areas. The yield gap between water non-limiting and water-limiting yields was 1580, 1250, and 1150 kg ha^{-1} for low, medium, and high potential sites, respectively, indicating the potential to increase yields with irrigation.

Sowing and harvest dates of chickpea. Mean sowing date for chickpea, after soybean harvest, ranged from 12 to 30 October. Generally, the variability in sowing dates was greater with the late mean sowing dates (Table 14). At most of the sites, chickpea could not be sown in many years as the minimum requirement of soil moisture content set in the model for chickpea sowing to occur could not be satisfied. At Sagar, Vidisha, Belgaum, and Patancheru sowing could occur every year whereas at Dhar, Kannod, Rajgarh, Shajapur, Indore, Ratlam, and Jhabua chickpea could not be sown for at least 25% of years. These results indicate the potential of double cropping at various sites in the absence of irrigation. Alternatively, growing of shorter duration soybean during the rainy season would help establishment of chickpea crop after soybean harvest. Variability in the harvest dates of chickpea was as high as for sowing dates. Sites having greater variability in sowing dates also had greater variability in harvest dates and vice-versa**.** Unlike soybean crop there was a lot of variation in the duration of chickpea. It ranged from 97 days at Wardha to 137 days at Nimuch.

Chickpea yields. Considering the mean simulated chickpea yields, the sites were classified into low (<750 kg ha^{-1}), medium (750–1200 kg ha^{-1}), and high (>1200 kg ha^{-1}) yield potential categories. Guna, Shajapur, Rajgarh, Indore, and Bhopal sites were analyzed with two soil series, i.e., deep and shallow soils (Table 15). Simulations for Patancheru were done for both shallow and deep soils within Kasireddipalli series. All the sites of the primary zone analyzed with shallow soil series (Saunther and Kamiliakheri) had mean yields below 550 kg ha^{-1}, which could be uneconomical. Therefore, it was not possible to grow chickpea on these shallow soils without irrigation. Other sites in the primary zone where the yields were low are Raisen, Guna, Kota, and Nimuch. The low yields at Raisen could be because of likely high estimation of solar radiation since only three years of minimum and maximum temperature data were available. The variation was considered to be high for chickpea when the CV was at least 70%. All sites except Raisen had high variation indicating that the risk is more in low potential areas. Nagpur, Bhopal (Jamra), Sagar, Ratlam, Betul, and Wardha fell under high yield potential areas while the other primary locations came under medium potential areas. At most of the sites the CV for chickpea yield was more than 50%, the highest being at Kota. When the yield potential of soybean and chickpea was compared, all primary locations with high soybean yield potential, except Guna (Jamra) and Raisen, had medium to high chickpea yield potential; whereas locations with medium to low soybean yield potential, except Kannod, had low chickpea yield potential. Akola, Belgaum, and Amravati of secondary zone and Patancheru (deep) and Nanded of tertiary zone fell under high chickpea yield potential category while others came under medium category. When yield potential of soybean and chickpea of secondary locations was compared, all sites of the secondary zone with medium soybean yield potential except Jhabua had high chickpea yield potential and vice-versa. Under the tertiary zone, Patancheru (shallow) with high and Nanded with medium soybean yield potential had medium and high chickpea potential respectively. All the sites with high yield potential had low variation except Akola and Amravati. Among sites with medium yield potential only Vidisha, Jabalpur, and Ujjain had low variation. Sites with high yield potential and low CV could be considered as stable and less risky to climatic variations.

Table 14. Sowing and harvest dates of simulated chickpea in sequential analysis for various sites in India.

	Sowing date					Harvest date			
Site	Early	Late	Mean	SD	% years not sown	Early	Late	Mean	SD
PRIMARY ZONE									
Low rainfall									
Kota	12 Oct	21 Nov	24 Oct	12	10	2 Feb	24 Mar	21 Feb	14
Medium rainfall									
Nimuch	10 Oct	17 Nov	18 Oct	8	15	29 Jan	12 Mar	1 Mar	9
Ujjain	10 Oct	30 Nov	23 Oct	16	22	31 Jan	1 Apr	21 Feb	17
Dhar	10 Oct	28 Nov	17 Oct	10	26	20 Jan	16 Mar	6 Feb	13
Kannod	10 Oct	29 Nov	23 Oct	17	25	28 Jan	28 Mar	12 Feb	18
Rajgarh (Saunther)	10 Oct	30 Nov	27 Oct	18	28	27 Jan	26 Mar	19 Feb	18
Rajgarh (Jamra)	10 Oct	30 Nov	30 Oct	18	28	26 Jan	28 Mar	23 Feb	18
High rainfall									
Guna (Saunther)	10 Oct	28 Nov	19 Oct	11	10	31 Jan	21 Mar	13 Feb	11
Guna (Jamra)	10 Oct	27 Nov	20 Oct	11	15	1 Feb	27 Mar	20 Feb	12
Nagpur	10 Oct	29 Nov	16 Oct	14	11	20 Jan	19 Mar	28 Jan	17
Shajapur (Saunther)	10 Oct	10 Nov	16 Oct	8	32	3 Feb	3 Mar	12 Feb	9
Shajapur (Sarol)	10 Oct	10 Nov	17 Oct	8	32	1 Feb	7 Mar	15 Feb	10
Wardha	10 Oct	30 Nov	23 Oct	19	12	11 Jan	10 Mar	28 Jan	19
Indore (Kamiliakheri)	10 Oct	30 Nov	27 Oct	18	25	19 Jan	16 Mar	10 Feb	17
Indore (Sarol)	10 Oct	30 Nov	25 Oct	18	21	24 Jan	29 Mar	13 Feb	18
Ratlam	10 Oct	18 Nov	19 Oct	13	27	22 Jan	11 Mar	5 Feb	15
Raisen (Jamra)	10 Oct	28 Nov	23 Oct	18	13	9 Feb	26 Mar	2 Mar	16
Raisen (Sarol)	10 Oct	28 Nov	19 Oct	16	-	12 Feb	6 Apr	2 Mar	14
Betul	10 Oct	29 Nov	14 Oct	11	10	25 Jan	23 Mar	7 Feb	13
Bhopal (Saunther)	10 Oct	30 Nov	21 Oct	16	22	19 Jan	23 Mar	8 Feb	19
Bhopal (Jamra)	10 Oct	30 Nov	24 Oct	16	22	23 Jan	26 Mar	14 Feb	19
Sagar	10 Oct	27 Nov	16 Oct	11	0	22 Jan	14 Mar	6 Feb	12
SECONDARY ZONE									
Medium rainfall									
Akola	10 Oct	10 Nov	14 Oct	8	19	20 Jan	27 Feb	30 Jan	10
Amravati	10 Oct	5 Nov	14 Oct	7	17	15 Jan	16 Feb	24 Jan	9
Jhabua	10 Oct	19 Nov	15 Oct	13	40	21 Jan	28 Feb	3 Feb	11
High rainfall									
Vidisha	10 Oct	21 Oct	15 Oct	3	0	8 Feb	26 Feb	15 Feb	5
Belgaum	10 Oct	5 Nov	12 Oct	7	0	16 Jan	21 Feb	25 Jan	8
Jabalpur	10 Oct	16 Oct	13 Oct	2	5	23 Jan	15 Feb	5 Feb	6
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	10 Oct	18 Nov	16 Oct	11	0	9 Jan	25 Feb	21 Jan	12
Patancheru (shallow soil)	10 Oct	18 Nov	15 Oct	10	0	7 Jan	24 Feb	20 Jan	12
Nanded	10 Oct	24 Oct	12 Oct	4	12	16 Jan	8 Feb	26 Jan	6

Table 15. Simulated seed yield, observed mean yield, and yield gap of chickpea in sequential analysis for various sites in India[1].

Site	Simulated yield					Observed mean yield	Yield gap with mean	Yield gap with maximum
	Min	25 percentile	Max	Mean	CV (%)			
PRIMARY ZONE								
Low rainfall								
Kota	0	120	2217	675	111	772	–97	1445
Medium rainfall								
Nimuch	0	230	1843	731	82	704	27	1139
Ujjain	0	473	2032	1089	66	641	448	1391
Dhar	0	0	2403	1118	78	498	620	1905
Kannod	0	0	2534	1055	73	741	314	1793
Rajgarh (Saunther)	0	0	999	354	86	530	–176	469
Rajgarh (Jamra)	0	0	2181	869	76	530	339	1651
High rainfall								
Guna (Saunther)	0	48	586	211	93	674	–463	–88
Guna (Jamra)	0	301	1391	662	72	586	76	805
Nagpur	0	483	2747	1227	63	408	819	2339
Shajapur (Saunther)	0	0	1115	401	76	736	–335	379
Shajapur (Sarol)	0	0	2370	1101	79	736	365	1634
Wardha	0	519	3148	1477	66	352	1125	2796
Indore (Kamiliakheri)	0	0	444	171	80	663	–493	–219
Indore (Sarol)	0	197	2013	992	74	663	329	1350
Ratlam	0	332	2721	1337	66	601	736	2120
Raisen (Saunther)	0	140	1108	611	64	685	–74	423
Raisen (Sarol)	0	178	1466	722	71	685	38	781
Betul	0	810	2710	1380	55	393	987	2317
Bhopal (Saunther)	0	248	1258	537	70	709	–172	549
Bhopal (Jamra)	0	937	2620	1233	65	709	525	1911
Sagar	139	462	2586	1247	56	571	677	2015
SECONDARY ZONE								
Medium rainfall								
Akola	0	337	2497	1282	72	392	889	2105
Amravati	0	190	3204	1352	82	472	880	2732
Jhabua	0	0	2774	972	96	504	468	2270
High rainfall								
Vidisha	46	555	1861	906	47	679	226	1182
Belgaum	188	620	2347	1337	53	428	909	1919
Jabalpur	0	477	2796	1177	55	622	555	2174
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	229	680	2919	1432	57	280	1152	2639
Patancheru (shallow soil)	194	475	2534	1100	65	280	820	2254
Nanded	0	1254	2521	1618	52	344	1274	2177

1. All values (except CV) are given in kg ha^{-1}.

There was total concurrence between total biomass and seed yield of chickpea, i.e., the sites with high biomass yield potential had higher seed yield and vice versa (Appendices V and VI).

Yield gap of chickpea. Simulated yields showed that chickpea could not be sown in many years at the selected sites. But district average yields were recorded in almost all the years because these were from large areas and chickpea would have been sown at many places due to variability in weather and soil. It was also not possible to determine whether the district averages included the chickpea area under irrigation, or chickpea was grown after fallow or in rotation with crops other than soybean. Mean simulated yields obtained for a location were compared with the mean observed yield (from 1975 to 1995 for Raisen, Wardha, and Belgaum) to calculate the yield gap. As for soybean the yield gap between potential and observed yields in general increased with increase in potential (Table 15). On an average, the yield gaps were about 47, 494, and 838 kg ha^{-1} for locations having low, medium, and high chickpea yield potential respectively. After excluding the negative values with shallow series the yield gap ranged from 27 kg ha^{-1} (Nimuch) to 76 kg ha^{-1} (Guna, Jamra series) for low potential, from 226 kg ha^{-1} (Vidisha) to 820 kg ha^{-1} (Patancheru, shallow soil) for medium potential, and from 525 kg ha^{-1} (Bhopal, Jamra series) to 1274 kg ha^{-1} (Nanded) for high potential locations. For sites, where the yield gap was more, it indicated greater scope for increasing the yield provided the yield constraints could be economically managed. The yield gap of chickpea was much less when compared with soybean because water stress is the major limiting factor for chickpea production during the postrainy season.

Total productivity of soybean-chickpea sequential system. Based on seed yields of both soybean and chickpea, the total productivity of the system was classified into low (<2500 kg ha^{-1}), medium (2500–3500 kg ha^{-1}), and high (>3500 kg ha^{-1}). In the primary zone, all sites which were simulated with shallow Saunther series and Kota came under low total productivity class whereas Sagar, Raisen, Bhopal (Jamra), Betul, Dhar, and Wardha came under high total productivity class (Table 16). All sites in the secondary zone, except Vidisha, had medium productivity, while all sites in the tertiary zone had high productivity. This indicates that soybean could also be cultivated successfully in other regions of India where it is presently not widespread.

Total yield gap of soybean-chickpea sequential system. Across sites the observed yields of the two crops ranged from 969 kg ha^{-1} at Belgaum to 1776 kg ha^{-1} at Kota, indicating the potential of the sites under existing management practices (Table 16). The sites with yield potential >1500 kg ha^{-1} were Kota, Ujjain, Kannod, Shajapur, Indore, Raisen, and Bhopal. For these sites the simulated mean yields were also high. In general, the sites with higher yield potential had wider yield gap. Also, the yield gap increased with the increase in rainfall except when the sites had very shallow soils. The total yield gap for the two crops as estimated with the mean potential yield ranged from 214 to 3326 kg ha^{-1} across sites and production zones. In the primary zone, Kota, Indore, and sites on the Saunther soil series (Rajgarh, Guna, Shajapur, and Bhopal) had yield gap of <1000 kg ha^{-1} whereas Nimuch, Ujjain, Kannod, Ratlam, Rajgarh, and Guna on Jamra series, and Shajapur and Indore on Sarol series had yield gap of 1000 to 2000 kg ha^{-1}. Nagpur, Wardha, Raisen, Betul, Bhopal (Jamra series), and Sagar had yield gap of >2000 kg ha^{-1}. In the secondary zone, Amravati, Jhabua, and Jabalpur had yield gap between 1000 and 2000 kg ha^{-1}; and Vidisha and Belgaum >2000 kg ha^{-1}. In the tertiary zone, Nanded had yield gap of >2000 kg ha^{-1}. For other sites the yield gap could not be estimated because the observed data were not available.

The yield gap estimated with the maximum simulated yields was almost twice or more than that estimated with the mean simulated yields for most of the sites, indicating the potential to improve productivity if irrigation is available (Table 16). The above analysis shows that the yields of the soybean-chickpea system could be substantially increased with improved management of natural resources under rainfed situations as well as with supplemental irrigation by harvesting and storing excess rainfall.

Table 16. Simulated seed yield, observed mean yield, and yield gap of soybean and chickpea in sequential analysis for various sites in India[1].

	Simulated yield					Observed	Yield gap	Yield gap
						mean	with	with
Site	Min	25 percentile	Max	Mean	CV (%)	yield	mean	maximum
PRIMARY ZONE								
Low rainfall								
Kota	540	1244	3893	1990	48	1776	214	2117
Medium rainfall								
Nimuch	867	1477	4188	2573	42	1473	1100	2715
Ujjain	899	2443	4985	3247	35	1524	1723	3461
Dhar	708	2899	6330	3840	39	1364	2476	4966
Kannod	991	2042	4933	2948	44	1577	1371	3356
Rajgarh (Saunther)	456	1237	2934	1692	40	1154	537	1780
Rajgarh (Jamra)	843	2082	4438	2772	35	1154	1618	3284
High rainfall								
Guna (Saunther)	330	1089	3343	1965	52	1334	631	2009
Guna (Jamra)	532	1850	4629	2872	46	1246	1626	3383
Nagpur	1230	2440	5052	3326	35	1195	2131	3857
Shajapur (Saunther)	726	1176	3875	2160	46	1527	633	2348
Shajapur (Sarol)	953	2083	5607	3211	43	1527	1684	4080
Wardha	2869	3479	6431	4585	20	1259	3326	5172
Indore (Kamiliakheri)	252	584	3090	1391	63	1595	–205	1495
Indore (Sarol)	1174	2027	5001	3301	39	1595	1705	3406
Ratlam	623	2228	5712	3354	43	1432	1922	4280
Raisen (Jamra)	1544	2221	5747	3560	39	1520	2040	4227
Raisen (Sarol)	1765	2254	5911	3747	38	1520	2227	4391
Betul	1547	2811	5963	3677	32	1140	2537	4823
Bhopal (Saunther)	843	1870	3839	2429	34	1565	864	2274
Bhopal (Jamra)	1268	2508	5479	3635	32	1565	2070	3914
Sagar	2119	2717	5441	3538	29	1342	2196	4099
SECONDARY ZONE								
Medium rainfall								
Akola	621	1626	4897	2797	49	1382	1415	3515
Amravati	1138	1684	5718	3092	45	1270	1822	4448
Jhabua	450	1642	5514	2891	49	1133	1758	4381
High rainfall								
Vidisha	2286	2612	4879	3552	22	1500	2052	3379
Belgaum	1359	2478	4612	3259	31	969	2290	3643
Jabalpur	1428	2560	5235	3310	28	1357	1953	3878
TERTIARY ZONE								
Medium rainfall								
Patancheru (deep soil)	1212	3739	5665	4305	23	-	-	-
Patancheru (shallow soil)	1137	3536	5285	3964	23	-	-	-
Nanded	433	2650	6188	3520	44	1339	2181	4849

1. All values (except CV) are given in kg ha^{-1}.

Water balance components of soybean-chickpea sequential system

Rainfall. Because of the carryover effect of soil moisture from the previous season the soybean crop in the sequential analysis was sown earlier than that in the seasonal analysis. Therefore, the amount of rainfall received by the soybean crop in sequential analysis was somewhat less compared to the soybean crop simulated with seasonal analysis (Table 17).

Except for Patancheru, the mean rabi (postrainy season) rainfall was <100 mm at all the sites and it was highly variable across seasons (Table 17). The CV in rabi rainfall across locations ranged from 60% at Belgaum to as much as 167% at Nimuch, indicating that the variability in rainfall across years at some locations was even more than the mean values of rabi rainfall. The potential for chickpea production at a site was primarily determined by the amount of rabi rainfall plus the amount of water stored in the soil profile at soybean harvest. A positive correlation (r = 0.45) existed between rabi rainfall and chickpea seed yield.

Surface runoff. Total amount of runoff simulated for the rainy season with sequential analysis was not much different from that simulated with seasonal analysis (Table 17). In sequential analysis the sites close to the Saunther soil series were also analyzed with the nearby deep soil series. Soil depth had no effect on surface runoff. In the primary zone, the lowest mean runoff was simulated for Kota (198 mm) in the low rainfall environment. For other sites within the primary zone mean runoff ranged from 261 to 411 mm depending upon the rainfall received at a site. In the secondary zone, the mean runoff ranged from 205 to 380 mm, whereas in the tertiary zone it ranged from 177 to 192 mm. Total runoff as percentage of rainfall ranged from 29 to 38% for the primary zone, 29 to 34% for the secondary zone, and about 25% for the tertiary zone. The CV in runoff across sites ranged from 40 to 70% depending upon the amount and variability in seasonal rainfall at a site.

As expected, the amount of rainfall lost as surface runoff during rabi was negligible (3 to 27 mm) compared to that simulated for the soybean growing season (Table 18). Across sites, mean runoff as percentage of mean rabi rainfall ranged from 7 to 30% for the primary zone, 9 to 21% for the secondary zone, and 16 to 24% for the tertiary zone. The surface runoff was highly variable across seasons.

Considering the total runoff simulated for both the seasons, about 96% of total runoff occurred during the soybean growing period. Depending upon the amount of rainfall received during the soybean and chickpea growing seasons, the mean values of runoff ranged from 202 to 424 mm across the production zones with a coefficient of variation ranging from 38 to 68%. A positive correlation (r = 0.93) existed between total rainfall received at a site and the amount of runoff produced. Total runoff of the two seasons as percentage of total rainfall was 27 to 36% for the primary zone, 28 to 30% for the secondary zone, and 23 to 26% for the tertiary zone (Table 19). These results indicate the potential for water harvesting at various sites in the soybean growing area of India.

Deep drainage. Because of the carryover effects of soil moisture from one season to another in the sequential analysis, deep drainage was significantly more with sequential analysis than with seasonal analysis (Table 17). Other components of water balance of soybean crop were not affected as much as deep drainage with sequential analysis. Amount of deep drainage across sites was influenced by the amount of rainfall during the season as well as the soil water retention characteristics of the site. Total deep drainage during the soybean growing period ranged from 82 to 318 mm for the primary zone, 78 to 417 mm for the secondary zone, and 42 to 71 mm for the tertiary zone. As percentage of rainfall it ranged from 8 to 28% for the primary zone, 11 to 34% for the secondary zone, and 6 to 9% for the tertiary zone. The CV for deep drainage was larger than that for surface runoff as deep drainage at some sites did not occur every year.

Table 17. Water balance components (mm) of simulated soybean in sequential analysis for various sites in India (values of extractable water are at soybean harvest).

Site	Rainfall				Surface runoff				Deep drainage				Evapotranspiration				Extractable water			
	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
PRIMARY ZONE																				
Low rainfall																				
Kota	306	1011	653	32	24	450	198	55	0	271	92	103	151	503	321	25	102	221	142	23
Medium rainfall																				
Nimuch	306	1448	735	33	28	688	236	62	0	509	132	77	220	466	332	18	57	138	103	19
Ujjain	454	1835	890	33	102	935	325	55	0	483	142	80	261	447	361	14	185	79	134	20
Dhar	596	1492	901	25	75	645	261	54	19	388	146	66	313	596	438	18	98	190	140	20
Kannod	426	1703	902	35	54	775	313	57	24	462	156	64	287	487	372	15	91	184	139	17
Rajgarh (Saunther)	407	1699	950	30	101	840	348	51	62	524	238	46	235	459	340	18	21	88	46	38
Rajgarh (Jamra)	407	1699	950	30	97	829	341	51	6	489	193	59	253	474	365	17	54	175	109	24
High rainfall																				
Guna (Saunther)	322	1758	943	33	66	929	325	60	41	349	226	41	229	501	375	20	15	92	41	41
Guna (Jamra)	322	1758	943	33	62	920	318	61	13	326	191	50	239	509	394	19	73	173	108	20
Nagpur	553	1463	950	23	105	675	306	41	29	423	199	49	292	455	395	9	90	161	125	16
Shajapur (Saunther)	580	1769	954	25	90	846	332	52	71	563	234	45	242	495	357	19	30	77	54	25
Shajapur (Sarol)	580	1769	954	25	85	844	331	52	52	513	182	57	270	506	376	17	104	183	148	16
Wardha	555	1571	958	25	91	731	300	49	0	341	134	73	358	550	464	11	48	177	106	42
Indore (Kamiliakheri)	555	1403	960	22	96	711	328	44	25	293	178	43	265	586	438	19	2	54	19	81
Indore (Sarol)	555	1438	966	23	96	825	335	48	0	203	82	91	327	649	495	18	64	203	124	29
Ratlam	582	1847	1014	31	148	895	378	49	84	471	227	51	231	442	345	16	192	110	149	16
Raisen (Jamra)	416	1567	1046	29	67	672	319	61	7	270	155	53	358	652	530	15	66	143	104	20
Raisen (Sarol)	416	1967	1046	29	70	682	326	60	0	250	128	62	377	668	541	14	76	174	129	19
Betul	555	1544	1084	23	145	691	377	40	88	402	271	34	296	449	370	11	218	287	248	6
Bhopal (Saunther)	441	1841	1089	31	78	926	410	49	94	545	302	40	250	424	349	13	14	86	54	34
Bhopal (Jamra)	441	1841	1091	31	74	916	402	50	57	514	264	46	284	446	369	11	66	178	120	20
Sagar	441	1991	1140	31	88	894	411	51	48	653	318	47	257	513	366	16	167	72	119	20
SECONDARY ZONE																				
Medium rainfall																				
Akola	278	1178	697	31	38	446	205	48	0	267	78	93	229	463	353	17	74	287	235	18
Amravati	488	1144	769	26	89	457	224	49	0	294	101	91	288	520	392	15	116	294	232	19
Jhabua	293	1421	793	46	72	553	273	65	0	441	125	120	237	415	343	13	58	185	129	26
High rainfall																				
Vidisha	562	1627	932	29	92	688	269	60	0	491	182	66	298	562	428	19	67	159	113	19
Belgaum	539	1553	938	25	98	740	306	48	32	384	193	52	321	511	384	15	130	191	160	12
Jabalpur	590	1989	1247	24	125	1002	380	62	73	664	417	38	280	438	387	13	123	175	146	10
TERTIARY ZONE																				
Medium rainfall																				
Patancheru (deep soil)	459	1044	683	29	51	336	177	51	0	215	42	164	327	442	395	7	55	179	116	37
Patancheru (shallow soil)	459	1044	683	29	50	334	175	51	0	233	51	145	321	442	394	7	33	151	90	43
Nanded	301	1509	772	32	37	601	192	69	0	264	71	110	239	612	428	24	123	290	245	17

Amount of deep drainage simulated for the postrainy season was negligible compared to the rainy season (Table 18). Although, there was year-to-year variation in the amount of drainage, the mean values ranged from nil to 12 mm across sites, which constituted 0 to 17% of postrainy season rainfall.

Evapotranspiration. As expected, ET in both the seasons was strongly correlated with seed yields of soybean and chickpea (r = 0.80), and it was the major component of water balance. Mean ET of soybean ranged from 321 to 541 mm depending upon the amount of rainfall and potential evapotranspiration in the primary production zone of soybean (Table 17). In the secondary zone, it ranged from 343 to 428 mm, whereas in the tertiary zone it ranged from 395 to 428 mm. Total ET of soybean when expressed as percentage of rainfall ranged from 32 to 52% for the primary zone, 31 to 51% for the secondary zone, and 55 to 58% for the tertiary zone. The CV in ET was very low across sites compared to other components of water balance.

During the postrainy season, the ET of chickpea crop in the primary zone ranged from 47 to 135 mm (Table 18). In the secondary zone ET of chickpea ranged from 62 to 125 mm, whereas in the tertiary zone it ranged from 120 to 145 mm. Year-to-year variation in ET of chickpea for a site was much higher than that simulated for the soybean crop.

Mean ET of the soybean-chickpea system ranged from 378 to 598 mm for the primary zone, 405 to 510 mm for the secondary zone, and 539 to 549 mm for the tertiary zone (Table 19). When expressed as percentage of rainfall received during the two seasons, it ranged from 35 to 58% for the primary zone, 37 to 59% for the secondary zone, and 63 to 69% for the tertiary zone. These values indicate the rainfall-use efficiency of the soybean-chickpea sequential system in various production zones and the potential to increase this efficiency through rainfall and cropping systems management at various sites in the region.

Soybean productivity constraints

Major constraints that limit the yields of soybean below the potential yield are:

- Undependable weather in terms of onset of rainy season and amount of rainfall and its distribution during the soybean growing period.
- Land degradation in the form of soil erosion, waterlogging, and nutrient depletion.
- Inefficient use of natural resources, particularly rainfall.
- Inappropriate soil and water management practices.
- Imbalanced use of chemical fertilizers and biofertilizers.
- Infestation by weeds, insect pests, and diseases.
- Lack of region-specific, high-yielding, and tolerant varieties to various abiotic and biotic stresses.
- Low adoption of improved varieties of variable duration and unavailability of quality seed.
- Inadequate use of improved farm equipment for various field operations such as sowing and harvesting.
- Inaccessibility to knowledge and inputs of improved technologies and low adoption of scientific crop production practices.
- Meager credit facilities to small farmers for appropriate investments.

Table 18. Water balance components (mm) of simulated chickpea sequential analysis for various locations in India (values of extractable water are at chickpea harvest).

	Rainfall				Surface runoff				Deep drainage				Evapotranspiration				Extractable water			
Location	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
PRIMARY ZONE																				
Low rainfall																				
Kota	0	116	31	116	0	34	5	180	0.0	0	0.00	0	1	135	58	86	85	145	111	17
Medium rainfall							0													
Nimuch	0	244	43	169	0	120	13	251	0.0	34	1.89	381	1	132	54	83	42	104	74	23
Ujjain	0	143	54	87	0	56	8	163	0.0	1	0.04	520	2	184	93	61	43	122	75	30
Dhar	2	135	51	82	0	56	6	224	0.0	2	0.10	400	2	185	88	61	51	150	87	29
Kannod	0	123	51	93	0	42	8	173	0.0	2	0.10	447	1	163	79	70	51	148	89	35
Rajgarh (Saunther)	1	233	65	107	0	121	12	216	0.0	5	0.28	379	2	149	56	78	9	49	24	46
Rajgarh (Jamra)	1	233	66	105	0	121	12	225	0.0	2	0.00	0	2	188	83	70	37	109	61	38
High rainfall					0															
Guna (Saunther)	0	102	38	92	0	17	3	167	0.0	0	0.00	1	1	103	47	70	9	44	27	33
Guna (Jamra)	0	102	42	93	0	16	3	167	0.0	0	0.00	0	1	155	70	69	34	110	72	29
Nagpur	2	286	99	76	0	145	24	142	0.0	91	11.19	2	3	218	106	52	50	114	76	25
Shajapur (Saunther)	0	176	46	108	0	74	6	242	0.0	15	1.04	351	1	151	55	70	9	40	26	36
Shajapur (Sarol)	0	176	49	104	0	74	6	242	0.0	15	0.60	3	1	194	88	74	49	151	87	34
Wardha	29	198	95	60	0	59	13	146	0.0	5	0.30	333	41	199	135	39	29	94	44	39
Indore (Kamiliakheri)	0	113	64	62	0	37	7	131	0.0	23	1.50	4	2	103	52	68	0	15	5	65
Indore (Sarol)	0	113	61	66	0	37	7	133	0.0	24	1.04	470	2	159	91	61	45	128	74	27
Ratlam	0	167	48	105	0	58	7	195	0.0	43	2.04	5	2	166	88	62	58	138	89	29
Raisen (Jamra)	22	238	79	76	2	128	10	320	0.0	4	0.30	333	8	175	101	51	30	93	66	32
Raisen (Sarol)	7	238	74	81	0	129	11	291	0.0	8	2.00	6	11	195	108	49	43	113	83	29
Betul	2	193	95	62	0	91	21	124	0.0	34	5.00	220	6	218	120	49	149	261	189	16
Bhopal (Saunther)	0	178	71	75	0	46	9	148	0.0	18	0.78	7	3	152	73	62	11	58	27	46
Bhopal (Jamra)	0	100	72	77	0	45	9	156	0.0	5	0.26	380	3	181	102	58	39	107	66	34
Sagar	0	215	69	86	0	108	14	177	0.0	69	3.96	8	21	160	96	42	49	155	78	30
SECONDARY ZONE																				
Medium rainfall																				
Akola	0	193	61	99	0	85	13	178	0.0	40	3.48	287	3	182	89	58	71	229	180	18
Amravati	21	199	76	68	0	50	13	123	0.0	2	0.20	500	4	199	96	59	115	239	187	17
Jhabua	0	87	33	108	0	26	3	224	0.0	1	0.07	0	1	126	62	84	54	154	86	33
High rainfall																				
Vidisha	0	177	34	124	0	75	6	294	0.0	20	0.87	480	6	140	80	48	30	94	61	24
Belgaum	30	212	99	60	0	64	18	111	0.0	46	7.00	200	52	183	125	33	82	146	111	20
Jabalpur	0	137	48	81	0	40	5	200	0.0	3	0.10	700	16	194	98	49	57	134	88	22
TERTIARY ZONE																				
Medium rainfall																				
Patancheru (deep soil)	7	368	111	94	0	142	27	152	0.0	95	9.27	251	57	257	152	35	26	60	40	23
Patancheru (shallow soil)	7	368	112	93	0	140	27	152	0.0	134	10.00	290	53	246	145	36	11	41	19	42
Nanded	7	306	69	90	0	111	11	218	0.0	134	12.00	250	4	194	120	44	72	218	168	15

Table 19. Water balance components (mm) of simulated soybean-chickpea sequential system for various sites in India.

	Rainfall				Surface runoff				Deep drainage				Evapotranspiration			
Site	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
PRIMARY ZONE																
Low rainfall																
Kota	306	1011	684	30	24	450	202	53	0	271	92	103	244	577	378	23
Medium rainfall																
Nimuch	494	1448	806	26	28	688	249	60	0	509	134	76	221	537	386	23
Ujjain	547	1862	984	29	102	935	332	54	0	483	142	80	264	572	454	18
Dhar	637	1503	978	25	75	645	267	54	19	388	146	66	405	718	525	18
Kannod	428	1734	994	33	54	776	321	55	0	462	156	66	295	606	451	19
Rajgarh (Saunther)	504	1704	1062	28	114	840	360	50	0	524	238	51	238	539	397	20
Rajgarh (Jamra)	504	1704	1062	28	109	829	353	51	6	489	193	59	255	602	448	20
High rainfall																
Guna (Saunther)	413	1771	977	32	71	929	328	60	41	349	226	41	233	568	422	20
Guna (Jamra)	413	1771	979	32	67	920	320	61	13	326	191	50	242	632	464	21
Nagpur	579	1597	1047	23	105	723	330	40	29	423	210	48	306	620	501	15
Shajapur (Saunther)	761	1784	1039	23	90	846	338	50	71	563	235	44	245	573	412	24
Shajapur (Sarol)	581	1784	1063	22	85	844	338	51	52	513	183	56	273	642	464	24
Wardha	709	1617	1044	21	132	731	312	45	0	341	134	73	525	706	598	9
Indore (Kamiliakheri)	555	1311	1025	20	96	711	336	44	25	299	180	44	318	633	490	18
Indore (Sarol)	555	1439	1027	20	96	825	342	47	0	203	83	91	448	764	586	17
Ratlam	712	1847	1075	20	153	895	385	49	103	471	229	50	235	560	433	19
Raisen (Jamra)	654	1618	1116	30	106	674	329	57	7	270	155	53	489	802	632	17
Raisen (Sarol)	654	1620	1115	25	113	684	337	55	0	250	129	61	498	829	649	17
Betul	678	1600	1197	25	183	705	398	38	88	430	276	34	302	625	489	16
Bhopal (Saunther)	572	1882	1196	21	121	930	419	47	94	545	303	40	255	521	422	16
Bhopal (Jamra)	572	1882	1199	29	116	920	411	48	57	514	264	46	288	578	471	17
Sagar	635	2026	1209	29	125	896	424	50	50	653	322	46	334	643	462	16
SECONDARY ZONE																
Medium rainfall																
Akola	471	1192	781	27	38	447	218	44	0	267	82	90	257	613	443	21
Amravati	544	1168	833	25	89	457	237	47	0	294	101	91	320	719	489	17
Jhabua	529	1421	998	35	72	553	276	65	0	441	125	120	238	487	405	19
High rainfall																
Vidisha	562	1630	966	27	92	688	275	58	0	491	182	66	334	669	508	19
Belgaum	699	1693	1037	22	141	757	324	44	32	385	200	50	396	639	510	15
Jabalpur	661	2035	1293	24	130	1005	384	62	73	664	417	38	318	592	485	17
TERTIARY ZONE																
Medium rainfall																
Patancheru (deep soil)	526	1121	794	24	63	340	204	42	0	215	52	142	429	657	547	11
Patancheru (shallow soil)	526	1121	794	24	61	335	202	42	0	233	63	124	422	647	539	11
Nanded	515	1525	874	25	37	60	203	67	0	264	80	106	760	249	549	23

Summary

Soybean is an important food crop grown during the rainy season in India. It is currently grown in the central-peninsular India on an area of about 6 million ha. It occupies a significant place in the agricultural economy of the country. The state of Madhya Pradesh contributes over 70% to the production and area in India. Other important soybean-growing states are Uttar Pradesh, Rajasthan, Maharashtra, Andhra Pradesh, Karnataka, Gujarat, Chhatisgarh, Uttaranchal, and Tamil Nadu. The productivity of soybean, however, continues to be low, and it is estimated at less than 1 t ha^{-1}. Most of the increase in soybean production has come from area increase over the years. There are several biophysical, technical, and socioeconomic constraints that limit the productivity of soybean-based systems at low levels which need to be mitigated before any increase in productivity is realized.

Major soils in the region are Vertisols and Vertic-Inceptisols which are variable in soil depth and other soil properties across the soybean production zones.

Annual rainfall varies from 700 mm to >1500 mm in the region, thus providing variable production environments in terms of production potential and management of natural resources. Before any investments to improve the productivity of the production systems are made it is essential to have an assessment of production potential of the environments in relation to current levels of production as well as the availability and use of natural resources. Using crop simulation models of soybean and chickpea we have quantified the water-limiting potential yields of the soybean-chickpea sequential system for the 24 selected benchmark sites for which the historical weather records were available. Considering the current productivity levels of these two crops the yield gap has also been estimated. Various components of water balance were also simulated to account for the use of rainfall and to evaluate the opportunities to increase its use efficiency.

The current levels of soybean yields across the 24 selected sites range from 540 to 1000 kg ha^{-1}, and the mean simulated potential yields ranged from 1200 to 3100 kg ha^{-1}. The yield gap for these sites ranged from 300 to 2200 kg ha^{-1}. Similarly the current productivity of chickpea across sites range from 280 to 770 kg ha^{-1}, and the mean simulated yields of chickpea ranged from 170 to 1600 kg ha^{-1}. As chickpea crop at some sites is irrigated the minimum observed yields were higher than the mean minimum simulated yields. The chickpea crop yield gap ranged from 30 to 1270 kg ha^{-1} across the benchmark sites. The yield gap in good rainfall years for the two crops were even large as the above mentioned yield gap data are based on the mean values of the simulated yields across several weather-years. Total simulated productivity of the soybean-chickpea system ranged from 1400 to 4580 kg ha^{-1}, thus giving yield gap ranging from 200 to 3300 kg ha^{-1} across sites. These results show the potential to increase the productivity of the soybean-chickpea sequential system under rainfed situation in the soybean production zones of India. The productivity of the system could be further increased by at least additional 1000 kg ha^{-1} if irrigation is available.

Mean rainfall across sites ranged from 680 to 1290 mm during the soybean-chickpea growth period. Water use (ET) by the two crops ranged from 380 to 650 mm, which amounted to 35 to 70% of seasonal rainfall. About 96% of surface runoff occurred during the soybean growth period. Total runoff for the two seasons across sites ranged from 200 to 425 mm (23 to 38% of rainfall). Deep drainage ranged from 50 to 420 mm (6 to 34% of rainfall) across benchmark sites depending upon the soil depth and rainfall. These results, while indicating the opportunities available at the sites to harvest and store excess water for supplemental irrigation to crops to increase their productivity, stress the need to control soil erosion through appropriate land and water management using watershed approach.

References

Bristow, R.L., and **Campbell, G.S.** 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agriculture and Forest Meteorology 31:159–166.

Directorate of Economics and Statistics, Government of India. 1970–92. Agricultural Situation in India (various issues).

Directorate of Economics and Statistics, Government of India. 1993–2000. Reports on Agricultural Statistics, 1993 to 2000. Government of Madhya Pradesh, Maharashtra, Uttar Pradesh, Gujarat, Karnataka, and Rajasthan.

FAO (Food and Agriculture Organization of the United Nations). 2002. Website: http://www.fao.org

Lal, S., Deshpande, S.B., and **Sehagal, J.** (eds.) 1994. Soil series of India. Soils Bulletin 40. Nagpur, India: National Bureau of Soil Survey and Land Use Planning. 684 pp.

Piara Singh, Vijaya, D., Chinh, N.T., Pongkanjana, Aroon, Prasad, K.S., Srinivas, K., and **Wani, S.P.** 2001. Potential productivity and yield gap of selected crops in the rainfed regions of India, Thailand, and Vietnam. Natural Resource Management Program, Report No. 5. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 50 pp.

Sehgal, J.L., Mandal, D.K., Mandal, C., and **Vadivelu, S.** (eds.) 1995. Agro-ecological subregions of India. Technical Bulletin, NBSS Publication-43. Nagpur, India: National Bureau of Soil Survey and Land Use Planning. 35 pp.

Tsuji, G.Y., Jones, J.W., and **Balas, S.** (eds.) 1994. DSSAT V3. Honolulu, Hawaii, USA: University of Hawaii.

Appendices

Appendix I. Total biomass yield (at various percentiles) of simulated soybean in seasonal analysis for various sites in India.

	Biomass yield (kg ha^{-1})								
Site	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	463	640	1286	1941	3757	4470	6014	2414	66
Medium rainfall									
Nimuch	380	1541	2401	2917	4442	4654	5279	3154	41
Ujjain	1223	1670	2481	3753	4357	4798	5024	3416	34
Dhar	1119	2474	2955	4407	5124	5707	6953	4146	35
Kannod	878	1646	2107	2691	4446	4984	5602	3087	45
Rajgarh (Saunther)	591	1425	1697	2169	3434	3533	4403	2396	42
High rainfall									
Guna (Saunther)	1050	1451	2040	3067	4668	4800	5332	3211	44
Nagpur	1738	2381	2789	3311	4000	4303	4798	3339	23
Shajapur (Saunther)	930	1551	1812	2739	4099	4707	5511	2952	44
Wardha	3225	3931	4840	5445	6154	6402	6702	5351	20
Indore (Kamiliakheri)	685	1187	1656	2325	3097	4560	5517	2575	53
Indore (Sarol)	1353	2178	2730	4495	4906	5593	7999	4134	37
Ratlam	846	1587	2116	3665	4560	4972	5206	3357	41
Raisen (Jamra)	1859	3246	4417	5897	6820	7342	8312	5576	31
Betul	1665	3059	3306	3937	4281	4893	5258	3793	22
Bhopal (Saunther)	1422	1792	2701	3421	4003	4401	4580	3273	29
Bhopal (Jamra)	2486	2796	3750	4464	5068	5183	5445	4278	22
Sagar	1850	2241	2787	3586	4708	5154	5339	3652	30
SECONDARY ZONE									
Medium rainfall									
Akola	176	682	1114	2348	3290	3948	4093	2279	55
Amravati	775	1484	1864	2681	3828	4204	4672	2772	41
Jhabua	487	1605	3004	4010	4010	4039	5026	3363	34
High rainfall									
Vidisha	2168	2720	3832	4260	4419	5300	6344	4200	23
Belgaum	1542	1768	2574	3185	3684	4170	4727	3100	30
Jabalpur	2249	2897	3435	3923	3923	4085	4149	3637	15
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	1636	2967	4237	4782	5111	5291	5504	4433	24
Patancheru (shallow soil)	1750	3136	4246	4793	5162	5346	5460	4489	23
Nanded	517	754	1395	2421	4112	4719	6150	2672	60

Appendix II. Seed yield (at various percentiles) of simulated soybean in seasonal analysis for various sites in India.

Site	Seed yield (kg ha^{-1})								
	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	80	282	486	873	1906	2476	3188	1205	77
Medium rainfall									
Nimuch	188	659	868	1437	2206	2638	2951	1595	51
Ujjain	704	816	1281	2067	2512	2724	2919	1867	39
Dhar	533	1188	1584	2604	2965	3509	4246	2385	41
Kannod	506	674	954	1243	2665	2728	3305	1642	55
Rajgarh (Saunther)	328	530	792	1057	1839	2136	2687	1259	52
High rainfall									
Guna (Saunther)	342	539	754	1255	2495	2785	2916	1633	56
Nagpur	1062	1286	1531	1992	2359	2532	2673	1941	25
Shajapur (Saunther)	566	727	878	1502	2317	2770	3293	1639	50
Wardha	1824	2237	2534	3258	3538	3674	3955	3040	21
Indore (Kamiliakheri)	175	520	668	1099	1446	2582	2758	1301	61
Indore (Sarol)	760	998	1399	2447	2893	3128	4588	2273	41
Ratlam	474	809	1023	2089	2601	2939	3043	1848	45
Raisen (Jamra)	393	1330	1973	3260	3996	4095	4670	2882	44
Betul	924	1518	1768	2193	2447	2852	3296	2141	28
Bhopal (Saunther)	361	887	1497	1959	2267	2550	2678	1807	35
Bhopal (Jamra)	805	1405	2020	2373	2855	2979	3064	2310	27
Sagar	610	1106	1474	1914	2450	2837	3198	1965	35
SECONDARY ZONE									
Medium rainfall									
Akola	133	340	737	1360	1941	2454	2537	1360	57
Amravati	440	761	937	1496	2236	2588	2624	1552	46
Jhabua	117	941	1551	2412	2412	2450	2716	1939	38
High rainfall									
Vidisha	911	1521	1810	2419	2460	2919	3250	2224	25
Belgaum	858	1018	1501	1769	2303	2603	2943	1844	34
Jabalpur	1132	1486	1937	2290	2300	2349	2477	2079	18
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	700	1839	2606	2853	3112	3271	3396	2664	26
Patancheru (shallow soil)	752	1932	2679	2888	3137	3300	3370	2700	26
Nanded	293	473	786	1539	2586	3104	3872	1662	63

Appendix III. Total biomass yield (at various percentiles) of simulated soybean in sequential analysis for various sites in India.

	Biomass yield (kg ha^{-1})								
Site	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	755	1011	1446	2665	3322	4350	5231	2669	50
Medium rainfall									
Nimuch	1586	1810	2311	3590	4613	5198	5546	3536	35
Ujjain	1628	2170	3298	3976	4636	5047	5567	3879	27
Dhar	1388	1567	3869	5151	5413	5861	6924	4658	29
Kannod	1634	1660	2350	3073	4459	5142	5584	3457	37
Rajgarh (Saunther)	634	1348	1594	2433	3354	3792	4130	2501	39
Rajgarh (Jamra)	1687	2077	2514	3706	4498	5218	5306	3587	32
High rainfall									
Guna (Saunther)	1005	1023	2134	3304	4703	4894	5522	3385	42
Guna (Jamra)	1469	1905	2810	4421	5499	5667	6517	4283	34
Nagpur	1944	2499	2933	3481	4462	4708	5008	3612	25
Shajapur (Saunther)	1240	1506	1941	2889	4413	4835	5520	3118	41
Shajapur (Sarol)	1979	2210	2503	3771	4882	5266	6322	3751	32
Wardha	3360	3786	4753	5664	6447	6478	6818	5568	19
Indore (Kamiliakheri)	778	804	977	1685	3147	4573	5279	2377	60
Indore (Sarol)	2172	2204	3072	4401	4884	5636	7216	4113	32
Ratlam	1329	1840	2510	4162	4760	5114	5777	3681	37
Raisen (Jamra)	2048	3607	4662	5723	6817	7412	8419	5770	28
Raisen (Sarol)	2163	3371	4687	5580	6844	7094	7707	5629	27
Betul	3002	3109	3639	4006	4276	4957	5258	4027	15
Bhopal (Saunther)	1469	1839	2587	3470	4239	4556	4653	3414	29
Bhopal (Jamra)	2417	2772	3845	4618	5108	5429	6016	4434	22
Sagar	2402	2845	3425	3949	5011	5340	5889	4198	23
SECONDARY ZONE									
Medium rainfall									
Akola	193	1155	1542	2504	3384	3914	4449	2523	47
Amravati	1635	2243	2414	2725	3836	4251	4517	3092	28
Jabua	1163	2018	2618	3612	3873	4886	5120	3415	33
High rainfall									
Vidisha	2905	3534	3979	5113	5267	5938	6523	4771	20
Belgaum	1726	1793	1978	3365	3720	4033	4625	3196	29
Jabalpur	2278	2524	3597	3946	4017	4156	4412	3748	15
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	2038	3617	4552	4983	5522	5647	5901	4828	21
Patancheru (shallow soil)	2026	3671	4528	5022	5433	5669	5885	4843	20
Nanded	684	1050	1748	2757	4190	5266	6383	3036	51

Appendix IV. Seed yield (at various percentiles) of simulated soybean in sequential analysis for various sites in India.

	Seed yield (kg ha^{-1})								
Site	0	10	25	50	75	90	100	Mean	C V (%)
PRIMARY ZONE									
Low rainfall									
Kota	350	532	575	1278	1858	2306	2896	1315	58
Medium rainfall									
Nimuch	653	881	1203	1823	2473	2867	3021	1842	41
Ujjain	899	1141	1530	2318	2638	2916	3011	2158	31
Dhar	708	814	2031	2899	3258	3714	4249	2722	34
Kannod	639	991	1102	1573	2664	3010	3325	1893	44
Rajgarh (Saunther)	348	564	810	1280	1848	2261	2385	1338	46
Rajgarh (Jamra)	787	875	997	1904	2438	2967	3023	1903	39
High rainfall									
Guna (Saunther)	301	423	1041	1640	2620	2808	3061	1755	52
Guna (Jamra)	532	583	1403	2448	2977	3225	3698	2209	46
Nagpur	1230	1362	1688	2031	2549	2784	2871	2099	26
Shajapur (Saunther)	726	774	919	1586	2518	2825	3316	1759	45
Shajapur (Sarol)	953	1215	1338	2083	2519	3074	3694	2110	35
Wardha	1904	2240	2442	3069	3654	3745	4026	3108	20
Indore (Kamiliakheri)	158	252	542	965	1505	2495	2855	1220	67
Indore (Sarol)	796	1174	1542	2289	2853	3231	4180	2308	36
Ratlam	623	875	1115	2141	2657	2998	3530	2016	42
Raisen (Jamra)	594	1588	1880	2707	3977	4173	4744	2949	40
Raisen (Sarol)	713	1794	2041	2856	4145	4169	4543	3024	37
Betul	1520	1547	1870	2285	2548	2886	3253	2297	20
Bhopal (Saunther)	375	901	1473	2010	2320	2582	2818	1892	34
Bhopal (Jamra)	732	1268	2134	2483	2773	3067	3339	2402	27
Sagar	1218	1470	1767	2322	2697	2913	3244	2291	24
SECONDARY ZONE									
Medium rainfall									
Akola	137	621	844	1540	1986	2375	2730	1515	48
Amravati	966	1138	1246	1571	2092	2514	2609	1740	31
Jhabua	450	1221	1420	1861	2310	2751	2782	1919	35
High rainfall									
Vidisha	1691	1870	2162	2776	3015	3328	3599	2646	20
Belgaum	960	998	1200	1898	2351	2523	2882	1922	32
Jabalpur	1184	1225	2046	2302	2325	2420	2566	2133	18
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	983	1881	2598	3011	3270	3476	3557	2873	24
Patancheru (shallow soil)	943	1857	2564	3026	3276	3459	3578	2865	24
Nanded	433	712	1204	1659	2615	3297	3950	1902	51

Appendix V. Total biomass yield (at various percentiles) of simulated chickpea in sequential analysis for various sites in India.

Site	Biomass yield (kg ha^{-1})								
	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	0	0	163	714	1108	3110	3622	1066	111
Medium rainfall									
Nimuch	0	0	332	737	2154	2445	2767	1133	85
Ujjain	0	0	713	2179	2822	3038	3575	1827	68
Dhar	0	0	0	1615	3001	3719	3971	1770	83
Kannod	0	0	0	1945	2277	3156	4132	1664	76
Rajgarh (Saunther)	0	0	0	591	950	1393	1643	608	88
Rajgarh (Jamra)	0	0	0	1576	2300	3223	3420	1498	77
High rainfall									
Guna (Saunther)	0	0	69	181	412	1057	1165	353	107
Guna (Jamra)	0	0	421	812	1647	2296	2825	1103	81
Nagpur	0	0	643	1974	2686	3133	4146	1900	63
Shajapur (Saunther)	0	0	0	540	1094	1203	1694	655	77
Shajapur (Sarol)	0	0	0	1942	3280	3494	3771	1822	80
Wardha	0	0	770	2280	3847	4673	5469	2585	68
Indore (Kamiliakheri)	0	0	0	319	490	639	705	309	80
Indore (Sarol)	0	0	270	1856	2333	3081	3612	1575	77
Ratlam	0	0	444	2212	3462	3812	4354	2114	69
Raisen (Jamra)	0	0	200	1227	1631	1828	2319	1108	70
Raisen (Sarol)	0	142	280	1126	1962	2130	3082	1317	75
Betul	0	0	1265	1758	3222	3247	4172	2119	57
Bhopal (Saunther)	0	0	368	973	1427	1514	1990	889	71
Bhopal (Jamra)	0	0	1483	2205	2863	3411	4217	2025	65
Sagar	200	468	618	2230	2734	3179	3955	1934	59
SECONDARY ZONE									
Medium rainfall									
Akola	0	0	446	2018	3041	3353	3759	1906	74
Amravati	0	0	262	1667	3276	3542	4582	1986	82
Jhabua	0	0	0	1783	2298	3831	3905	1504	96
High rainfall									
Vidisha	68	566	756	1363	1950	2565	2827	1471	54
Belgaum	257	474	839	2154	2699	2973	3333	1935	55
Jabalpur	0	528	699	2107	2264	2695	4436	1783	58
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	395	477	1356	2716	3642	4064	4624	2598	53
Patancheru (shallow soil)	327	475	997	2032	3488	3753	4233	2214	59
Nanded	0	195	1778	3059	3390	3589	4065	2470	53

Appendix VI. Seed yield (at various percentiles) of simulated chickpea in sequential analysis for various sites in India.

	Seed yield (kg ha^{-1})								
Site	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	0	0	120	435	680	2035	2217	675	111
Medium rainfall									
Nimuch	0	0	230	522	1182	1430	1843	731	82
Ujjain	0	0	473	1273	1674	1821	2032	1089	66
Dhar	0	0	0	1149	1916	2093	2403	1118	78
Kannod	0	0	0	1175	1533	1703	2534	1055	73
Rajgarh (Saunther)	0	0	0	370	540	673	999	354	86
Rajgarh (Jamra)	0	0	0	997	1247	1658	2181	869	76
High rainfall									
Guna (Saunther)	0	0	48	131	291	543	586	211	93
Guna (Jamra)	0	0	301	545	1110	1332	1391	662	72
Nagpur	0	0	483	1353	1603	2036	2747	1227	63
Shajapur (Saunther)	0	0	0	369	591	709	1115	401	76
Shajapur (Sarol)	0	0	0	1271	1778	2273	2370	1101	79
Wardha	0	0	519	1348	2157	2578	3148	1477	66
Indore (Kamiliakheri)	0	0	0	182	258	349	444	171	80
Indore (Sarol)	0	0	197	1144	1693	1860	2013	992	74
Ratlam	0	0	332	1517	2109	2264	2721	1337	66
Raisen (Jamra)	0	0	140	637	950	1001	1108	611	64
Raisen (Sarol)	0	99	178	561	1122	1285	1466	722	71
Betul	0	0	810	1211	1989	2016	2710	1380	55
Bhopal (Saunther)	0	0	248	585	826	904	1258	537	70
Bhopal (Jamra)	0	0	937	1200	1691	2065	2620	1233	65
Sagar	139	340	462	1452	1672	1951	2586	1247	56
SECONDARY ZONE									
Medium rainfall									
Akola	0	0	337	1436	2124	2192	2497	1282	72
Amravati	0	0	190	1181	2208	2319	3204	1352	82
Jabua	0	0	0	1174	1504	2254	2774	972	96
High rainfall									
Vidisha	46	397	555	921	1140	1381	1861	906	47
Belgaum	188	355	620	1526	1829	2112	2347	1337	53
Jabalpur	0	380	477	1412	1502	1747	2796	1177	55
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	229	348	680	1376	1999	2482	2919	1432	57
Patancheru (shallow soil)	194	316	475	857	1807	2078	2534	1100	65
Nanded	0	146	1254	2051	2190	2341	2521	1618	52

Appendix VII. Total biomass yield (at various percentiles) of simulated soybean-chickpea sequential system for various sites in India.

	Biomass yield (kg ha^{-1})								
Site	0	10	25	50	75	90	100	Mean	CV (%)
PRIMARY ZONE									
Low rainfall									
Kota	1599	1624	2744	3548	4677	5353	6975	3775	41
Medium rainfall									
Nimuch	1586	2311	2825	4756	6025	6980	7467	4670	39
Ujjain	1628	2456	4289	5973	6715	8034	8652	5707	33
Dhar	1388	2359	5151	6460	7961	8969	10724	6427	35
Kannod	2152	2178	2868	3591	4977	5660	6102	3975	32
Rajgarh (Saunther)	1067	1574	2234	3159	3922	4451	4909	3109	34
Rajgarh (Jamra)	1755	2647	3723	5306	6158	6972	7928	5085	32
High rainfall									
Guna (Saunther)	1023	1055	2368	3700	5147	5680	5703	3738	43
Guna (Jamra)	1469	2326	3754	5425	6748	7792	8467	5385	37
Nagpur	2499	2578	4018	5758	7223	7539	8222	5512	33
Shajapur (Saunther)	1570	1845	2244	3383	5319	5928	6508	3773	42
Shajapur (Sarol)	2210	2818	3758	5333	7681	8521	9602	5573	41
Wardha	5861	5861	6478	8004	8970	10222	11252	8153	20
Indore (Kamiliakheri)	866	922	1368	2227	3584	4757	5769	2686	56
Indore (Sarol)	2172	2715	3697	6216	7216	8057	9195	5688	36
Ratlam	1335	2285	4188	6374	7292	8574	9401	5796	39
Raisen (Jamra)	3698	3876	5406	7087	8329	8779	10738	6878	29
Raisen (Sarol)	3513	4000	5147	6890	8359	8974	10655	6946	30
Betul	3109	3355	4962	5468	7336	8098	9430	6146	28
Bhopal (Saunther)	1839	2260	3341	4611	4959	5626	6546	4302	29
Bhopal (Jamra)	2772	3845	4708	7002	7752	8029	9400	6459	29
Sagar	3784	4055	4632	5629	7744	8380	9397	6132	28
SECONDARY ZONE									
Medium rainfall									
Akola	1155	1887	2620	3556	6412	7284	7706	4429	48
Amravati	2285	2658	2984	4964	6814	7526	8847	5078	40
Jhabua	1163	2018	3092	5471	6804	7555	8463	4919	48
High rainfall									
Vidisha	3661	4567	5181	6456	6929	7756	8045	6242	20
Belgaum	2286	2632	3850	5171	6358	6634	7304	5130	30
Jabalpur	2864	2898	4352	6053	6105	6616	8721	5531	26
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	2433	5596	6058	7566	8435	9099	9696	7426	22
Patancheru (shallow soil)	2390	5626	5941	7265	7800	8749	9269	7056	22
Nanded	684	1659	4105	5651	7570	8428	9879	5506	44

Appendix VIII. Seed yield (at various percentiles) of simulated soybean-chickpea sequential system for various sites in India.

Site	Seed yield (kg ha^{-1})								
	0	10	25	50	75	90	100	Mean	C V%
PRIMARY ZONE									
Low rainfall									
Kota	540	631	1244	1801	2570	3084	3893	1990	48
Medium rainfall									
Nimuch	867	1203	1477	2505	3414	4020	4188	2573	42
Ujjain	899	1151	2443	3450	3829	4413	4985	3247	35
Dhar	708	1378	2899	3629	5063	5576	6330	3840	39
Kannod	991	1016	2042	2505	4186	4713	4933	2948	44
Rajgarh (Saunther)	456	789	1237	1673	2120	2709	2934	1692	40
Rajgarh (Jamra)	843	1316	2082	2997	3459	3752	4438	2772	35
High rainfall									
Guna (Saunther)	330	423	1089	1688	2755	3206	3343	1965	52
Guna (Jamra)	532	741	1850	3017	3963	4364	4629	2872	46
Nagpur	1230	1663	2440	3530	4218	4438	5052	3326	35
Shajapur (Saunther)	726	842	1176	1972	3054	3441	3875	2160	46
Shajapur (Sarol)	953	1215	2083	2934	4522	4815	5607	3211	43
Wardha	2869	3267	3479	4723	5051	5377	6431	4585	20
Indore (Kamiliakheri)	252	365	584	1088	1787	2790	3090	1391	63
Indore (Sarol)	1174	1260	2027	3530	4180	4900	5001	3301	39
Ratlam	623	1050	2228	3718	4291	5262	5712	3354	43
Raisen (Jamra)	1544	1768	2221	3385	4696	5028	5747	3560	39
Raisen (Sarol)	1765	1893	2254	3818	4801	5321	5911	3747	38
Betul	1547	1731	2811	3399	4561	4884	5963	3677	32
Bhopal (Saunther)	843	1045	1870	2549	2911	3231	3839	2429	34
Bhopal (Jamra)	1268	1669	2508	3922	4338	4804	5479	3635	32
Sagar	2119	2262	2717	3344	4588	4810	5441	3538	29
SECONDARY ZONE									
Medium rainfall									
Akola	621	822	1626	2356	3906	4584	4897	2797	49
Amravati	1138	1321	1684	3121	4276	4667	5718	3092	45
Jhabua	450	1392	1642	3169	3925	4286	5514	2891	49
High rainfall									
Vidisha	2286	2559	2612	3524	4196	4450	4879	3552	22
Belgaum	1359	1676	2478	3336	3989	4463	4612	3259	31
Jabalpur	1428	1620	2560	3711	3752	4084	5235	3310	28
TERTIARY ZONE									
Medium rainfall									
Patancheru (deep soil)	1212	3283	3739	4373	4872	5387	5665	4305	23
Patancheru (shallow soil)	1137	3135	3536	3934	4474	5005	5285	3964	23
Nanded	433	1209	2650	3514	4805	5366	6188	3520	44