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Yield Gap Analysis of Sorghum and Pearl Millet in India Using Simulation Modeling

International Crops Research Institute for the Semi-Arid Tropics

Comprehensive Assessment of Water Management in Agriculture

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Abstract

Sorghum and pearl millet are the staple cereals and important source of fodder for animals in the semi-arid and arid parts of India. In the present study, we have: a) characterized the distribution of sorghum and pearl millet in different production zones in India; b) estimated their rainfed potential, achievable and current levels of farmers' yields; c) quantified the gaps between farmers' yields and rainfed potential yields; and d) suggested ways to abridge the yield gaps.

Using CERES-sorghum and CERES-pearl millet crop growth models and historical weather data, rainfed potential yields and water balance of sorghum (*kharif* and *rabi*) and pearl millet were estimated for selected locations in different production zones. Simulated yields were supplemented with the research station yields of rainfed trials and yields of frontline demonstrations, both obtained from the reports of the All India Coordinated Crop Improvement Projects on Sorghum and Pearl Millet. District level yields were considered as farmers' yields. Based on these data, the yield gaps at various management levels were estimated.

The farmers' average yield was 970 kg ha^{-1} for *kharif* sorghum, 590 kg ha^{-1} for *rabi* sorghum and 990 kg ha^{-1} for pearl millet. Simulated rainfed potential yield in different production zones ranged from 3210 to 3410 kg ha^{-1} for *kharif* sorghum, 1000 to 1360 kg ha^{-1} for *rabi* sorghum and 1430 to 2090 kg ha^{-1} for pearl millet. Total yield gap (simulated rainfed potential yield - farmers' yield) in production zones ranged from 2130 to 2560 kg ha^{-1} for *kharif* sorghum, 280 to 830 kg ha^{-1} for *rabi* sorghum and 680 to 1040 kg ha^{-1} for pearl millet. This indicates that productivity of *kharif* sorghum can be increased 3.0 to 4.0 times, *rabi* sorghum 1.4 to 2.7 times and pearl millet 1.8 to 2.3 times from their current levels of productivity.

To abridge the yield gaps of sorghum and pearl millet, integrated watershed-based approach encompassing harvesting of excess rainfall for supplemental irrigation, growing high yielding crop cultivars, integrated nutrient management and integrated pest and disease management would be required. Value addition of products and their multiple uses are necessary to make them more remunerative for the farmers.

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Executive Summary

Sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br) are the staple cereals grown in the semi-arid and arid parts of India. They are also an important source of fodder for animals. While sorghum is grown both in the rainy (*kharif*) and postrainy (*rabi*) seasons, pearl millet is a completely rainy season crop, grown in hot and arid climate on marginal and least fertile soils where no other crop can survive.

With the increase in human and animal population and a fragile balance between food supplies and its demand, production of sorghum and pearl millet must be increased to meet the current and future food and fodder needs. The present study estimated the production potential, yield gap and water balance of various production zones under sorghum and pearl millet cultivation to assess the scope for enhancing their production in India.

Based on the share of cultivated area in a district to the total cropped area in the country, the districts were ranked for each crop. The top districts covering 50% of the cropped area were grouped into primary production zone. Similarly, next group of districts covering 35% (50% to 85%) of the total cropped area were placed in the secondary production zone. The districts which had <1000 ha sown to the crop were grouped as "others" and the rest were placed in the category of tertiary production zone. Similarly, the production and productivity were also studied in different states and AEZs.

CERES-sorghum and CERES-pearl millet models available in DSSAT v3.5 were used to simulate the growth and yield of sorghum and pearl millet, respectively, to quantify their potential productivity at selected locations in India. These estimates of potential yields, along with the experiment station, frontline demonstration (FLD) and district level yields, were used to assess yield gaps at various levels of technology adoption. Total yield gap (YG) was defined as the yield gap between simulated long–term mean yield and the district level mean yield. Total yield gap was further divided into yield gap I (YG I) and yield gap II (YG II). YG I is the gap between simulated long–term mean yield and the on-farm (FLD) mean yield. YG II is the gap between FLD mean yield and district level mean yield.

Kharif sorghum is currently grown on 4.56 million hectares (M ha) with a production of 4.40 million tons (M t) and an average productivity of 970 kg ha^{-1}. Maharashtra, Madhya Pradesh and Karnataka are the major *kharif* sorghum producing states. For the primary production zone, the simulated rainfed potential, frontline demonstration (FLD) and district mean yields were 3210, 1810 and 1080 kg ha^{-1}, respectively. For the secondary zone, the yields in the same order were 3390, 1880 and 860 kg ha^{-1}, respectively; and for the tertiary zone, these were 3410, 1840 and 850 kg ha^{-1}, respectively. Total yield gaps for the primary, secondary and tertiary zones were 2130, 2530 and 2560 kg ha^{-1}, respectively. The lowest yield gap in the primary production is mainly due to the low and erratic rainfall. While YG I was 60 to 65%, YG II was 35 to 40% of the total yield gap. Mean seasonal rainfall was 660 mm for the primary zone, 770 mm for the secondary zone and 660 mm for the tertiary zone, respectively. It was estimated that out of 660 to 770 mm of seasonal rainfall in the production zones, about 50% was lost as surface runoff and deep drainage.

Mid-season drought is the major constraint for *kharif* sorghum across the production zones in India. Apart from that, pests like shoot fly, stem borer and head bug cause damage to the crop. Diseases like grain mold, followed by ergot are the major yield reducers. Farmer's preference for pearly white grain

and roundness of the grain are the other constraints for the adoption of improved varieties and hybrids of sorghum. These grain qualities are consumer preferred and often dictate market prices for the produce.

Rabi sorghum is grown on 5.11 M ha with a total production of 2.99 M t and an average productivity of 590 kg ha^{-1}. It is grown mostly in Maharashtra and Karnataka and in some parts of Andhra Pradesh. Simulated rainfed potential, FLD and district mean yields of *rabi* sorghum were 1310, 1480 and 480 kg ha^{-1}, respectively, for the primary zone. For the secondary zone, the yields in the same order were 1360, 1290 and 680 kg ha^{-1}, respectively. For the tertiary zone, simulated rainfed potential and district mean yields were 1000 and 750 kg ha^{-1}, respectively and the FLD yields were not available. Primary production zone had the highest gap of 830 kg ha^{-1}, followed by secondary production zone with a gap of 680 kg ha^{-1} and tertiary zone with a gap of 280 kg ha^{-1}. Yield gaps I and II for the production zones could not be estimated accurately because of insufficient FLD data.

Mean rainfall during *rabi* season varied from 60 mm for the tertiary zone to 180 mm for the primary zone, with a high coefficient of variation ranging from 43% to 94% across locations within each production zone. Water surplus (runoff plus deep drainage) was negligible ranging from 20 to 90 mm in the production zones. Terminal drought is the major abiotic constraint for *rabi* sorghum. Shoot fly, head bugs and stalk rot are the major biotic constraints for *rabi* sorghum.

Pearl millet is grown on 9.4 M ha producing 8.5 M t with an average productivity of 990 kg ha^{-1}. Most of the area under pearl millet is in Rajasthan, Gujarat and Maharashtra. For the primary production zone, the simulated rainfed potential, frontline demonstration (FLD) and district mean yields were 1430, 1810 and 750 kg ha^{-1}, respectively. For the secondary zone, the yields in the same order were 1960, 1600 and 1060 kg ha^{-1}; and for the tertiary zone, these were 2090, 2190 and 1050 kg ha^{-1}, respectively. Mean FLD yield across the production zones was 1870 kg ha^{-1}, which is similar to the simulated rainfed mean yield. Primary production zone had the lowest yield gap of 680 kg ha^{-1}, followed by the secondary zone with a gap of 900 kg ha^{-1} and the tertiary zone with a gap of 1040 kg ha^{-1}. Total yield gap across all the production zones was 880 kg ha^{-1}. Yield gap II formed a larger part of the total yield gap, indicating greater scope for adopting the already available technologies by farmers for increasing production.

Mean seasonal rainfall in the primary zone was the lowest at 330 mm, followed by 420 mm in the secondary zone and 530 mm in the tertiary zone. Mean simulated water surplus (runoff plus deep drainage) was 140 mm for the primary, 180 mm for the secondary and 270 mm for the tertiary zones. Drought is the major constraint of pearl millet across all the production zones. Among the biotic constraints, downy mildew is the most widespread and destructive disease of pearl millet, causing severe economic losses. Other minor diseases affecting pearl millet are smut, ergot and rust.

The above analysis indicated that under rainfed situation the productivity of *kharif* sorghum could be increased 3.0 to 4.0 times, *rabi* sorghum 1.4 to 2.7 times and pearl millet 1.8 to 2.3 times from their current levels of productivity. Further improvements in yield are possible with the provision of supplemental irrigation. This requires integrated watershed-based approach that involves harvesting of excess rainfall for supplemental irrigation, growing high yielding crop cultivars with desirable quality traits, integrated nutrient management and integrated pest and disease management. Value addition of products and their multiple uses are necessary to make them more remunerative for the farmers.

1. Background

Sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br) are the rainfed cereals grown in the semi-arid and arid parts of India. Apart from serving as staple cereal for the poor in India, they are also an important source of fodder for domestic animals. While sorghum is grown both in the rainy (*kharif*) and postrainy (*rabi*) seasons, pearl millet is rainy season crop, grown in relatively warmer climate than sorghum.

After mid-eighties, the production of sorghum declined sharply. This was due to a steep decline in the total cultivated area as a result of changes in government policies and expanding irrigation facilities that favored cultivation of other high value crops and changes in food habits of people. Currently, *kharif* and *rabi* sorghum are grown on about 9.67 million hectare (M ha) in India (Database: 2000-02). Maharashtra accounts for the largest production, followed by Karnataka, Andhra Pradesh and Madhya Pradesh. Despite decline in total production in recent years, the overall productivity of the sorghum has increased from 470 kg ha^{-1} in 1970 to 880 kg ha^{-1} in 2005. There is a huge demand for *rabi* sorghum for grain and fodder, especially during lean months in Maharashtra and the neighboring states. Rather than high yielding varieties, good irrigational facilities contributed to the rise in productivity of *rabi* sorghum.

Pearl millet is the most important cereal crop in the arid regions of India. It is grown on 9.4 M ha with an average productivity of 900 kg ha^{-1} (Database: 2001-03). However, even with an increased production over the years, its productivity is still much below the potential levels. The production can be increased with improved management and high yielding cultivars.

In order to develop a suitable strategy to improve the productivity levels of sorghum and pearl millet, it is imperative to assess the potential yield and yield gaps between potential and actual yields. Many field trials are conducted every year at research stations and on-farms under the All India Coordinated Crop Improvement Projects on Sorghum and Pearl Millet. The yields reported in these trials can be used for determining production potential at various management levels. However, there are hiccups as the yields reported in these trials conducted over locations and seasons are sometimes confounded because of inadequate considerations to genotype, climatic factors and their variability and agronomic management. Alternatively, crop growth models, which integrate the effect of different factors on yield, could be used to estimate the potential productivity for large number of diverse locations. The present study investigated the potential productivity and yield gap of *kharif* and *rabi* sorghum and pearl millet for their production zones in India. Spatial and temporal variations in yield gap at various technological levels, i.e., yield gaps between simulated potential rainfed yields, experimental station rainfed yields, frontline demonstration yields and farmer's actual yields have been presented. Water balance components for the production zones of these crops were also estimated to assess constraints and opportunities for increasing their production and productivity in India.

2. Definitions, Data Sources and Methods

2.1 Delineation of Production Zones

District level databases on area, production and productivity of *kharif* and *rabi* sorghum and pearl millet crops available for 2000-2003 were used to delineate the production zones for each crop. The delineation procedure was the same for the three crops. The districts were ranked based on the share of area in a district to the total area for the crop in the country. The top districts covering 50% of the cropped area were grouped into primary production zone. The next group of districts covering 35% (50% to 85%) of the total cropped area were placed in secondary production zone. The next group of districts which had <1000 ha sown to the crop were grouped as "others" and the rest were placed in the category of tertiary production zone.

2.2 Experimental Station Yield

This is the maximum possible rainfed yield (observed rainfed yield potential) using an improved cultivar. The crop is grown under controlled field conditions with improved management practices. For *kharif* and *rabi* sorghum, we reviewed the annual reports of the All India Coordinated Sorghum Improvement Project (AICSIP) and collected yield data of all the entries in rainfed trials conducted at several locations for the last ten-years. The yield data thus obtained for a given crop was averaged over all the entries in the trial for each location and year. Subsequently, these means were further averaged over the ten-year period for each location to determine the mean yield potential for a location.

For pearl millet, we reviewed the annual reports of the All India Coordinated Pearl Millet Improvement Project (AICPMIP) and collected yield data of all entries in the rainfed trials conducted from 1990 to 2002 under improved management practices at 15 locations in the country. Mean yield potential of pearl millet for a location was calculated using the similar method as for sorghum.

2.3 On-farm Yields with Improved Management

The crop yield data of front line demonstrations (FLD) conducted by ICAR and reported in AICSIP and AICPMIP annual reports were used. FLD trials were conducted each year at several locations in a district and a mean value for the district was calculated. The FLD data were averaged over the years to calculate the mean FLD yield for the district. FLD yields represented the achievable yields with improved management under on-farm situations.

2.4 District Average Yields

District yields represent farmers' yields under traditional management. District level area and production data of *kharif* and *rabi* sorghum and pearl millet were obtained from the reports published by the Bureau of Economics and Statistics of different state governments. District average yields were then calculated from the data and averaged over the years as done for experimental yields data of sorghum and pearl millet.

2.5 Data sets of Experimental Station, On-Farm and District Yields of *Kharif* and *Rabi* Sorghum

For *kharif* sorghum, the experimental station data was available from 20 locations. Seven locations belonged to the primary, six to the secondary and seven to the tertiary zone. FLD data was available for four, one and two locations falling in the primary, secondary and tertiary zones, respectively. District yield data was available for all the locations, except for one location in tertiary zone of Gujarat.

For *rabi* sorghum, the experimental station data was available for 11 locations. Four locations belonged to the primary, five to the secondary and two to the tertiary zone. FLD data was available for three locations in the primary zone, one location in the secondary zone and none in the tertiary zone. District yield data was available for all the locations.

2.6 Data sets of Experimental Station, On-Farm and District Yields of Pearl Millet

Experimental station data for pearl millet was available for 16 locations. Three locations belonged to the primary, five to the secondary and six to the tertiary zone and two to the "others" category. FLD data was available for only one location in the primary, three locations in the secondary and two locations in the tertiary zone and none in the "others" category. District yield data was available for all the locations.

2.7 Simulation of *Kharif* and *Rabi* Sorghum Yields

ICRISAT has extensively validated the CERES-sorghum model to evaluate yield gaps in different agroecological subregions in peninsular India (Virmani and Alagarswamy 1993). For the present study, the same version of the model available in DSSAT v3.5 (Decision Support System for Agro-Technology Transfer, Jones et al. 1998) was adopted to carryout multi-year simulations of sorghum growth and yield for each selected location in the production area. The model needs inputs of daily data of rainfall, maximum and minimum temperatures and solar radiation, cultivar-specific coefficients (genetic coefficients) and soil profile characteristics for model execution. For this purpose, long-term real weather data were collected for the *kharif* and *rabi* sorghum locations (Tables 1 & 2). When solar radiation data was not available, it was estimated from sunshine hours. Otherwise, radiation was estimated from air temperatures, according to Bristow and Campbell (1984). Soil inputs for different locations were extracted from descriptions of established soil series of India (Lal et al. 1994). This model was further tested with the crop growth and soil water dynamics data of two seasons at ICRISAT. Crop growth and yield of an improved variety under rainfed situation for a location were simulated considering nutrients and pests are not limiting the crop growth. For rainy season (*kharif*) sorghum, we used cv. CSV 15 and for the postrainy season (*rabi*) sorghum we used cv. M 35-1. The same cultivars were used for model calibration, testing and long-term simulations for different locations. The details of locations for which simulations were carried out are given in Tables 1 and 2. Long-term outputs of crop yields and water balance were used to assess the potentials and constraints to crop production for several locations across India.

Table 1. Geographic details of locations, soil series and number of years for which simulations were carried out for *kharif* sorghum in India.

Location	State	Soil series	AWHC* (mm)	No. of years	Latitude (°N)	Longitude (°E)	AEZ+
Primary Zone							
Akola	Maharashtra	Jambha	280	26	20.50	77.17	6.3
Akola	Maharashtra	Annapur	120	26	20.50	77.17	6.3
Akola	Maharashtra	Otur	140	26	20.50	77.17	6.3
Akola	Maharashtra	Umbraj	170	26	20.50	77.17	6.3
Amravati	Maharashtra	Jambha	280	18	21.13	77.67	6.3
Dharwad	Karnataka	Achmatti	190	18	15.47	75.02	6.4
Dharwad	Karnataka	Huguluru	230	18	15.47	75.02	6.4
Jalgaon	Maharashtra	Jambha	280	23	21.00	75.50	6.3
Parbhani	Maharashtra	Jambha	280	26	19.50	76.75	6.2
Parbhani	Maharashtra	Otur	140	26	19.50	76.75	6.2
Parbhani	Maharashtra	Annapur	120	26	19.50	76.75	6.2
Parbhani	Maharashtra	Umbraj	170	26	19.50	76.75	6.2
Rajgarh	Madhya Pradesh	Jamra	170	24	23.83	76.75	10.1
Secondary Zone							
Jodhpur	Rajasthan	Chirai	190	26	26.75	72.75	2.1
Dhar	Madhya Pradesh	Sarol	200	22	22.50	75.25	5.2
Kota	Rajasthan	Chambal	220	35	25.00	76.50	5.2
Shajapur	Madhya Pradesh	Sarol	200	23	23.50	76.25	5.2
Shajapur	Madhya Pradesh	Saunther	90	23	23.50	76.25	5.2
Aurangabad	Maharashtra	Otur	140	27	19.92	75.33	6.2
Belgaum	Karnataka	Achmatti	190	16	16.33	74.75	6.4
Belgaum	Karnataka	Huguluru	230	19	16.33	74.75	6.4
Guna	Madhya Pradesh	Saunther	90	18	24.50	77.50	10.1
Guna	Madhya Pradesh	Jamra	170	26	24.50	77.50	10.1
Nagpur	Maharashtra	Linga	120	16	21.00	79.00	10.2
Wardha	Maharashtra	Sukali	180	20	20.83	78.60	10.2
Betul	Madhya Pradesh	Jambha	280	20	21.83	77.83	10.2
Tertiary Zone							
Indore	Madhya Pradesh	Sarol	200	27	22.67	75.75	5.2
Ujjain	Madhya Pradesh	Sarol	200	26	23.42	75.50	5.2
Rahuri	Maharashtra	Annapur	120	17	19.38	74.65	6.1
Sholapur	Maharashtra	Barsi	190	19	17.75	75.50	6.1
Sholapur	Maharashtra	Otur	140	19	17.75	75.50	6.1
Sholapur	Maharashtra	Umbraj	170	19	17.75	75.50	6.1
Pune	Maharashtra	Otur	140	15	18.75	73.75	6.4
Bhopal	Madhya Pradesh	Jamra	170	33	23.50	77.42	10.1
Bhopal	Madhya Pradesh	Saunther	90	33	23.50	77.42	10.1
Others							
Kannod	Madhya Pradesh	Sarol	200	19	22.40	76.44	10.1

* Available water holding capacity of soil profile; + Agroecological zone.

Table 2. Geographic details of locations, soil series and number of years for which simulations were carried out for *rabi* sorghum in India.

Location	State	Soil series	AWHC* (mm)	No. of years	Latitude (°N)	Longitude (°E)	AEZ+
Primary Zone							
Rahuri	Maharashtra	Annapur	120	18	19.38	74.65	6.1
Sholapur	Maharashtra	Barsi	190	19	17.75	75.50	6.1
Sholapur	Maharashtra	Otur	140	19	17.75	75.50	6.1
Sholapur	Maharashtra	Umbraj	170	19	17.75	75.50	6.1
Secondary Zone							
Aurangabad	Maharashtra	Otur	140	26	19.92	75.33	6.2
Belgaum	Karnataka	Achmatti	190	15	16.33	74.75	6.4
Belgaum	Karnataka	Huguluru	230	15	16.33	74.75	6.4
Dharwad	Karnataka	Achmatti	190	18	15.47	75.02	6.4
Dharwad	Karnataka	Huguluru	230	18	15.47	75.02	6.4
Parbhani	Maharashtra	Jambha	280	26	19.50	76.75	6.2
Parbhani	Maharashtra	Otur	140	26	19.50	76.75	6.2
Parbhani	Maharashtra	Annapur	120	26	19.50	76.75	6.2
Parbhani	Maharashtra	Umbraj	170	26	19.50	76.75	6.2
Tertiary Zone							
Wardha	Maharashtra	Sukali	180	16	20.60	78.20	10.2
Akola	Maharashtra	Jambha	180	26	20.50	77.17	6.3
Akola	Maharashtra	Annapur	120	26	20.50	77.17	6.3
Akola	Maharashtra	Otur	140	26	20.50	77.17	6.3
Jalgaon	Maharashtra	Jambha	200	23	21.00	75.50	6.3
Jalgaon	Maharashtra	Linga	160	23	21.00	75.50	6.3
Others							
Amravati	Maharashtra	Jambha	280	18	21.13	77.67	6.3

* Available water holding capacity of soil profile; + Agroecological zone.

2.8 Simulation of Pearl Millet Yields

To simulate rainfed potential yields of pearl millet, we used CERES-pearl millet model available in DSSAT v3.5 (Decision Support System for Agro-Technology Transfer, Jones et al. 1998). The model was calibrated and validated with two seasons of crop growth and soil water dynamics data from ICRISAT. For pearl millet, we used cultivar ICTP 8203. The same cultivar was used for model calibration, testing and long-term simulations for different locations. The details of locations and the number of years for which simulation runs were carried out are given in Table 3. Other model inputs and treatment of data for model simulation were the same as for the CERES-sorghum model.

Table 3. Geographic details of locations, soil series and number of years for which simulations were carried out for pearl millet.

Location	State	Soil series	AWHC* (mm)	No. of years	Latitude (°N)	Longitude (°E)	AEZ+
Primary Zone							
Rahuri	Maharashtra	Annapur	120	17	19.38	74.65	6.1
Jodhpur	Rajasthan	Chirai	190	26	26.75	72.75	2.1
Jaipur	Rajasthan	Chomu	160	9	26.92	75.02	4.1
Secondary Zone							
Pune	Maharashtra	Otur	140	15	18.75	73.75	6.4
Gulbarga	Karnataka	Hungund	120	20	17.17	77.08	6.2
Gulbarga	Karnataka	Huguluru	230	22	17.17	77.08	6.2
Bijapur	Karnataka	Hungund	120	12	16.67	75.92	3.0
Jalgaon	Maharashtra	Jambha	280	23	21.00	75.50	6.3
Jalgaon	Maharashtra	Linga	160	23	21.00	75.50	6.3
Aurangabad	Maharashtra	Otur	140	27	19.92	75.33	6.2
Tertiary Zone							
Akola	Maharashtra	Jambha	280	26	20.50	77.17	6.3
Akola	Maharashtra	Annapur	120	26	20.50	77.17	6.3
Akola	Maharashtra	Otur	140	26	20.50	77.17	6.3
Akola	Maharashtra	Umbraj	170	26	20.50	77.17	6.3
Amravati	Maharashtra	Jambha	280	18	21.13	77.67	6.3
Belgaum	Karnataka	Achmatti	190	16	16.33	74.75	6.4
Belgaum	Karnataka	Huguluru	230	16	16.33	74.75	6.4
Dharwad	Karnataka	Achmatti	190	18	15.47	75.02	6.4
Dharwad	Karnataka	Huguluru	230	18	15.47	75.02	6.4
Kota	Rajasthan	Chambal	220	35	25.00	76.50	5.2
Parbhani	Maharashtra	Jambha	280	26	19.50	76.75	6.2
Parbhani	Maharashtra	Otur	140	26	19.50	76.75	6.2
Parbhani	Maharashtra	Annapur	120	26	19.50	76.75	6.2
Parbhani	Maharashtra	Umbraj	170	26	19.50	76.75	6.2
Sholapur	Maharashtra	Barsi	190	19	17.75	75.50	6.1
Sholapur	Maharashtra	Otur	140	19	17.75	75.50	6.1
Sholapur	Maharashtra	Umbraj	170	19	17.75	75.50	6.1
Others							
Rajgarh	Madhya Pradesh	Jamra	170	24	23.83	76.75	10.1
Indore	Madhya Pradesh	Sarol	200	27	22.67	75.75	5.2
Guna	Madhya Pradesh	Saunther	90	18	24.50	77.50	10.1
Guna	Madhya Pradesh	Jamra	170	19	24.50	77.50	10.1

* Available water holding capacity of soil profile; + Agroecological zone.

2.9 Quantification of Yield Gaps

Yield gaps were estimated using simulated yields, experimental station yields, FLD yields and district average yields. Two types of yield gaps estimated were yield gap I and yield gap II. Yield gap I is the yield gap between the experimental station yield and the yield of the front line demonstrations (FLD). Yield gap II is the yield gap between FLD yield and the district average yield. Difference between the experimental station yield and the farmers' average yield is the total yield gap. The yield gaps were also calculated as the difference between simulated rainfed yields and the district average yields.

3. Production Trends of Sorghum in the World and India

3.1 Sorghum Production in the World

Globally, about 49 M ha of sorghum was cultivated in 1970. Since then, over the 36 years period, its area has declined to 44.7 M ha in 2005 (Fig. 1). World productivity of sorghum hovered around 1 t ha^{-1} during early seventies and gradually increased to 1.4 t ha^{-1} towards early eighties. Productivity of sorghum was 1.3 t ha^{-1} in 2005. About 19 per cent of the sorghum area is in India. India, Nigeria and Sudan put together have more than 50 per cent of global area under sorghum (Table 4). However, in terms of productivity, Nigeria is at 48th position with a productivity of 1260 kg ha^{-1}, India is at 67th position with a productivity of 880 kg ha^{-1} and Sudan is at 73rd position with a productivity of 660 kg ha^{-1}. It is clear that the countries with large areas under sorghum cultivation have very low productivity (Table 4).

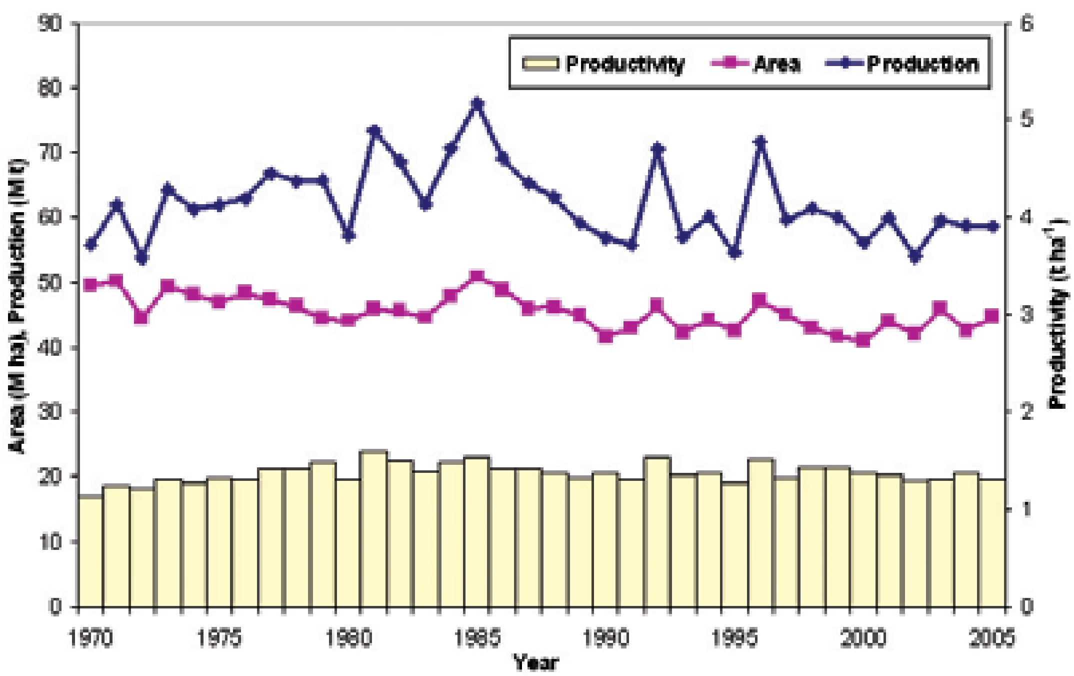

Figure 1. Global trends of area, production and productivity of sorghum (FAOSTAT, 2006).

Table 4. Area, production and productivity of sorghum in major sorghum producing countries (Database: FAOSTAT, 2006).

Countries	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	% area	Productivity ranking
India*	8.7	7.6	880	22	67
Nigeria	7.3	9.2	1260	17	48
Sudan	6.4	4.3	660	15	73
Niger	2.9	0.9	330	7	86
USA	2.3	10.0	4300	5	8
Mexico	1.6	5.5	3450	4	14
Ethiopia	1.5	2.2	1450	3	42
Burkino Faso	1.4	1.6	1080	3	56
China	1.1	2.6	2350	2	26
Tanzania	0.9	0.9	1000	2	57
Chad	0.8	0.6	740	2	71
Brazil	0.8	1.5	1930	2	35
Australia	0.8	2.0	2660	2	23

* Source: Ministry of Agriculture, India, 2006.

3.2 Sorghum Production in India

In India, sorghum area has declined from 17 M ha in 1970 to about 8.7 M ha in 2005. However, sharp decline in area occurred after mid-eighties (Table 4 and Fig. 2). In spite of year-to-year variation in total production, the production of sorghum increased until mid-eighties primarily due to yield increase. After mid-eighties, the production declined sharply due to decline in area because of competition by other crops. Maharashtra is the largest state with 52.7 per cent of total sorghum area and contributing 54.8 per cent of the total production of sorghum in India. Karnataka, Andhra Pradesh and Madhya Pradesh are the other three major sorghum producing states with 30.9 per cent to total sorghum area and 34.1 per cent to total production. In spite of decline in total production in recent years, the productivity of the crop increased from 470 kg ha^{-1} in 1970 to 880 kg ha^{-1} in 2005.

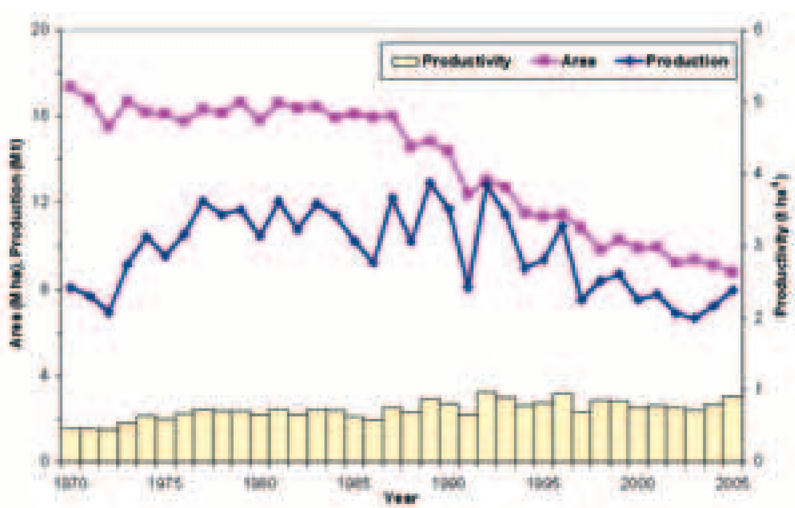

Figure 2. Area, production and productivity of sorghum in India (Source: FAOSTAT, 2006).

4.0 Yield Gap Analysis of *Kharif* Sorghum

4.1 Abstract

Kharif sorghum is an important staple food for poor people and source of feed and fodder for livestock production in India. Considering its importance in the near future as a source of food for people, feed and fodder for animals for draft and milk production and also as a source of bio-energy, its production and productivity must be increased. The present study estimated the production potential and yield gap of *kharif* sorghum to assess the scope for increasing its production.

CERES-sorghum model available in DSSAT v3.5 was used to simulate sorghum growth and yield to quantify the potential productivity of *kharif* sorghum for selected locations. These estimates along with experiment station yields, frontline demonstration (FLD) yields and district level yield data were used to assess yield gaps. For the primary production zone, the simulated rainfed potential, frontline demonstration (FLD) and district mean yields were 3210, 1810 and 1080 kg ha^{-1}, respectively. For the secondary zone, the yields were 3390, 1880 and 860 kg ha^{-1}; and for the tertiary zone, these were 3410, 1840 and 850 kg ha^{-1}, respectively. Total yield gaps (simulated potential minus district average yield) for the primary, secondary and tertiary zones were 2130, 2530 and 2560 kg ha^{-1}, respectively. Yield gap I (simulated potential minus FLD yield) was 60 to 65% and yield gap II (FLD minus average farmer yield) was 35 to 40% of the total yield gap, indicating the need to transfer available *kharif* sorghum production technologies from experiment station to the on-farm situations. Mid-season drought is the major yield reducer of *kharif* sorghum. It was estimated that out of 660 to 770 mm of seasonal rainfall in the production zones, about 50% is lost as surface runoff and deep drainage. Integrated watershed management approach, encompassing harvesting and storing of excess water for supplemental irrigation, improved cultivars, integrated nutrient and pest management practices are required to abridge the yield gaps of *kharif* sorghum.

4.2 Introduction

Traditionally, *kharif* sorghum has been grown in the states of Maharashtra, Gujarat, Karnataka, Andhra Pradesh and Madhya Pradesh. With the exception of Maharashtra, there has been significant reduction in area and production of *kharif* sorghum. Over the years, *kharif* sorghum growing area has been replaced variously across states by competing high value crops like groundnut, sunflower, soybean, pigeonpea, chickpea, maize, castor and cotton. Currently, Maharashtra, Karnataka, Andhra Pradesh and Madhya Pradesh are the major sorghum producing states. As per the current estimates, *kharif* sorghum is grown on 4.56 M ha with an average productivity of 970 kg ha^{-1}. Despite the declining trends in per capita consumption of sorghum as food, it remains as the important and easily accessible staple cereal for the economically deprived people in India.

The present study investigated the production potential and yield gap of *kharif* sorghum in the major sorghum growing areas of India. Spatial and temporal variations in yield gap at various technological levels, i.e., yield gaps between simulated potential rainfed yields, experimental station rainfed yields, frontline demonstration yields and farmer's actual yields are also presented. Water balance components of *kharif* sorghum production were also evaluated to assess constraints and opportunities for increasing its production and productivity in India.

4.3 Production Zones and Soil Resources of *Kharif* Sorghum

In India, the primary *kharif* sorghum production zone comprises 22 districts with about 2.26 M ha (Fig. 3). Out of these districts, 11 districts belong to Maharashtra with annual rainfall ranging from 300 to 750 mm. The remaining districts are in Rajasthan, Madhya Pradesh, Andhra Pradesh, Karnataka and Tamil Nadu. The secondary production zone covers 55 districts with 35 per cent of the total area; whereas the tertiary zone covers 137 districts with 15 per cent of the total area under *kharif* sorghum. The 116 districts in the category of "others" have negligible area and production of the crop.

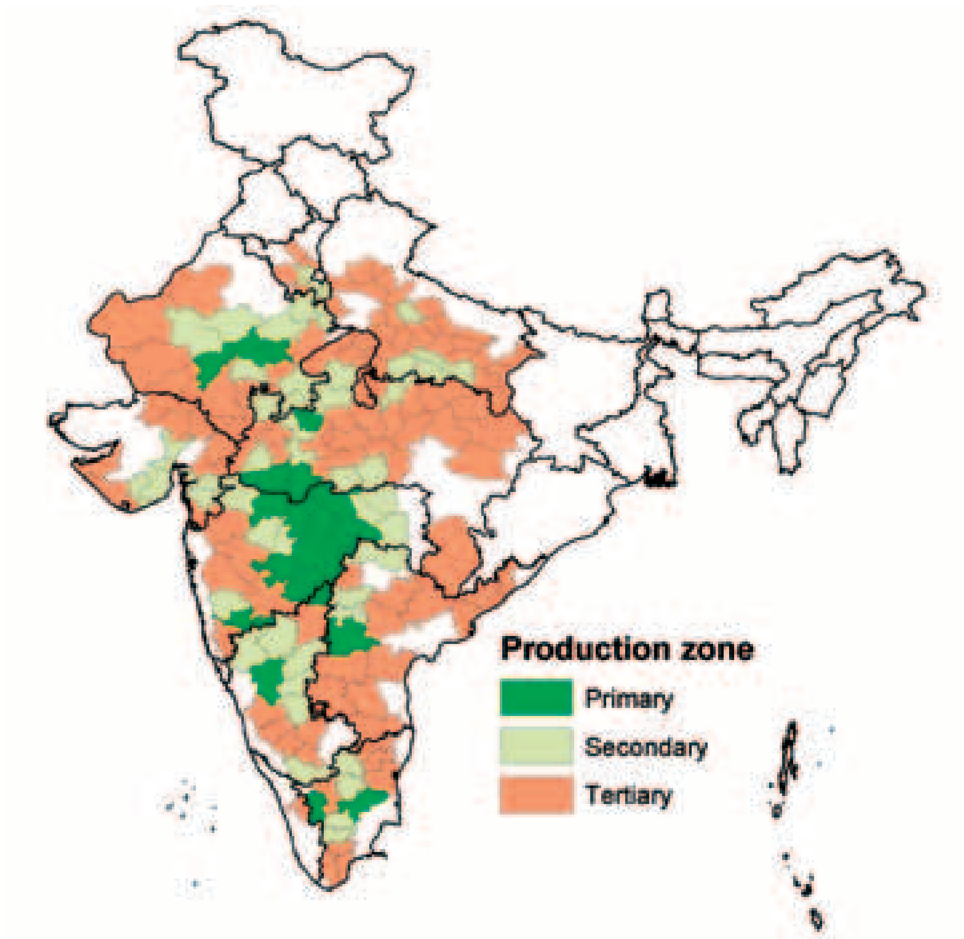

Figure 3. Production zones of *kharif* sorghum in India *(Database: 1995-98)*.

Primary production zone is dominated by Entisols, occupying about 45.6 per cent area, followed by Vertisols with 36.2% area (Table 5 and Fig. 4). Other important soils are Alfisols, Inceptisols and Aridisols. Vertisols (mainly Usterts) occupy 38 per cent of the secondary production zone. Entisols cover 27.5 per cent of the area, followed by Inceptisols, Alfisols and Aridisols. Tertiary production zone has a fairly even distribution of Entisols, Alfisols, Inceptisols and Vertisols with a little area covered by Aridisols. Thus, Vertisols and Entisols are dominant soil orders in primary and secondary zones where *kharif* sorghum production is concentrated. High rainfall or irrigation may be the reason for its even distribution on soil orders in the tertiary zone.

Table 5. Relative distribution of soil resources in production zones of *kharif* sorghum.

Primary zone		Secondary zone		Tertiary zone	
Soil type	Area (%)	Soil type	Area (%)	Soil type	Area (%)
Entisols	45.6	Vertisols	38.0	Entisols	29.1
Vertisols	36.2	Entisols	27.5	Alfisols	25.7
Alfisols	9.3	Inceptisols	13.3	Inceptisols	20.7
Inceptisols	5.5	Alfisols	12.2	Vertisols	16.3
Aridisols	3.3	Aridisols	8.2	Aridisols	6.6

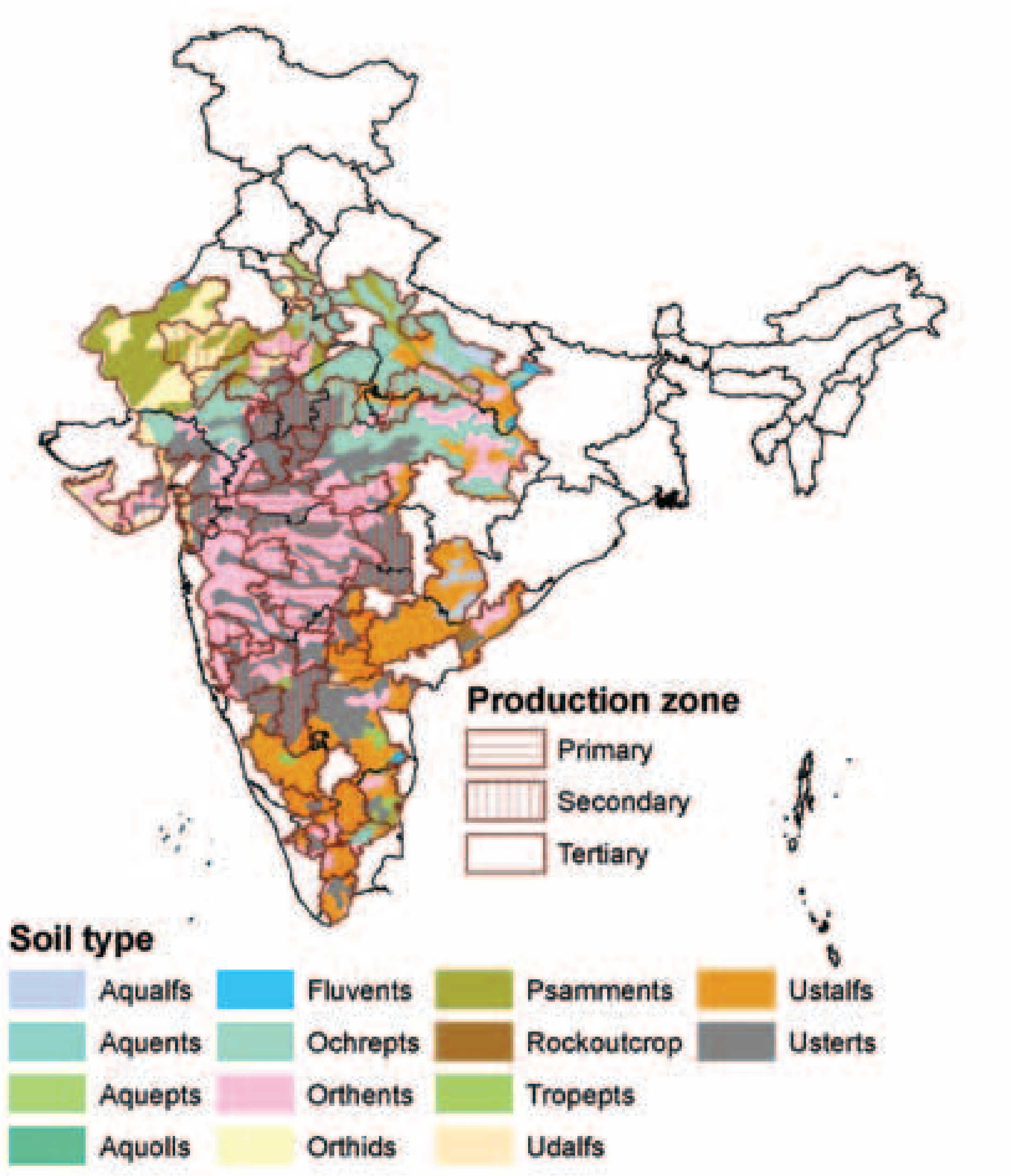

Figure 4. Soil resources in different production zones of *kharif* sorghum in India.

4.4 *Kharif S*orghum Productivity in Production Zones, AEZs and States of India

***Kharif* sorghum productivity in production zones:** Productivity of primary zone is the highest at 1080 kg ha^{-1} with a coefficient of variation (CV) of 47% (Table 6). Secondary and tertiary zones have similar productivities (860 and 850 kg ha^{-1}, respectively) with a CV of 51% and 47%, respectively. The production zone classified as "others" has the lowest productivity of 740 kg ha^{-1} with a CV of 52%. These results show that production of *kharif* sorghum decreases as one moves away from the primary production zone to the secondary or tertiary zone with little change in CV of yields.

Table 6. Area, production and productivity of *kharif* sorghum in different production zones of India (Database: 2000-02).

Production zones	No. of districts	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	CV* (%)
Primary	22	2.26	2.44	1080	47
Secondary	55	1.60	1.37	860	51
Tertiary	137	0.68	0.57	850	47
Others	116	0.02	0.02	740	52
Total	330	4.56	4.40	970	50

*Coefficient of variation among districts.

***Kharif* sorghum productivity in agroecological zones:** AEZ 6 is termed as semi-arid dry and moist zone. Length of growing period (LGP) varies from 60 to 180 days. This zone encompasses 31 districts, with most of them from Maharashtra and Karnataka. AEZ 6 has the maximum area (1.91 M ha) and the maximum *kharif* sorghum production (2.49 M t) in the country, constituting 42% of the total area and 56% of total production (Table 7 and Fig. 5). Average productivity of this zone is one of the highest (1300 kg ha^{-1}).

AEZ 4 has semi-arid dry climate with LGP varying from 90 to 120 days. Available water holding capacity (AWHC) of soils in the rooting zone varies from 100 to 200 mm. Ajmer and Tonk districts of Rajasthan are in this zone. AEZ 4 ranks second in terms of area (0.77 M ha) and production (0.39 M t) in the country. The average productivity of this zone is 500 kg ha^{-1}. This zone is followed by AEZ 5 in terms of area (0.42 M ha) and production (0.37 M t) of *kharif* sorghum. AEZ 5 has semi-arid moist climate. AWHC of soils in this zone range from 50 to 150 mm. The LGP is 90 to 150 days. East and West Nimar districts of Madhya Pradesh fall in this zone. Average productivity of this zone is 880 kg ha^{-1}. *Kharif* sorghum in AEZ 8 comes under semi-arid dry and moist climate with LGP varying from 90 to 150 days. Soils have low AWHC (50 to 150 mm). The total area under the crop is 0.38 M ha with a total production of 0.32 M t and average productivity of 830 kg ha^{-1}. AEZ 10 has sub-humid moist and dry climate, covering 32 districts. It has the fifth largest area (0.37 M ha) and production (0.33 M t) in the country. The average productivity is 890 kg ha^{-1}. Coimbatore and Tiruchirapally districts of Tamil Nadu fall in this zone. AEZ 7 is termed as semi-arid moist zone with a growing season of 90 to 100 days. AWHC of soils range from 100 to 120 mm. Mahabubnagar, Medak and Ranga Reddy districts of Andhra Pradesh come in this zone. This zone has an average productivity of 860 kg ha^{-1}. AEZ 2 and 3 have arid climate and LGP is about 60 days. Jodhpur and Nagaur (AEZ 2) of Rajasthan and Bellary and Bijapur districts of Karnataka (AEZ 3) fall in this agroclimate. The average productivity of AEZ 2 and AEZ 3 is 220 kg ha^{-1} and 1420 kg ha^{-1}, respectively. The other AEZs have small area under *kharif* sorghum and their average productivity range from 430 to 1440 kg ha^{-1}.

Table 7. Area, production and productivity in different agroecological zones (AEZs) of *kharif* sorghum in India (Database: 2000-02).

AEZ	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	CV* (%)	No. of districts
2	0.233	0.051	220	62	21
3	0.077	0.110	1420	29	5
4	0.771	0.388	500	56	71
5	0.422	0.373	880	49	29
6	1.911	2.486	1300	25	31
7	0.244	0.210	860	38	13
8	0.381	0.316	830	58	33
9	0.039	0.037	950	18	17
10	0.372	0.332	890	28	32
11	0.041	0.032	770	20	15
12	0.036	0.034	940	42	29
13	0.007	0.005	830	19	14
15	0.001	0.001	540	30	5
18	0.001	0.000	430	13	3
19	0.019	0.028	1440	61	12
Total	4.555	4.403	970	50	330

*Coefficient of variation among districts.

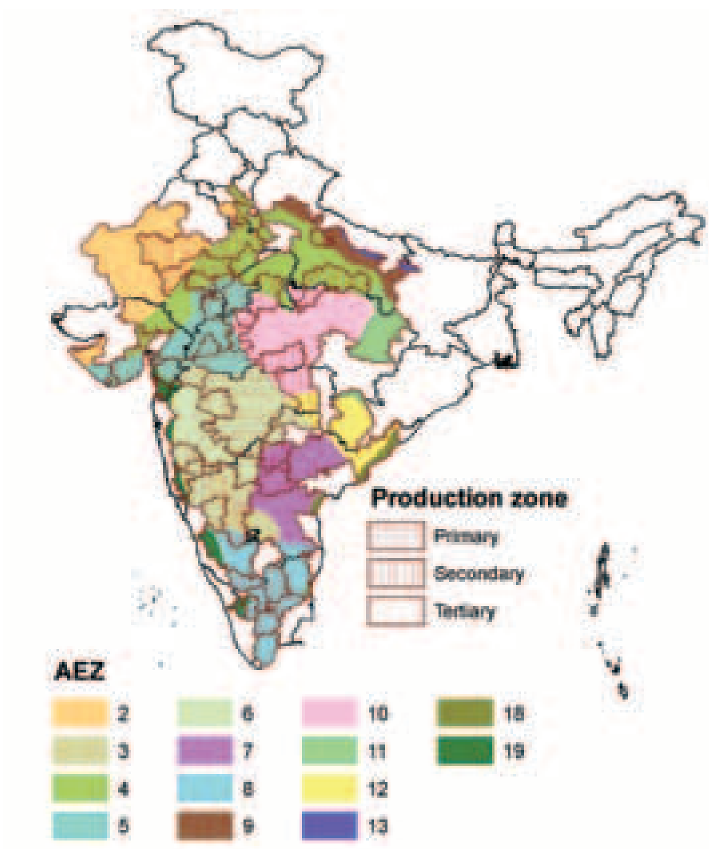

Figure 5. Agroecological zones of *kharif* sorghum in India.

***Kharif* sorghum productivity in different states of India:** Maharashtra is the largest *kharif* sorghum growing state with about 1.8 M ha out of the total 4.56 M ha grown in India. Madhya Pradesh and Rajasthan come next with 0.61 M ha each followed by Karnataka with 0.34 M ha (Table 8). Maharashtra produces 2.3 M t out of a total production of 4.40 M t of sorghum produced in the country. The productivity in Maharashtra is 1280 kg ha^{-1}. About 28 districts in Maharashtra grow *kharif* sorghum. The variability of productivity across these districts is also high with a CV of 26 per cent. Madhya Pradesh grows sorghum in 45 districts with a mean productivity of 860 kg ha^{-1}. Variability of productivity across districts in this state is high with a CV of 30 per cent. Karnataka grows *kharif* sorghum in 21 districts with a mean productivity of 1300 kg ha^{-1}, which is the highest in the country. Uttar Pradesh, Andhra Pradesh, Tamil Nadu and Gujarat are the other states having large area under sorghum. However, the area under sorghum in these states has declined drastically in the recent years. All other states have very little areas under sorghum.

Table 8. Area, production and productivity of *kharif* sorghum in different states of India (Database: 2000-02).

State	No. of districts	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	CV* (%)
Andhra Pradesh	22	0.30	0.29	980	56
Gujarat	23	0.16	0.14	910	50
Karnataka	21	0.34	0.44	1300	35
Madhya Pradesh	45	0.61	0.53	860	30
Maharashtra	28	1.80	2.30	1280	26
Rajasthan	32	0.61	0.15	250	54
Tamil Nadu	24	0.29	0.21	730	64
Uttar Pradesh	69	0.31	0.29	940	20
Others	66	0.13	0.04	310	46
Total	330	4.56	4.40	970	50

*Coefficient of variation among districts.

4.5 Rainfed Yield Potential of *Kharif* Sorghum

Experimental station yields and yield gaps: Primary zone has locations from Maharashtra, Karnataka and Andhra Pradesh. Out of all the locations, Dharwad had the maximum experiment station and FLD yields. For other locations, the experiment station yields ranged from 3230 to 3810 kg ha^{-1} (Table 9). For the primary zone, the mean experiment station yield was 3770 kg ha^{-1}, the mean FLD yield was 1810 kg ha^{-1} and the mean district yield was 1330 kg ha^{-1}. The yield gaps I and II for this zone were 2120 and 630 kg ha^{-1}, respectively. Based on the mean experiment station and the mean district yields, the total yield gap was 2440 kg ha^{-1}. For the secondary zone, the experiment station yields ranged from 2240 to 4080 kg ha^{-1} across locations. FLD yield was available only for Surat in Gujarat, which was 1880 kg ha^{-1}. For this zone, mean experimental station yield was 3440 kg ha^{-1} and the corresponding mean district yield was 1250 kg ha^{-1}. Mean yield gaps I and II were 2010 and 680 kg ha^{-1}, respectively. Total yield gap for the secondary zone on average was 2190 kg ha^{-1}. Mean experimental station yields for the tertiary zone ranged from 2280 to 3960 kg ha^{-1} across locations. FLD yields were available for only two locations. For this zone, mean experimental yield was 3250 kg ha^{-1}, mean FLD yield was 1840 kg ha^{-1} and the district average yield was 1050 kg ha^{-1}. Yield gaps I and II for this zone were 1430 kg ha^{-1} and 1050 kg ha^{-1}, respectively. Thus, the total yield gap was 2260 kg ha^{-1} (Table 9). These results indicate that substantial total yield gap (2190 to 2440 kg ha^{-1}) for *kharif* sorghum exists for the production zones. Yield gap I was larger than yield gap II for the production zones, indicating the need to transfer and adopt technologies from on-station to on-farm to benefit farmers.

Table 9. Experimental station, FLD and district average yields and yield gaps (kg ha^{-1}) of *kharif* sorghum in India.

Location	State	Expt. stn.	FLD	District	Yield gap I	Yield gap II	Total yield gap
Primary Zone							
Akola	Maharashtra	3580	2000	1560	1580	440	2020
Buldana	Maharashtra	3610	–	1640	–	–	1970
Parbhani	Maharashtra	3230	1460	1300	1770	150	1930
Yavatmal	Maharashtra	3240	–	1220	–	–	2020
Jalgaon	Maharashtra	3810	–	1760	–	–	2050
Dharwad	Karnataka	5660	2590	1240	3070	1340	4410
Palem	Andhra Pradesh	3260	1200	620	2060	580	2650
Mean		3770	1810	1330	2120	630	2440
Secondary Zone							
Aurangabad	Maharashtra	2240	–	1110	–	–	1130
Dhule	Maharashtra	3170	–	1290	–	–	1890
Adilabad	Andhra Pradesh	3740	–	990	–	–	2760
Bailhonga	Karnataka	3510	–	1350	–	–	2160
Surat	Gujarat	3890	1880	1200	2010	680	2690
Karad	Maharashtra	4080	–	1570	–	–	2510
Mean		3440	1880	1250	2010	680	2190
Tertiary Zone							
Gandhinglaj	Maharashtra	3400	–	1970	–	–	1430
Somnath	Maharashtra	3960	–	520	–	–	3440
Indore	Madhya Pradesh	3290	2120	1130	1170	980	2160
Deesa	Gujarat	3200	–	320	–	–	2880
Kanpur	Uttar Pradesh	2280	–	1420	–	–	860
Navsari	Gujarat	3400	–	–	–	–	–
Udaipur	Rajasthan	3260	1570	440	1690	1120	2820
Mean		3250	1840	970	1430	1050	2260

4.6 Simulated Potential Rainfed Yields

Potential yield of locations: In the primary zone, the mean yield across locations ranged from 2510 kg ha^{-1} to 3670 kg ha^{-1} with a mean yield of 3210 kg ha^{-1} (Table 10). The coefficient of variation ranged from 9% to 30%, primarily due to variability in rainfall at these locations. Maximum possible yield under rainfed situation ranged from 3770 kg ha^{-1} to 5250 kg ha^{-1} and the minimum yields from 580 kg ha^{-1} to 3240 kg ha^{-1}. For the secondary production zone, the mean yield across locations ranged from 1570 kg ha^{-1} (Jodhpur) to 4430 kg ha^{-1} (Dhar) with an overall mean of 3390 kg ha^{-1} (Table 10).

Table 10. Seasonal rainfall and simulated grain yield of *kharif* sorghum at different locations across India.

Location	State	Soil series	No. of years	Rainfall (mm)				Grain yield ($kg\ ha^{-1}$)				District yield ($kg\ ha^{-1}$)	Yield gap ($kg\ ha^{-1}$)
				Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max		
Primary Zone													
Akola	Maharashtra	Jambha	26	660	29	280	990	3650	14	2280	4600	1740	1910
Akola	Maharashtra	Annapur	26	660	29	280	990	3560	19	1540	4590	1740	1820
Akola	Maharashtra	Otur	26	660	29	280	990	3420	20	1730	4520	1740	1680
Akola	Maharashtra	Umbraj	26	660	29	280	990	3320	21	1940	4510	1740	1580
Amravati	Maharashtra	Jambha	18	680	26	400	970	3610	25	1240	5250	1640	1970
Dharwad	Karnataka	Achmatti	18	420	32	250	750	3450	23	580	4420	1600	1850
Dharwad	Karnataka	Huguluru	18	420	32	250	750	3670	9	3240	4530	1600	2070
Jalgaon	Maharashtra	Jambha	23	630	19	370	860	3230	29	870	4210	1990	1240
Parbhani	Maharashtra	Jambha	26	700	41	280	1300	2510	22	1410	3770	1400	1110
Parbhani	Maharashtra	Otur	26	700	41	280	1300	2680	17	1850	3850	1400	1280
Parbhani	Maharashtra	Annapur	26	700	42	280	1300	2810	13	2140	3870	1400	1410
Parbhani	Maharashtra	Umbraj	26	690	41	280	1300	2610	19	1700	3820	1400	1210
Rajgarh	Madhya Pradesh	Jamra	24	880	30	410	1700	3210	30	160	4290	650	2560
Mean	–	–	–	660	–	–	–	3210	–	–	–	1500	1670
Secondary Zone													
Jodhpur	Rajasthan	Chirai	26	310	55	50	710	1570	46	0	2830	450	1120
Dhar	Madhya Pradesh	Sarol	22	840	23	570	1360	4430	23	1260	5340	550	3880
Kota	Rajasthan	Chambal	35	620	39	300	1450	2440	53	0	4880	960	1480
Shajapur	Madhya Pradesh	Sarol	23	840	35	0	1720	3230	29	650	4500	1070	2160
Shajapur	Madhya Pradesh	Saunther	23	900	26	580	1740	3210	31	420	4470	1070	2140
Aurangabad	Maharashtra	Otur	27	560	32	180	880	3840	28	870	5040	1350	2490
Belgaum	Karnataka	Achmatti	16	870	29	530	1530	3510	33	770	4900	1360	2150
Belgaum	Karnataka	Huguluru	16	870	29	530	1530	3910	17	2470	5070	1360	2550
Guna	Madhya Pradesh	Saunther	19	710	36	270	1170	2910	27	1710	4300	720	2190
Guna	Madhya Pradesh	Jamra	18	880	32	320	1320	4000	24	1600	4910	720	3280
Nagpur	Maharashtra	Linga	26	830	26	490	1460	3030	25	1390	3960	1160	1870
Wardha	Maharashtra	Sukali	16	880	29	530	1530	4010	18	2500	5330	1080	2930
Betul	Madhya Pradesh	Jambha	20	1030	22	550	1530	4040	14	3110	5180	770	3270
Mean	–	–	–	770	–	–	–	3390	–	–	–	950	2420

Table 10. *Continued*

Location	State	Soil series	No. of years	Rainfall (mm) Mean	CV (%)	Min	Max	Grain yield ($kg\ ha^{-1}$) Mean	CV (%)	Min	Max	District yield ($kg\ ha^{-1}$)	Yield gap ($kg\ ha^{-1}$)
Tertiary Zone													
Indore	Madhya Pradesh	Sarol	27	820	30	370	1400	3780	20	1550	4470	1200	2580
Ujjain	Madhya Pradesh	Sarol	26	860	35	450	1810	3790	22	580	4650	880	2910
Rahuri	Maharashtra	Annapur	17	360	41	140	680	2520	38	960	3750	1620	900
Sholapur	Maharashtra	Barsi	19	400	43	90	900	3130	41	570	4530	1110	2020
Sholapur	Maharashtra	Otur	19	390	44	90	900	2910	49	30	4530	1110	1800
Sholapur	Maharashtra	Umbraj	19	390	44	90	900	2730	50	190	4330	1110	1620
Pune	Maharashtra	Otur	15	540	28	370	820	4380	16	2050	4870	1240	3140
Bhopal	Madhya Pradesh	Jamra	33	1040	31	440	1840	3870	11	2600	4450	890	2980
Bhopal	Madhya Pradesh	Saunther	33	1040	31	440	1840	3520	22	1120	4420	890	2630
Mean	–	–	–	670	–	–	–	3410	–	–	–	1160	2290
Others													
Kannod	Madhya Pradesh	Sarol	19	810	37	110	1580	3340	30	500	4870	1220	2120

Rajasthan had the highest coefficient of variation (CV) in yield with 46% for Jodhpur and 53% for Kota, respectively. The locations with low CV were Belgaum (17%) and Betul (14%), which is due to high rainfall at these locations. Maximum yields ranged from 2830 kg ha^{-1} to 5340 kg ha^{-1}; whereas the minimum yields ranged from nil to 3110 kg ha^{-1} across locations. For the tertiary zone, the mean yields across locations ranged from 2520 kg ha^{-1} to 4380 kg ha^{-1} with a mean yield of 3410 kg ha^{-1}. Maximum yields across locations ranged from 3750 to 4870 kg ha^{-1}; whereas the minimum yields ranged from 0 to 2680 kg ha^{-1}. The CV ranged from 11 to 50%. Complete crop failure (nil simulated yield) occurred in the years with a long spell of drought after germination.

Potential yield of production zones: Primary production zone had the lowest mean rainfed yield potential with 3210 kg ha^{-1}, while the tertiary zone had 3410 kg ha^{-1}. Because of high mean rainfall, the range and CV in mean yield were the highest in the secondary zone; whereas these were low for the primary and tertiary zones because of better distribution of crop season rainfall. Within the production zones, the mean yield of locations ranged from 2510 to 3670 kg ha^{-1} for the primary zone; 1570 to 4430 kg ha^{-1} for the secondary zone; and 2520 to 4380 kg ha^{-1} for the tertiary zone.

Potential yield of major states: Simulated rainfed sorghum yields in Karnataka, Maharashtra and Madhya Pradesh were more than 3 t ha^{-1} (Table 11). Maharashtra had the lowest mean simulated yield of 3220 kg ha^{-1}. The mean rainfed potential yield in Karnataka and Madhya Pradesh were 3640 and 3610 kg ha^{-1}, respectively. Mean crop season rainfall was the maximum (890 mm) in Madhya Pradesh. Karnataka had a mean crop season rainfall of 650 mm, with high CV of 40% across the locations. High rainfed potential yields were associated with the high amount of seasonal rainfall in a state.

Potential yield of agroecological zones: AEZ 6 had the lowest crop season mean rainfall of 600 mm with a CV of 26 per cent across locations (Table 11). The lowest long-term mean yield of 3270 kg ha^{-1} was simulated for the AEZ 6. AEZ 5 had a mean yield of 3480 kg ha^{-1} with a high CV of 20 per cent across locations. AEZ 10 had the highest mean simulated yield of 3550 kg ha^{-1}. This zone also had the highest mean rainfall of 900 mm.

Table 11. Rainfed simulated potential yields (kg ha^{-1}) of *kharif* sorghum and seasonal rainfall (mm) in different crop production zones, states and AEZs.

	No. of	Yield				Rainfall			
	locations	Min	Max	Mean	CV* (%)	Min	Max	Mean	CV* (%)
Production Zones									
Primary	13	2510	3670	3210	13	420	880	650	18
Secondary	13	1570	4430	3390	23	310	1030	780	24
Tertiary	9	2520	4380	3410	18	360	1040	650	45
States									
Karnataka	4	3450	3910	3640	6	420	870	650	40
Maharashtra	18	2510	4380	3220	17	360	880	620	24
Madhya Pradesh	12	2910	4430	3610	12	710	1040	890	11
AEZs									
5	6	2440	4430	3480	20	620	900	810	12
6	20	2510	4380	3270	16	360	870	600	26
10	9	2910	4040	3550	13	710	1040	900	13

*Coefficient of variation among locations in AEZ.

4.7 Yield gaps

Yield gap of production zones: Simulated mean yields varied from 3210 kg ha^{-1} to 3410 kg ha^{-1}, progressively increasing from primary zone to tertiary zone (Table 12). The experimental station mean yields varied from 3770 kg ha^{-1} to 3250 kg ha^{-1}, the highest being in the primary zone and decreasing towards tertiary production zone. Mean experimental yields being greater than simulated rainfed yields, reflect the possibility of life saving irrigations given to the experimental trials. On-farm mean yields represented by FLD trials remained at around 1800 kg ha^{-1} throughout the three production zones. Yield gap I, taken as the difference of simulated mean and on-farm mean yield, increased from 1400 kg ha^{-1} in the primary zone to 1570 kg ha^{-1} in the tertiary zone. Another indicator of yield gap I taken as the difference between experimental station yield and on-farm yield, decreased from 1960 kg ha^{-1} in the primary zone to 1410 kg ha^{-1} in the tertiary zone. Difference between on-farm and district means termed as yield gap II, was 730, 1020 and 990 kg ha^{-1} in primary to tertiary zones. The total yield gap, which is the sum of these two yield gaps, increased, respectively from 2130 kg ha^{-1} in the primary zone to 2560 kg ha^{-1} in the tertiary zone.

Table 12. Yield gap of *kharif* sorghum in different production zones of India.

	Primary	Secondary	Tertiary
		(kg ha^{-1})	
Rainfed yields			
Simulated mean	3210	3390	3410
Experimental station mean	3770	3440	3250
On-farm mean*	1810	1880	1840
District mean#	1080	860	850
Yield gaps			
Simulated – on-farm (YG I)	1400	1510	1570
Experimental station – on-farm (YG I)	1960	1560	1410
On-farm – District mean (YG II)	730	1020	990
Total gap (simulated-District mean)	2130	2530	2560

* Based on limited FLD data (Table 9)
\# Mean of all districts for each *kharif* sorghum production zone (Table 6).

Yield gap of agroecological zones: Simulated and on-farm mean yields were not available for AEZ 2. The experiment station mean yield for this zone was 3580 kg ha^{-1}; and the gap between experimental station yields and district means was 3360 kg ha^{-1} (Table 13). AEZ 2 being an arid zone, the variability in crop season rainfalls is often very high both spatially and temporally. As there were a few experimental station yields available, the mean yield presented here may not be a true indicator of the potential productivity for the entire AEZ 2. The gap between simulated rainfed mean and on-farm yield was 1260 kg ha^{-1} for AEZ 6 and 1480 kg ha^{-1} for AEZ 5. Similarly, the yield gap between experimental station and on-farm means ranged from 1200 kg ha^{-1} in AEZ 4 to 2060 kg ha^{-1} in AEZ 7. Gap between on-farm mean yield and the district mean yield was low in AEZ 6 and 7 (710 to 340 kg ha^{-1}). The yield gap was the largest at 1120 kg ha^{-1} in AEZ 5. Total yield gap across AEZs ranged from 2270 to 3360 kg ha^{-1}.

Table 13. Yield gap of *kharif* sorghum in different AEZs of India.

	AEZs					
	2	4	5	6	7	10
	(kg ha^{-1})					
Rainfed yields						
Simulated mean	–	–	3480	3270	–	3550
Experimental station mean	3580	2770	3590	3600	3260	–
On-farm mean	–	1570	2000	2010	1200	–
District mean	220	500	880	1300	860	890
Yield gaps						
Simulated-on-farm (YG I)	–	–	1480	1260	–	–
Experimental station-on-farm (YG I)	–	1200	1590	1590	2060	–
On-farm-district (YG II)	–	1070	1120	710	340	–
Total yield gap	3360	2270	2710	2300	2400	2660

Yield gap of major states: The gap between simulated rainfed mean yield and on-farm yield ranged from 1040 kg ha^{-1} in Karnataka to 1490 kg ha^{-1} in Maharashtra and Madhya Pradesh, respectively (Table 14). The yield gap between experimental station mean yield and on-farm mean yield ranged from 1170 kg ha^{-1} in Madhya Pradesh to 2300 kg ha^{-1} in Andhra Pradesh. The gap between on-farm and district mean yield was the lowest in Andhra Pradesh at 220 kg ha^{-1}, followed by 450 kg ha^{-1} in Maharashtra. In Gujarat, Karnataka, Madhya Pradesh and Rajasthan, these yield gaps ranged from 970 to 1320 kg ha^{-1}. Total yield gap ranged from 1340 kg ha^{-1} in Uttar Pradesh to 3280 kg ha^{-1} in Karnataka. The magnitudes of yield gap I and II for different states indicate the extent of technology transfer that has happened from research station to demonstration sites and from demonstration sites to average farmer's fields in a state.

Table 14. Yield gap of *kharif* sorghum in major states of India.

	AP	Guj	KA	MP	Mah	Raj	UP
State	(kg ha^{-1})						
Rainfed yields							
Simulated mean	–	–	3630	3610	3220	–	–
Experimental station mean	3500	3540	4580	3290	3430	3260	2280
On-farm mean	1200	1880	2590	2120	1730	1570	
District mean	980	910	1300	860	1280	250	940
Yield gaps							
Simulated-on-farm (YG I)	–	–	1040	1490	1490	–	–
Experimental station-on-farm (YG I)	2300	1660	1990	1170	1700	1690	–
On-farm-district (YG II)	220	970	1290	1260	450	1320	–
Total yield gap	2520	2630	3280	2430	2150	3010	1340

AP= Andhra Pradesh; Guj= Gujarat; KA= Karnataka; MP= Madhya Pradesh; Mah= Maharashtra; Raj= Rajasthan; UP= Uttar Pradesh

4.8 Water Balance Components of *Kharif* Sorghum

Rainfall: Rainfall is the major source of water supply for crop production in semi-arid regions. Mean rainfall in the primary zone was 660 mm (Tables 15 & 17). Variability across years was high in some locations like Parbhani, Dharwad and Rajgarh. Because of this, the yields in these locations also had a high variability across years. Mean rainfall in the secondary zone was higher at 770 mm. Jodhpur, Kota, Shajapur and Guna showed a very high variability in rainfall across the years and the CV ranged from 35 to 55% for these locations. This was reflected in the yield variability across years at these locations. Mean rainfall in the tertiary zone was 670 mm. Sholapur and Rahuri had a lower mean rainfall of less than 400 mm in this zone. These locations also had a high degree of variability across years.

Evapotranspiration: Crop growth and yield are strongly correlated with evapotranspiration (ET) in water-limited environments. Mean ET in the primary zone was 340 mm during the crop growth (Tables 15 & 17). Akola had a higher ET than the mean. Mean ET in the secondary zone was 350 mm. Variability across years in this zone was higher than the primary zone. The lowest ET of 210 mm was estimated for Jodhpur where the mean rainfall was also lower with a high degree of variability. Mean ET for the tertiary zone was 340 mm. The lowest ET estimated was in Rahuri, which also had lower rainfall with high CV.

Runoff: Mean runoff in the primary zone was 110 mm. But there was a lot of variation across the locations in the amount of runoff (Tables 16 & 17). Amravati, Dharwad and Jalgaon had about 70 mm of runoff during the crop growth period, which was lower than the mean value. Akola, Parbhani and Rajgarh had mean runoff of more than 200 mm, indicating that there is a great potential to harness this runoff through water harvesting measures for supplemental irrigation to the crop. Secondary zone had a mean runoff of 220 mm. Jodhpur had the lowest runoff potential, which was about 50 mm in this zone. Tertiary zone had a mean runoff of 200 mm. Sholapur and Rahuri had a low runoff, which was 50 mm. Even though the mean runoff in all the zones was more, several locations across the zones had very little runoff. These locations also had a lower rainfall with a high degree of variability across years. Barring these locations, there is a good scope for water harvesting at other locations which can increase the efficiency of crop performance.

Deep Drainage: Primary zone had a mean of 210 mm deep drainage (Tables 16 & 17). Deep drainage is the fraction of rainfall that enters the soil and goes below the root zone after saturating the soil profile. However, this fraction is not useful to the crop in the field. It has a major contribution in recharging the groundwater table during the season. Secondary zone had a mean deep drainage of 190 mm. Jodhpur and Aurangabad in the zone had a very low component of deep drainage. Tertiary zone had a mean of 140 mm during the crop season. Rahuri, Sholapur and Pune in this zone recorded a very low deep drainage.

Extractable soil water: Extractable soil water is the water available to the crop in the root zone, which is still left at the end of the crop season. This gives a good idea about the water availability for the subsequent crop. Mean extractable water content in the primary zone was 220 mm, followed by secondary zone (140 mm) and tertiary zone (110 mm). Sholapur, Guna, Pune and Aurangabad had very low extractable water contents, indicating that though the seasonal rainfall was low, the crop extracted a larger extent of the water to survive.

Table 15. Water balance components of simulated *kharif* sorghum in India.

Location	State	Soil series	No. of Years	Rainfall (mm) Mean	CV (%)	Min	Max	Evapotranspiration (mm)* Mean	CV (%)	Min	Max
Primary Zone											
Akola	Maharashtra	Jambha	26	660	29	280	990	380	11	310	500
Akola	Maharashtra	Annapur	26	660	29	280	990	380	12	310	520
Akola	Maharashtra	Otur	26	660	29	280	990	380	12	300	500
Akola	Maharashtra	Umbraj	26	660	29	280	990	370	12	300	500
Amravati	Maharashtra	Jambha	18	680	26	400	970	370	19	270	490
Dharwad	Karnataka	Achmatti	18	420	32	250	750	310	12	210	360
Dharwad	Karnataka	Huguluru	18	420	32	250	750	320	11	240	360
Jalgaon	Maharashtra	Jambha	23	630	19	370	860	340	13	230	400
Parbhani	Maharashtra	Jambha	26	700	41	280	1300	280	8	250	340
Parbhani	Maharashtra	Otur	26	700	41	280	1300	280	8	250	340
Parbhani	Maharashtra	Annapur	26	700	42	280	1300	280	8	250	340
Parbhani	Maharashtra	Umbraj	26	690	41	280	1300	280	8	250	330
Rajgarh	Madhya Pradesh	Jamra	24	880	30	410	1700	350	17	180	470
Mean	–	–	–	660	–	–	–	340	–	–	–
Secondary Zone											
Jodhpur	Rajasthan	Chirai	25	310	55	50	710	210	19	110	270
Dhar	Madhya Pradesh	Sarol	23	840	23	570	1360	440	21	220	650
Kota	Rajasthan	Chambal	34	620	39	300	1450	320	26	140	470
Shajapur	Madhya Pradesh	Sarol	23	840	35	50	1720	300	21	60	370
Shajapur	Madhya Pradesh	Saunther	23	900	26	580	1740	340	15	240	470
Aurangabad	Maharashtra	Otur	27	560	32	180	880	380	18	250	490
Belgaum	Karnataka	Achmatti	16	870	29	530	1530	360	16	250	440
Belgaum	Karnataka	Huguluru	16	870	29	530	1530	370	14	280	450
Guna	Madhya Pradesh	Saunther	19	710	36	270	1170	290	32	100	400
Guna	Madhya Pradesh	Jamra	18	880	32	320	1320	400	16	260	510
Nagpur	Maharashtra	Linga	26	830	26	490	1460	330	10	260	380
Wardha	Maharashtra	Sukali	16	880	29	530	1530	380	14	290	460
Betul	Madhya Pradesh	Jambha	20	1030	22	550	1530	370	14	310	500
Mean	–	–	–	770	–	–	–	350	–	–	–
Tertiary Zone											
Indore	Madhya Pradesh	Sarol	27	820	30	370	1400	360	13	230	470
Ujjain	Madhya Pradesh	Sarol	26	860	35	450	1810	360	15	190	460
Rahuri	Maharashtra	Annapur	17	360	41	140	680	260	13	200	310
Sholapur	Maharashtra	Barsi	19	400	43	90	900	320	18	150	390
Sholapur	Maharashtra	Otur	19	390	44	90	900	310	23	130	390
Sholapur	Maharashtra	Umbraj	19	390	44	90	900	300	23	140	380
Pune	Maharashtra	Otur	15	540	28	370	820	360	9	290	400
Bhopal	Madhya Pradesh	Jamra	33	1040	31	440	1840	380	7	320	450
Bhopal	Madhya Pradesh	Saunther	33	1040	31	440	1840	360	10	270	440
Mean	–	–	–	670	–	–	–	340	–	–	–
Others											
Kannod	Madhya Pradesh	Sarol	19	810	37	110	1580	350	20	160	540

* During the crop growth period

Table 16. Water balance components of simulated *kharif* sorghum in India.

Location	State	Soil series	No. of years	Runoff (mm) Mean	Runoff CV (%)	Runoff Min	Runoff Max	Deep drainage (mm) Mean	Deep drainage CV (%)	Deep drainage Min	Deep drainage Max	Extractable soil water (mm) Mean	Extractable soil water CV (%)	Extractable soil water Min	Extractable soil water Max
Primary Zone															
Akola	Maharashtra	Jambha	26	70	52	10	150	210	63	20	540	220	21	140	290
Akola	Maharashtra	Annapur	26	130	46	20	240	150	68	10	450	70	66	10	160
Akola	Maharashtra	Otur	26	200	40	40	340	90	91	0	350	70	55	10	150
Akola	Maharashtra	Umbraj	26	200	40	40	340	90	88	0	350	100	37	40	170
Amravati	Maharashtra	Jambha	18	80	67	10	210	230	59	10	510	240	14	170	300
Dharwad	Karnataka	Achmatti	18	70	63	10	190	70	74	0	190	150	21	100	210
Dharwad	Karnataka	Huguluru	18	70	67	10	180	60	82	0	170	190	18	120	260
Jalgaon	Maharashtra	Jambha	23	60	58	10	180	220	34	60	340	260	11	170	300
Parbhani	Maharashtra	Jambha	26	100	76	10	310	320	62	60	730	260	8	220	300
Parbhani	Maharashtra	Otur	26	240	60	40	590	170	74	20	450	120	20	80	150
Parbhani	Maharashtra	Annapur	26	170	70	10	470	240	67	40	590	100	25	60	150
Parbhani	Maharashtra	Umbraj	26	240	60	40	590	170	73	30	460	150	15	110	180
Rajgarh	Madhya Pradesh	Jamra	24	310	50	100	830	210	59	10	510	120	41	20	170
Mean	–	–	–	110	–	–	–	210	–	–	–	220	–	–	–
Secondary Zone															
Jodhpur	Rajasthan	Chirai	25	50	151	0	290	50	120	0	200	130	36	50	190
Dhar	Madhya Pradesh	Sarol	22	240	48	80	560	160	65	0	410	120	40	20	200
Kota	Rajasthan	Chambal	34	190	66	20	660	100	85	0	280	150	42	20	230
Shajapur	Madhya Pradesh	Sarol	23	300	62	0	850	220	55	0	570	180	14	100	200
Shajapur	Madhya Pradesh	Saunther	23	320	53	100	840	240	48	60	560	50	58	10	90
Aurangabad	Maharashtra	Otur	27	140	48	20	270	60	103	0	200	60	67	0	160
Belgaum	Karnataka	Achmatti	16	300	51	100	750	220	47	40	370	150	26	70	200
Belgaum	Karnataka	Huguluru	16	310	51	100	770	170	55	10	310	210	23	110	290
Guna	Madhya Pradesh	Saunther	19	230	54	50	460	190	50	30	310	70	35	30	90
Guna	Madhya Pradesh	Jamra	18	290	56	60	650	190	57	0	350	90	54	10	170
Nagpur	Maharashtra	Limga	26	280	46	100	690	210	42	70	430	140	17	90	170
Wardha	Maharashtra	Sukali	16	290	53	90	720	220	52	20	420	130	35	30	200
Betul	Madhya Pradesh	Jambha	20	170	58	50	390	490	34	170	810	250	13	180	290
Mean	–	–	–	220	–	–	–	190	–	–	–	140	–	–	–

Table 16. *Continued*

Location	State	Soil series	No. of years	Runoff (mm) Mean	Runoff CV (%)	Runoff Min	Runoff Max	Deep drainage (mm) Mean	Deep drainage CV (%)	Deep drainage Min	Deep drainage Max	Extractable soil water (mm) Mean	Extractable soil water CV (%)	Extractable soil water Min	Extractable soil water Max
Tertiary Zone															
Indore	Madhya Pradesh	Sarol	27	280	48	80	620	170	58	20	440	150	23	70	200
Ujjain	Madhya Pradesh	Sarol	26	320	58	100	930	180	69	50	460	130	36	50	200
Rahuri	Maharashtra	Annapur	17	50	76	10	160	50	121	0	180	120	34	60	200
Sholapur	Maharashtra	Barsi	19	30	89	0	120	90	112	0	410	130	35	60	200
Sholapur	Maharashtra	Otur	19	30	86	0	120	90	109	0	410	90	46	30	180
Sholapur	Maharashtra	Umbraj	19	100	68	10	300	40	138	0	220	130	36	50	200
Pune	Maharashtra	Otur	15	130	54	50	300	90	78	0	260	60	56	20	150
Bhopal	Madhya Pradesh	Jamra	33	370	52	70	910	290	44	80	570	100	38	20	160
Bhopal	Madhya Pradesh	Saunther	33	380	51	80	920	300	42	100	560	40	69	0	90
Mean	–	–	–	200	–	–	–	140	–	–	–	110	–	–	–
Others															
Kannod	Madhya Pradesh	Sarol	19	280	60	0	730	180	59	0	420	140	38	40	200

Table 17. Mean seasonal water balance components of *kharif* sorghum for different production zones of India.

Water balance components	Primary zone		Secondary zone		Tertiary zone	
	Mean	Range	Mean	Range	Mean	Range
Rainfall (mm)	660	250–1700	770	50–1740	670	90–1840
Runoff (mm)	110	10–830	220	0–850	200	0–930
Deep drainage (mm)	210	0–730	190	0–810	140	0–570
Evapotranspiration (mm)	340	180–520	350	60–650	340	130–470

4.9 Constraints and Opportunities to *Kharif* Sorghum Production

Across all the regions, shoot fly is an important insect pest. Stem borer is identified as an important constraint in Rajasthan, Haryana, Uttar Pradesh and Uttaranchal. Head bug is another constraint in Tamil Nadu, Andhra Pradesh and Maharashtra. Among the diseases, grain mold is the most important in Tamil Nadu, Karnataka, Andhra Pradesh and Gujarat. The second most important disease in sorghum is identified as ergot in Maharashtra, Andhra Pradesh and Gujarat. All other diseases like downy mildew and rust are not major yield reducers. However, anthracnose can be an important constraint in fodder sorghum.

Among the abiotic stresses, mid-season drought is identified as the most important constraint to sorghum production across the states in India. Drought is common in Maharashtra, Rajasthan, Karnataka, Andhra Pradesh, Tamil Nadu and Uttar Pradesh. Appropriate water conservation and management practices including *in-situ* water conservation and on-farm water harvesting to utilize rainfall runoff will improve the rainfed yields.

Lack of remunerative market price is a major economic constraint. Farmer's preference for the pearly white grain and roundness of the grain are the major grain quality constraints for adoption of the improved varieties and hybrids. These grain qualities are preferred by consumers and often dictate market prices for the produce. Adoption of improved varieties, integrated nutrient management and IPM practices need to be adopted in the context of integrated watershed management to enhance productivity of *kharif* sorghum.

4.10 Summary

Currently, the total area under *kharif* sorghum in India is 4.56 M ha with a total production of 4.40 M t and an average productivity of 970 kg ha^{-1}. Maharashtra, Madhya Pradesh and Karnataka are the major states producing *kharif* sorghum. Based on the share of sorghum area to the total cropped area in a district, the districts were grouped into production zones for *kharif* sorghum. The top districts covering 50% of the cropped area were grouped into primary zone; the next group of districts covering 35% of area (50 to 85%) were categorized into secondary zone; and the remaining districts having more than 1000 ha under the cropped area were categorized into the tertiary zone. Similarly, the production and productivity was also studied in different states and AEZs.

Primary production zone had the highest productivity of 1080 kg ha^{-1}. Secondary and tertiary zones had a mean productivity of 860 and 850 kg ha^{-1}, respectively. In the primary zone, the mean simulated yield across locations ranged from 2510 to 3670 kg ha^{-1} with a mean of 3210 kg ha^{-1}. For the secondary zone, the range in simulated yield was 1590 to 4430 kg ha^{-1} with an overall mean of 3390 kg ha^{-1}; and for the tertiary zone it ranged from 2520 to 4380 kg ha^{-1} with a mean of 3410 kg ha^{-1}. The total yield gap was divided into yield gap I and yield gap II. The yield gap I or the gap between simulated means and the on-farm means was 1400, 1510 and 1570 kg ha^{-1} for the primary, secondary and tertiary zones, respectively. The yield gap II or the gap between on-farm mean yield and the district mean yield was 730, 1020 and 990 kg ha^{-1}. The gap between simulated long–term mean yield and the mean district level farmers' yield is termed as total yield gap. The total yield gap for all the production zones was 2410 kg ha^{-1}. Primary production zone had the lowest gap of 2130 kg ha^{-1}, followed by secondary production zone with a gap of 2530 kg ha^{-1} and tertiary zone with a gap of 2560 kg ha^{-1}. The lowest long-term mean gap in the primary production was mainly due to the low and erratic rainfall.

Mean seasonal rainfall was 660 mm for the primary zone, 770 mm for the secondary zone and 670 mm for the tertiary zone. Simulated mean runoff for the primary production zone was 110 mm, followed by 220 mm for the secondary zone and 200 mm for the tertiary zone. The fraction of runoff to the seasonal rainfall was higher in the secondary and tertiary zones. Mean simulated deep drainage in the primary production zone was 210 mm, followed by 190 mm for the secondary production zone and 140 mm for the tertiary production zone. Mean deep drainage was 32, 25 and 21per cent of the rainfall for the primary, secondary and tertiary zones, respectively.

For *kharif* sorghum, among the abiotic stresses, mid-season drought was identified as the most important constraint across the states in India. Across all the regions, shoot fly was an important pest. Stem borer was an important constraint in Rajasthan, Haryana, Uttar Pradesh and Uttaranchal. Head bug was another constraint in Tamil Nadu, Andhra Pradesh and Maharashtra. Grain mold disease affected the growth of the crop in Tamil Nadu, Karnataka, Andhra Pradesh and Gujarat. Ergot also caused a decline in production in Maharashtra, Andhra Pradesh and Gujarat. Lack of remunerative market price is a major economic constraint.

To enhance the productivity of *kharif* sorghum, integrated watershed-based approach that will involve harvesting of excess rainfall for supplemental irrigation, growing high yielding crop cultivars with desirable quality traits, integrated nutrient management and integrated pest and disease management are needed. Value addition of sorghum products and its multiple uses such as for bio-energy can make it more remunerative for the farmers.

5.0 Yield Gap Analysis of *Rabi* Sorghum

5.1 Abstract

Rabi sorghum has better economic value for farmers as compared to *kharif* sorghum because of its better grain quality for food as well as source of fodder for animals during lean summer period, prior to the onset of rainy season. The present study estimated the production potential and yield gap of *rabi* sorghum to assess the scope for enhancing its production in various production zones.

CERES-sorghum model available in DSSAT v3.5 was used to simulate sorghum growth and yield to quantify the potential productivity of *rabi* sorghum for the selected locations. These estimates along with experiment station yield, frontline demonstration (FLD) yield and district level yield data were used to estimate the yield gaps at various technological levels. Simulated rainfed potential, FLD and district mean yields of *rabi* sorghum were 1310, 1480 and 480 kg ha^{-1}, respectively, for the primary

zone. For the secondary zone, the yields in the same order were 1360, 1290 and 680 kg ha^{-1}. For the tertiary zone, simulated rainfed potential and district mean yields were 1000 and 750 kg ha^{-1}, respectively. Total yield gaps for the primary, secondary and tertiary zones was 830, 680 and 280 kg ha^{-1}, respectively, indicating the need to scale up the available *rabi* sorghum production technologies to farmers in the region to abridge the existing yield gaps.

Terminal drought is the major yield constraint for *rabi* sorghum. Integrated watershed management approach, encompassing harvesting and storing of excess water during the rainy season for supplemental irrigation, high yielding drought resistant cultivars, integrated nutrient and pest management practices are needed to enhance the productivity of *rabi* sorghum.

5.2 Introduction

Rabi sorghum is the important source of food for people and fodder for livestock in the rainfed regions of India. Maharashtra, Karnataka and Andhra Pradesh are the major *rabi* sorghum producing states occupying about 90% of the *rabi* sorghum area. Since 1971, the area under *rabi* sorghum has decreased, while the productivity has substantially increased. Most of the decline in area has occurred in Andhra Pradesh and Karnataka, where *rabi* sorghum has been replaced by high value cereals, pulses and oilseeds. There is no decline in area in Maharashtra, which has the lowest average yield. This is due to the high demand for *rabi* sorghum for grain and fodder during lean months.

Unfavorable soil physical conditions preventing advanced sowing and low water holding capacity of shallow black soils leading to terminal drought to the crop are the main reasons for the lack of increase in productivity in a sustainable manner. Therefore, the input components including supplemental irrigation, rather than the high yielding varieties of *rabi* sorghum, were responsible for increase in productivity. Currently, *rabi* sorghum is grown on 5.11 M ha area with a productivity of 590 kg ha^{-1} (Database: 2000-02). In view of increasing human and animal population in India, it is important to increase production and productivity to meet the future food and fodder needs. The present study estimated the productivity potential, yield gap and water balance of *rabi* sorghum in order to assess the scope for enhancing its production.

5.3 Production Zones and Soil Resources of *Rabi* Sorghum

The primary zone of production covers 2.58 M ha in just six districts. This is about 50 per cent of the total *rabi* sorghum area in India. Out of these six districts, four are in Maharashtra and the rest in Karnataka (Fig. 6 & Table 19). The secondary zone of production comprises of 12 districts and has 35 per cent (1.75 M ha) of the total area sown under *rabi sorghum* in India. The secondary zone of production falls in parts of Maharashtra, Karnataka and Andhra Pradesh. The tertiary zone comprises 55 districts in India, covering remaining 15% (0.77 M ha) of the total area under *rabi* sorghum. Tertiary zone is spread out in parts of Maharashtra, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat and Madhya Pradesh. These areas are characterized by low annual rainfall from 200 mm to 500 mm. Besides, *rabi* sorghum is a postrainy season crop, purely depending on residual soil moisture and very little occasional rainfall during the crop growth period.

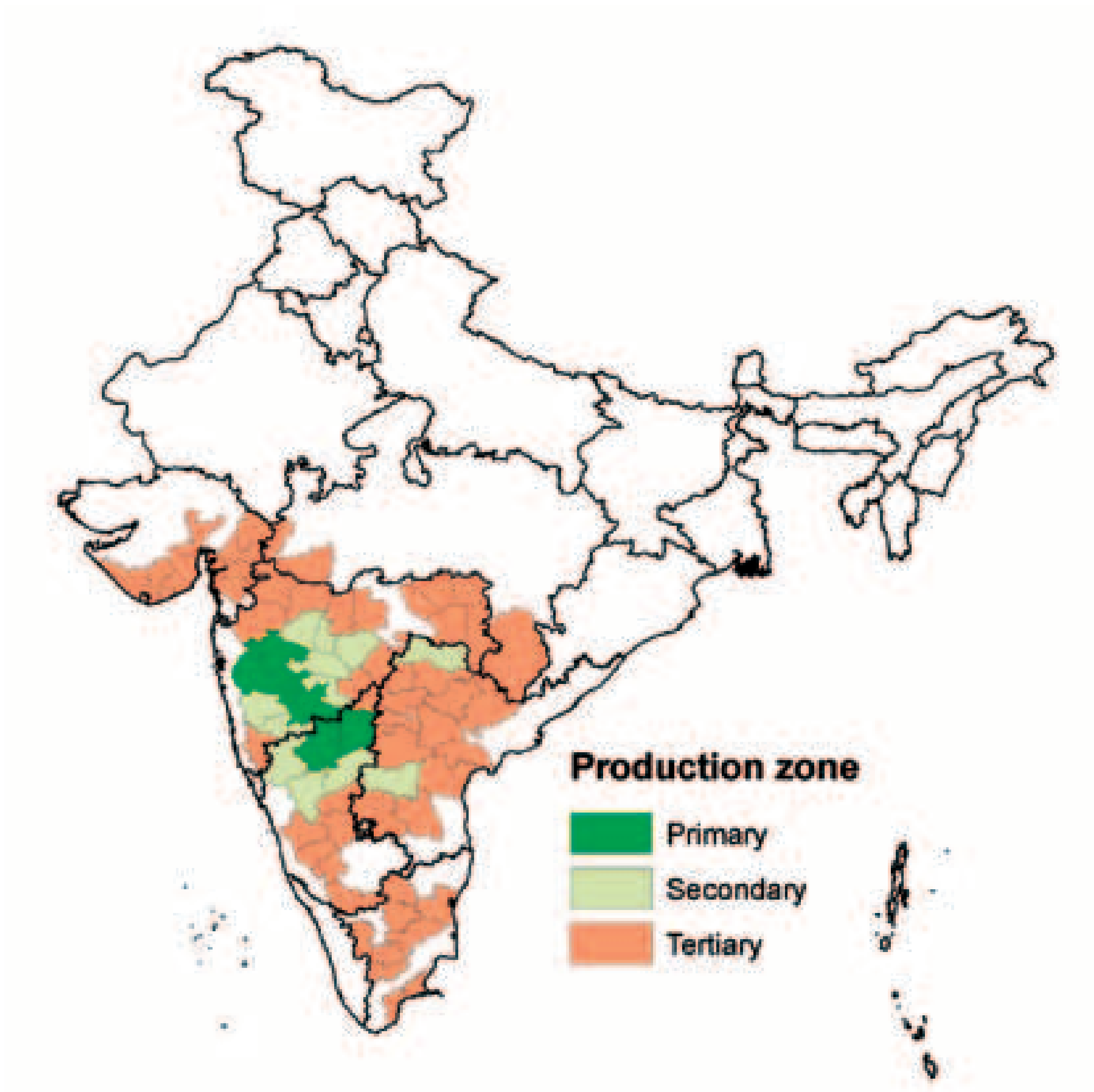

Figure 6. Major production zones of *rabi* sorghum in India.

Entisols (excluding Orthents) occupy about 60 per cent of the primary production zone of postrainy season sorghum (Fig. 7 & Table 18). Next to these soils, Vertisols occupy about 37 per cent area. These soils usually have high contents of montmorillonite or illite type of clays. These soils exhibit deep vertical cracks depending on the amount and type of expanding minerals in the profile. Timely operation of tillage becomes crucial in these soils. However, because of the type and amount of clay contents, these profiles usually have high AWHC resulting in high residual moisture storage capacities. This is a useful trait for the postrainy season crops. The secondary zone is dominated by Vertisols occupying 57 per cent of the area followed by Entisols (Orthents) occupying 38 per cent. Tertiary zone is dominated by Alfisols occupying 41 per cent of the area. Vertisols occupy 31 per cent of the area followed by Entisols.

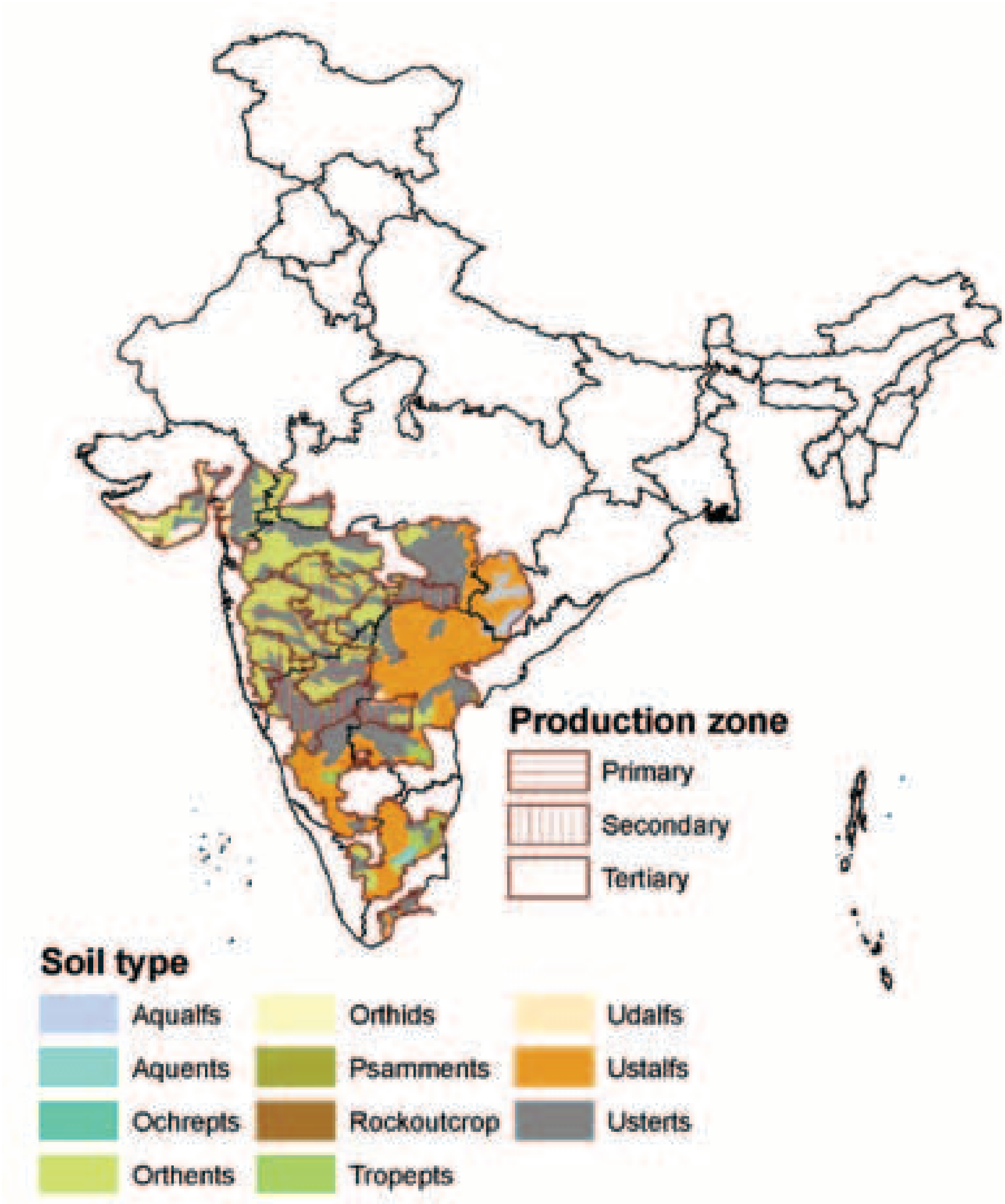

Figure 7. Soil resources in different production zones of *rabi* sorghum in India.

Table 18. Relative occurrence of soil resources in *rabi* sorghum growing environments.

Primary zone		Secondary zone		Tertiary zone	
Soil type	Area (%)	Soil type	Area (%)	Soil type	Area (%)
Entisols	60.1	Vertisols	56.8	Alfisols	40.5
Vertisols	36.8	Entisols	38.0	Vertisols	30.7
Inceptisols	2.3	Alfisols	3.9	Entisols	21.6
Alfisols	0.8	Inceptisols	1.3	Aridisols	3.3
				Inceptisols	2.5

5.4 *Rabi* Sorghum Productivity in Production Zones, AEZs and States of India

***Rabi* sorghum productivity in production zones:** Primary zone has a total production of 1.23 M t with an average productivity of 480 kg ha^{-1} (Table 19). The secondary zone has a total production of 1.19 M t with a productivity level of 680 kg ha^{-1}. The tertiary zone has 0.55 M ha under the crop with the highest productivity of 720 kg ha^{-1}, but the coefficient of variation for yield is very high (60%). Total area under *rabi* sorghum in India is 5.11 M ha with a total production and productivity of 2.99 M t and 590 kg ha^{-1}, respectively. Increase in productivity from primary to secondary zone may be attributed to the better moisture availability as one moves away from the core area.

Table 19. Area (M ha), production (M t) and productivity (kg ha^{-1}) of different production zones of *rabi* sorghum in India (Database: 2000-02).

Production zone	No. of districts	Area	Production	Productivity	CV* (%)
Primary	6	2.58	1.24	480	34
Secondary	12	1.75	1.19	680	35
Tertiary	55	0.77	0.55	720	60
Others	32	0.01	0.01	1440	74
Total	105	5.11	2.99	590	70

*Coefficient of variation among districts.

***Rabi* sorghum productivity in agroecological zones:** AEZ 6, which is termed as semi-arid dry, has about 4.1 M ha under *rabi* sorghum, spread in 31 districts of Maharashtra and Karnataka (Fig. 8 & Table 20). The primary districts are Sholapur, Ahmednagar and Pune in Maharashtra and Gulbarga in Karnataka. Eighty per cent of *rabi* sorghum growing area and 73% of total production is from AEZ 6. Average productivity of this zone is about 540 kg ha^{-1}. AEZ 6 is followed by AEZ 3 (0.58 M ha), AEZ 7 (0.24 M ha) and AEZ 8 (0.07 M ha) in terms of area under *rabi* sorghum. AEZ 3, termed as arid zone, has about 0.58 M ha under *rabi* sorghum, primarily in Bijapur district of Karnataka. It has about 11% of the total area under the crop and contributes about 14% to the total production of *rabi* sorghum. It has an average productivity of 700 kg ha^{-1}. AEZ 7, which is a semi-arid zone, has 5% of the total area and contributes about 8% to the total *rabi* sorghum production. Kurnool district of Andhra Pradesh comes in this AEZ. It has an average productivity of 970 kg ha^{-1}. AEZ 12 is a sub-humid moist zone and encompasses Chandrapur district of Maharashtra and has the lowest productivity of 360 kg ha^{-1}. Other AEZs have negligible area under the crop, thus contributing little to total *rabi* sorghum production in the country.

***Rabi* sorghum productivity in different states of India:** Maharashtra, Karnataka and Andhra Pradesh are the three major states growing *rabi* sorghum in India (Table 21). Madhya Pradesh, Tamil Nadu and Gujarat have negligible area under the crops. Recent years have seen a further reduction in the total *rabi* sorghum area. Maharashtra is the largest state growing *rabi* sorghum on 3.21 M ha out of the total of 5.11 M ha of *rabi* sorghum in India. It is grown in 28 districts and Maharashtra produces about 1.63 M t of sorghum. The average productivity is the lowest among the states at 510 kg ha^{-1} with a CV of 43 per cent. Karnataka is the second largest *rabi* sorghum growing state with 1.45 M ha under this crop. It produces 0.94 M t of sorghum with a mean productivity of 650 kg ha^{-1}. Variability of productivity across the districts is very high with 44 per cent coefficient of variation.

Table 20. Area (M ha), production (M t) and productivity (kg ha^{-1}) in different agroecological zones of *rabi* sorghum in India (Database: 2000-02).

AEZ	Area	Production	Productivity	CV* (%)	No. of districts
2	0.005	0.002	460	–	1
3	0.585	0.407	700	34	5
5	0.064	0.043	680	30	14
6	4.069	2.189	540	39	31
7	0.243	0.235	970	31	13
8	0.070	0.078	1110	79	24
10	0.012	0.005	390	70	9
12	0.046	0.016	360	52	3
18	0.001	0.001	1130	–	2
19	0.011	0.016	1390	29	3
Total	5.106	2.992	590	70	105

*Coefficient of variation among locations in AEZ.

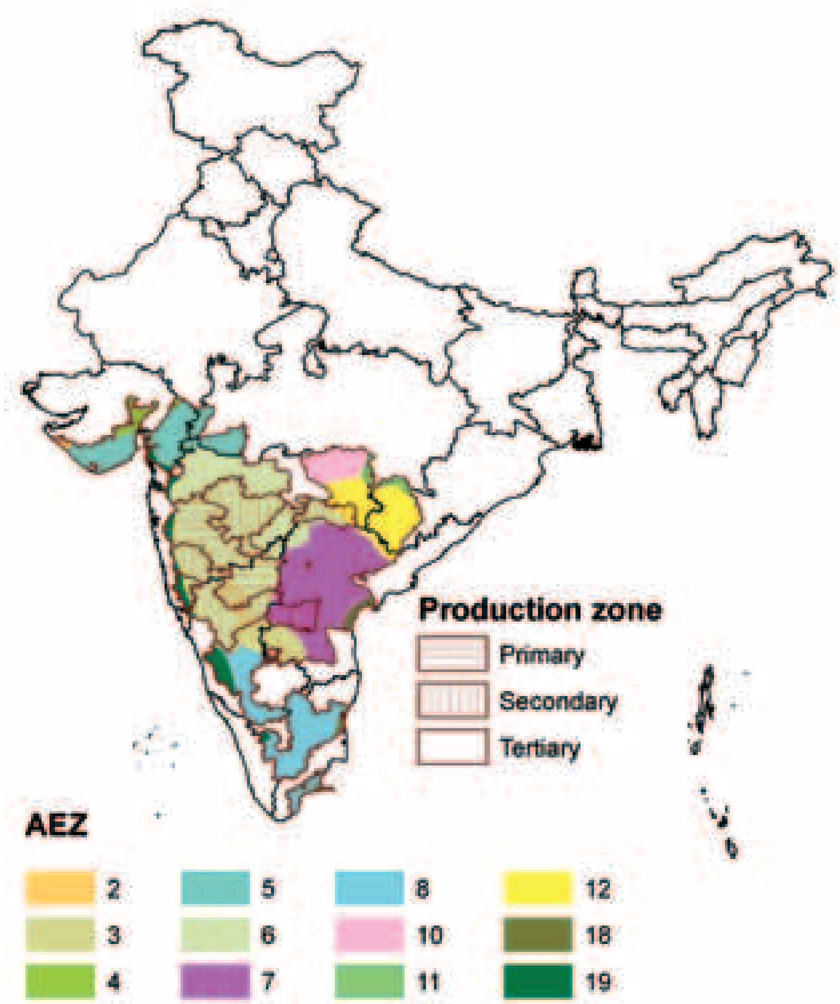

Figure 8. Agroecological zones of *rabi* sorghum in India.

Table 21. Area (M ha), production (M t) and productivity (kg ha^{-1}) of *rabi* sorghum in different states in India (Database: 2000-02).

State	No. of districts	Area	Production	Productivity	CV * (%)
Andhra Pradesh	19	0.35	0.33	940	33
Gujarat	12	0.07	0.04	660	33
Karnataka	20	1.45	0.94	650	44
Madhya Pradesh	10	0.004	0.003	830	47
Maharashtra	28	3.21	1.63	510	43
Tamil Nadu	16	0.03	0.05	1530	76
Total	105	5.11	2.99	590	70

*Coefficient of variation among districts.

5.5 Rainfed Yield Potential of *Rabi* Sorghum

Experimental station yields and yield gaps: In the primary zone, Gulbarga had the highest yield (2360 kg ha^{-1}) and Sholapur the least (1230 kg ha^{-1}) experimental station yield, with an overall mean yield of 1990 kg ha^{-1} (Table 22). The mean yields of FLDs in this zone were 1480 kg ha^{-1} and the corresponding mean district yields were 530 kg ha^{-1}. Yield gap I for this zone was 530 kg ha^{-1}. The yield gap II was about 1010 kg ha^{-1}. Total mean yield gap for this zone was about 1460 kg ha^{-1}. In the secondary zone, Karad, Dharwad and Nandyal had high *rabi* sorghum yields (2560 to 2710 kg ha^{-1}). Whereas, Parbhani had the lowest yield (1570 kg ha^{-1}). The mean yield of the experimental stations in the secondary zone was 2270 kg ha^{-1}. FLD yield for this zone was available only for Parbhani (1290 kg ha^{-1}). Mean district yields for the zone was 750 kg ha^{-1}. Yield gap I for the secondary zone was only 280 kg ha^{-1}. Yield gap II for the zone was 630 kg ha^{-1}. These yield gaps are rather poor estimates because of scanty data on FLD yields. Total yield gap for the secondary zone was 1520 kg ha^{-1}. There were only two locations in the tertiary zone. Mean experimental station yields for the tertiary zone was 2940 kg ha^{-1}. Data on FLDs were not available for this zone. Considering the mean district yields of 700 kg ha^{-1}, the total yield gap for the tertiary zone was 2230 kg ha^{-1} (Table 22).

In general, the yield gaps for *rabi* sorghum were much less than those estimated for *kharif* sorghum across locations. This is because the experimental station yields of *rabi* sorghum were less than those of *kharif* sorghum as the postrainy sorghum is solely grown on residual soil moisture with little rainfall during the season.

5.6 Simulated Potential Rainfed Yields

Potential yield of locations: In the primary zone, Sholapur with Barsi soil series had the maximum simulated potential productivity (1850 kg ha^{-1}) and the lowest was on Umbraj soil series (1010 kg ha^{-1}) (Table 23). The CV in yield ranged from 46 to 58% across locations. The mean maximum and minimum yields were 3070 and 270 kg ha^{-1}, respectively. Secondary zone had a mean yield of 1360 kg ha^{-1}. The highest mean yield of 2150 kg ha^{-1} was recorded at Belgaum with Huguluru series and the lowest of 930 kg ha^{-1} at Parbhani with Jambha series. CV varied from 23% at Belgaum with Huguluru series to 56% at Aurangabad. Mean yield of tertiary zone was 1000 kg ha^{-1}. Maximum mean yield of 2050 kg ha^{-1} was at Wardha; whereas the lowest mean yield of 450 kg ha^{-1} was at Jalgaon with Linga series. CV in the tertiary zone ranged from 31% at Wardha to 62% at Jalgaon with Linga series.

Table 22. Experimental station, FLD and district average yields and yield gaps (kg ha^{-1}) of *rabi* sorghum in India.

Location	State	Expt. station	FLD	District	Yield gap I	Yield gap II	Total yield gaps
Primary Zone							
Sholapur	Maharashtra	1230	1640	380	0	1250	850
Bijapur	Karnataka	2110	1560	640	550	920	1470
Rahuri	Maharashtra	2270	1250	400	1030	850	1870
Gulbarga	Karnataka	2360	–	690	–	–	1670
Mean		1990	1480	530	530	1010	1460
Secondary Zone							
Karad	Maharashtra	2710	–	740	–	–	1970
Parbhani	Maharashtra	1570	1290	650	280	630	920
Dharwad	Karnataka	2560	–	640	–	–	1920
Annigeri	Karnataka	1860	–	720	–	–	1130
Nandyal	Andhra Pradesh	2660		1010			1640
Mean		2270	1290	750	280	630	1520
Tertiary Zone							
Hagari	Karnataka	2620	–	800	–	–	1820
Madhira	Andhra Pradesh	3260	–	610	–	–	2640
Mean		2940	–	710	–	–	2230

Potential yield of production zones: The long-term simulated mean rainfed yield in the primary zone was 1310 kg ha^{-1} with a CV of 28% (Table 24). Mean yield in the secondary zone was 1360 kg ha^{-1} with a CV of 31%. Tertiary zone had a mean yield of 1000 kg ha^{-1} with a high CV of 58% across locations. Though there was not much of a difference in the mean yields across zones, the secondary zone had the highest grain yield. Despite low yield levels, farmers prefer to grow this crop on marginal lands mainly for fodder as there is usually no alternative crop in the absence of irrigation.

Potential yields of major states: Maharashtra and Karnataka account for 4.65 M ha of *rabi* sorghum. Mean rainfed yield of several locations in Maharashtra was 1110 kg ha^{-1} (Table 24). Such low yields of *rabi* sorghum were due to its major dependency on soil-profile stored moisture. Mean rainfall was only 90 mm during the crop growth period. Variability in the yields across locations was high with a CV of 37 per cent. This was due to a high variability in the rainfall (CV 65 per cent) across locations coupled with poor soils. Mean yield in Karnataka was slightly higher at 1640 kg ha^{-1} with a coefficient of variation of 30 per cent across locations in this state. Mean rainfall during the crop season in Karnataka was also the same as in Maharashtra (Table 22).

Simulated rainfed potential yields of agroecological zones: Majority of the locations in Maharashtra and Karnataka come under AEZ 6. This zone had a simulated mean yield of 1170 kg ha^{-1} for *rabi* sorghum (Table 24). Variability in yield across locations was very high with a CV of 37 per cent. Lower mean yields were because the crop is mainly grown on residual soil moisture. Mean crop season rainfall was only 90 mm with a high CV of 59% across locations. AEZ 10 had data from only one station. The yield in this location was 2050 kg ha^{-1} with a crop season rainfall of 100 mm.

Table 23. Simulated rainfed grain yield and yield gap of postrainy (*rabi*) season sorghum at different locations across India.

Station	State	Soil series	No. of years	Grain yield (kg ha^{-1}) Mean	CV (%)	Min	Max	Dist. yield (kg ha^{-1})	Yield gap (kg ha^{-1})
Primary Zone									
Rahuri	Maharashtra	Annapur	18	1180	46	360	2670	470	710
Sholapur	Maharashtra	Barsi	19	1850	58	350	4070	490	1360
Sholapur	Maharashtra	Otur	19	1200	49	160	2980	490	710
Sholapur	Maharashtra	Umbraj	19	1010	48	210	2550	490	520
Mean	–	–	–	1310	–	270	3070	480	830
Secondary Zone									
Aurangabad	Maharashtra	Otur	26	1270	56	210	3490	590	680
Parbhani	Maharashtra	Jambha	26	930	42	30	2010	600	330
Parbhani	Maharashtra	Otur	26	1220	24	780	1830	600	620
Parbhani	Maharashtra	Annapur	26	1260	31	810	2380	600	660
Parbhani	Maharashtra	Umbraj	26	1010	25	590	1520	600	410
Belgaum	Karnataka	Achmatti	15	1000	35	390	1590	670	330
Belgaum	Karnataka	Huguluru	15	2150	23	1480	2800	670	1480
Dharwad	Karnataka	Achmatti	18	1530	27	1080	2500	750	780
Dharwad	Karnataka	Huguluru	18	1890	27	1050	3200	750	1140
Mean	–	–	–	1360	–	710	2370	650	710
Tertiary Zone									
Akola	Maharashtra	Jambha	26	810	42	20	1500	250	560
Akola	Maharashtra	Annapur	26	1120	42	740	2610	1130	870
Akola	Maharashtra	Otur	26	1090	32	450	2270	1130	840
Jalgaon	Maharashtra	Jambha	23	510	61	10	970	1130	0
Jalgaon	Maharashtra	Linga	23	450	62	10	870	1130	0
Wardha	Maharashtra	Sukali	16	2050	31	1280	3330	460	1590
Mean	–	–	–	1000	–	410	1930	610	640
Others									
Amravati	Maharashtra	Jambha	18	850	53	320	1960	1000	0

Table 24. Simulated rainfed potential yields of *rabi* sorghum and crop season rainfall in different crop production zones, states and AEZs.

Production zones	No. of stations	Yield (kg ha^{-1}) Min	Max	Mean	CV (%)	Rainfall (mm) Min	Max	Mean	CV (%)
Primary	4	1010	1850	1310	28	70	300	140	74
Secondary	9	930	2150	1360	31	70	100	80	16
Tertiary	6	450	2050	1000	58	60	100	70	22
States									
Karnataka	4	1000	2150	1640	30	90	100	90	6
Maharashtra	16	450	2050	1110	37	60	300	90	65
AEZs									
6	19	450	2150	1170	37	60	300	90	59
10	1	–	2050	–	–	–	–	100	–

5.7 Yield Gaps

Yield gaps of production zones: Mean simulated yields were 1310, 1360 and 1000 kg ha^{-1} from primary to tertiary zones (Table 25). The corresponding experimental station yields were 1990, 2270 and 2940 kg ha^{-1}, respectively. On-farm yields were 1480 and 1290 kg ha^{-1} for the primary and secondary zone, respectively. We did not have any on-farm yield data for the tertiary zone. District mean yields for the three production zones were very low at 480, 680 and 720 kg ha^{-1}. Yield gap I taken as the difference between experimental station and on-farm mean yield was 510 and 980 kg ha^{-1} for the primary and secondary zone, respectively. As the on-farm yield was more than simulated mean yield, the yield gap I for the primary zone was taken as zero. Yield gap I for the secondary zone was also negligible (70 kg ha^{-1}). As *rabi* sorghum is mainly grown on the residual soil moisture with negligible rainfall during the crop growth period, the simulated rainfed long-term averages were a mere reflection of this. Higher mean experimental station and some FLD yields indicated the possibility of life saving irrigations given in these trials. Total yield gap taken as the difference between the simulated mean yield and district mean yield was 830, 680 and 280 kg ha^{-1} for primary, secondary and tertiary zones, respectively. In general, the *rabi* sorghum yield levels were much lower than the *kharif* sorghum yields and the coefficient of variation (CV) was very high indicating high yield instability across years.

Table 25. Yield gap of *rabi* sorghum in different production zones of India.

	Primary	Secondary	Tertiary
		(kg ha^{-1})	
Rainfed yields			
Simulated mean	1310	1360	1000
Experimental station mean	1990	2270	2940
On-farm mean*	1480	1290	–
District mean#	480	680	720
Yield gaps			
Simulated – on-farm (YG I)	0	70	–
Experimental station – on-farm (YG I)	510	980	–
On-farm – district mean (YG II)	1000	610	–
Total gap (simulated-district mean)	830	680	280

* Based on limited FLD data (Table 22)

\# Mean of all districts for each *rabi* sorghum production zone (Table 19).

Yield gap of agroecological zones: Major *rabi* sorghum producing AEZs are 3 and 6. In AEZ 6, simulated rainfed yields were lower than the on-farm yields. This could be because the simulated rainfed yields shown here are long-term mean of yield simulations of several locations; whereas the on-farm data was available only for less than three years. The yield gap between experimental station and on-farm yield was the lowest at 690 kg ha^{-1} in AEZ 6 (Table 26). On-farm to district level yield gaps was 850 kg ha^{-1}. These yield gaps were in fact more than the district means for these AEZs. This gap may not be possible to abridge easily in practice because the district level data is an average of the whole district yield and reflects the effect of the spatial variability in rainfall and soil moisture storage capacities and other soil properties. But the on-farm trial yields were the result of very few locations and often reflect the best possible situations in terms of natural resources in that region. Through appropriate soil, crop and nutrient management practices a part of this yield gap can be reduced at least for locations where the biophysical conditions in terms of rainfall and soils are favorable.

Experimental station to on-farm and on-farm to district yield gaps in AEZ 3 were around 800 kg ha^{-1}. In AEZ 7, experimental station to on-farm yield gaps were high at 1400 kg ha^{-1}; whereas on-farm to district yield gaps were 590 kg ha^{-1} (Table 26).

Table 26. Yield gap of *rabi* sorghum in different AEZs of India.

	AEZs			
	3	6	7	10
	(kg ha^{-1})			
Rainfed yields				
Simulated mean	–	1170	–	2050
Experimental station mean	2360	2080	2960	–
On-farm mean	1560	1390	1560	–
District mean	700	540	970	390
Yield gaps				
Simulated-on-farm (YG I)	–	0	–	–
Experimental station-on-farm (YG I)	800	690	1400	–
On-farm-district (YG II)	860	850	590	–
Total gap	1660*	630	1990*	1660

* Based on experiment station data in the absence of simulated yields

Yield gap of major states: Simulated rainfed yields were lower than the on-farm yields in Maharashtra (Table 27). This is because rainfed simulations were carried out for a longer time period, often for 15 to 26 years for each location, than the number of years for which the actual crop yield data were available. The data of on-farm yields were available from very few locations and often for two or three years only. Thus, the simulations captured the effects of temporal and spatial variations in rainfall on crop yields. On-farm to district level yield gap in Maharashtra was about 880 kg ha^{-1}, indicating that yield gap could be narrowed through improved crop and nutrient management. For Karnataka, the gap between simulated and on-farm yield was just 80 kg ha^{-1}. The gap between on-farm and district mean yield was about 910 kg ha^{-1}, again indicating the potential to increase *rabi* sorghum yields by scaling up of the improved technologies from on-farm demonstrations to the average farmers' situation.

Table 27. Yield gap of *rabi* sorghum in major states of India.

	States		
	Andhra Pradesh	Karnataka	Maharashtra
	(kg ha^{-1})		
Rainfed yields			
Simulated mean	–	1640	1110
Experimental station mean	2960	2300	1940
On-farm mean	–	1560	1390
District mean	940	650	510
Yield gaps			
Simulated-on-farm (YG I)	–	80	0
Experimental station-on-farm (YG I)	–	740	550
On-farm-district (YG II)	–	910	880
Total gap	2020*	990	600

* Based on experiment station data in the absence of simulated yields

5.8 Water Balance Components of *Rabi S*orghum

Rainfall: The rainfall during crop growth period in all the production zones was low and highly variable, which caused high variability in the crop yields across years. Mean rainfall was 180 mm for the primary zone, 90 mm for the secondary zone and 70 mm for the tertiary zone (Tables 28 & 30). Coefficient of variation in rainfall across various production zones ranged from 43 to 94%. Low rainfall and its high spatial and temporal variability were the main constraints for the *rabi* sorghum crop to perform optimally. Water harvesting in the rainy season and supplemental irrigation during the postrainy season can enhance *rabi* sorghum yields in these areas.

Evapotranspiration: *E*vapotranspiration (ET) by the crop during the season had a direct bearing on the biomass and grain yield of the crop. Mean seasonal ET was 200 mm for the primary zone, 160 mm for the secondary zone and 130 mm for the tertiary zone (Tables 28 & 30).

Table 28. Water balance components of simulated *rabi* sorghum.

				Rainfall (mm)				Evapotranspiration (mm)			
Location	State	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone											
Rahuri	Maharashtra	Annapur	18	70	94	0	270	140	26	100	230
Sholapur	Maharashtra	Barsi	19	300	43	50	510	250	27	120	340
Sholapur	Maharashtra	Otur	19	100	79	20	250	160	27	70	260
Sholapur	Maharashtra	Umbraj	19	100	79	20	250	150	29	70	240
Mean	–	–	–	180	–	–	–	200	–	–	–
Secondary Zone											
Aurangabad	Maharashtra	Otur	26	90	90	0	350	170	27	60	270
Belgaum	Karnataka	Achmatti	15	100	51	40	200	150	27	60	200
Belgaum	Karnataka	Huguluru	15	100	51	40	200	260	11	220	320
Dharwad	Karnataka	Achmatti	18	90	79	0	330	170	26	110	280
Dharwad	Karnataka	Huguluru	18	90	79	0	330	210	18	150	280
Parbhani	Maharashtra	Jambha	26	70	80	0	270	120	36	30	220
Parbhani	Maharashtra	Otur	26	70	80	0	270	140	24	80	200
Parbhani	Maharashtra	Annapur	26	70	80	0	270	150	22	90	210
Parbhani	Maharashtra	Umbraj	26	70	80	0	270	130	26	70	190
Mean	–	–	–	90	–	–	–	160	–	–	–
Tertiary Zone											
Wardha	Maharashtra	Sukali	16	100	54	40	200	230	13	190	290
Akola	Maharashtra	Jambha	26	60	84	0	190	110	34	20	160
Akola	Maharashtra	Annapur	26	60	80	10	190	140	17	110	200
Akola	Maharashtra	Otur	26	60	80	10	190	130	22	60	190
Jalgaon	Maharashtra	Jambha	23	70	85	0	200	80	39	20	130
Jalgaon	Maharashtra	Linga	23	70	85	0	200	80	39	20	130
Mean	–	–	–	70	–	–	–	130	–	–	–
Others											
Amravati	Maharashtra	Jambha	18	70	70	0	180	120	44	40	240

Runoff: The amount of runoff is determind by the amount and intensity of rainfall besides soil physical attributes. As the rainfall during the crop growth period was less, the absolute mounts of runoff can be expected to be very little. Mean runoff in the primary zone was only 20 mm with some chance of significant runoff in some years (Tables 29 & 30). Mean runoff in the secondary zone was also 20 mm with a high variability across years indicating greater potential to harvest runoff in some years compared to the primary zone. Mean runoff in the tertiary zone was still low at 10 mm.

Deep Drainage: Mean value of deep drainage in the primary zone was about 70 mm, with a high variability. Both secondary and tertiary zones had 10 mm of deep drainage each with high variability across years (Tables 29 & 30). Very little deep drainage across production zones was again because of the low input of rainfall during the crop growth period.

Extractable soil water: Extractable soil water is the water available for plant growth at the end of the crop growth period. Mean extractable soil water in the primary zone was 40 mm in the entire soil profile with a high degree of variability. This shows that most of available water in the profile had been utilized by the crop and the crop performance was limited by the water availability. Mean available water in the secondary zone was 100 mm with the lowest of 10 mm at Aurangabad and Parbhani. Mean available water in the tertiary zone was also 100 mm. Jambha soil series, both in Akola and Jalgaon regions, had the highest extractable soil water at the end of the season. The variability across locations in this zone was also very high.

5.9 Constraints and Opportunities to *Rabi* Sorghum Production

Major abiotic constraint for *rabi* sorghum production is terminal drought as the crop is mainly dependent on stored soil moisture. Shoot fly, head bugs and stalk rots are constraints in southern Andhra Pradesh and southern Karnataka. In Gujarat, north Karnataka and southern Maharashtra, shoot fly and stalk rot are common. Shallow soils are common constraint, leading to low levels of stored moisture. Variability of rainfall across years in the rainy season resulted in periodic deficits in the stored moisture.

5.10 Summary

Currently, total area under *rabi* sorghum is 5.11 M ha with a total production of 2.99 M t and an average productivity of 590 kg ha^{-1}. Primary production zone had the lowest productivity of 480 kg ha^{-1}. Secondary and tertiary zones had a mean productivity of 680 and 720 kg ha^{-1}, respectively. The district level farmers mean yield of the three production zones for *rabi* sorghum was 630 kg ha^{-1}. Mean FLD yield of primary and secondary production zones was 1380 kg ha^{-1}. Long-term simulated rainfed mean yield of all the production zones was 1220 kg ha^{-1}. Mean simulated yields were high in the primary and secondary zones (1310-1360 kg ha^{-1}) and decreased towards the tertiary zone (1000 kg ha^{-1}). Total yield gap (simulated mean rainfed yield minus farmers mean yield) for all the production zones was 590 kg ha^{-1}. Primary production zone had the highest gap of 830 kg ha^{-1}, followed by secondary production zone with a gap of 680 kg ha^{-1} and tertiary zone with a gap of 280 kg ha^{-1}. Yield gaps I and II for the production could not be estimated accurately because of insufficient FLD data. Wherever FLD data were available, the FLD yields were more than the simulated yields. This may be due to the supplemental irrigation to the *rabi* crop given by some farmers in the zone.

Table 29. Water balance components of simulated *rabi* sorghum.

				Runoff (mm)				Deep drainage (mm)				Extractable soil water (mm)			
State	Station	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone															
Maharashtra	Rahuri	Annapur	18	10	178	0	50	20	158	0	110	10	121	0	30
Maharashtra	Sholapur	Barsi	19	20	66	0	50	120	66	0	260	70	40	40	150
Maharashtra	Sholapur	Otur	19	20	118	0	70	20	137	0	100	20	63	0	60
Maharashtra	Sholapur	Umbraj	19	20	118	0	70	20	135	0	100	60	25	40	100
Mean	–	–	–	20	–	–	–	70	–	–	–	40	–	–	–
Secondary Zone															
Maharashtra	Aurangabad	Otur	26	30	145	0	140	10	171	0	90	10	131	0	60
Karnataka	Belgaum	Achmatti	15	20	102	0	60	10	156	0	30	110	17	80	150
Karnataka	Belgaum	Huguluru	15	20	109	0	60	0	254	0	50	40	39	20	80
Karnataka	Dharwad	Achmatti	18	20	147	0	120	20	106	0	70	70	32	30	100
Karnataka	Dharwad	Huguluru	18	20	161	0	110	20	120	0	50	70	29	40	120
Maharashtra	Parbhani	Jambha	26	0	241	0	50	20	158	0	170	200	14	160	270
Maharashtra	Parbhani	Otur	26	20	153	0	120	10	161	0	90	30	43	10	60
Maharashtra	Parbhani	Annapur	26	10	195	0	90	20	140	0	130	10	73	0	20
Maharashtra	Parbhani	Umbraj	26	20	152	0	120	10	159	0	100	70	20	50	100
Mean	–	–	–	20	–	–	–	10	–	–	–	100	–	–	–
Tertiary Zone															
Maharashtra	Wardha	Sukali	16	10	115	0	60	0	233	0	40	10	97	0	50
Maharashtra	Akola	Jambha	26	0	227	0	50	20	162	0	90	200	13	170	260
Maharashtra	Akola	Annapur	26	10	191	0	70	10	168	0	60	10	108	0	60
Maharashtra	Akola	Otur	26	10	158	0	80	10	187	0	50	30	48	20	80
Maharashtra	Jalgaon	Jambha	23	0	186	0	30	20	142	0	120	230	10	200	270
Maharashtra	Jalgaon	Linga	23	20	127	0	80	10	179	0	70	110	19	80	140
Mean	–	–	–	10	–	–	–	10	–	–	–	100	–	–	–
Others															
Maharashtra	Amravati	Jambha	18	0	184	0	20	20	171	0	100	210	12	160	250

Table 30. Mean water balance components of *rabi* sorghum during the season in different production zones of India.

	Primary zone		Secondary zone		Tertiary zone	
Water balance components	Mean	Range	Mean	Range	Mean	Range
Rainfall (mm)	180	0-510	90	0-350	70	0-200
Runoff (mm)	20	0-70	20	0-140	10	0-80
Deep drainage (mm)	70	0-260	10	0-170	10	0-120
Evapotranspiration (mm)	200	70-340	160	30-320	130	20-290

High yielding drought-resistant *rabi* sorghum varieties and hybrids of good grain quality are required to increase *rabi* sorghum production. Integrated watershed management approach, encompassing storing of excess water harvested during the rainy period to provide for supplemental irrigation to the *rabi* crop, growing of high yielding drought-resistant cultivars and integrated nutrient and pest management practices are needed to enhance the productivity of the crop.

6.0 Production Trends of Millet in the World and India

6.1 Pearl Millet Production in the World

India, Niger, Nigeria, Sudan, Mali, Burkina Faso and Senegal are the major countries producing pearl millet in the world. Total area under pearl millet production is 28 M ha with total production of 21.8 M t. As the FAO database does not report pearl millet data separately from the data of other types of millets grown in the world, these data may include a very small fraction of other minor millets grown in these countries. Initially the area under pearl millet declined from about 30 M ha in 1970 to about 25 M ha in 1987, but later it recovered to almost to original levels (Fig. 9). However, total production continued to increase from 17 M t in 1970 to 24 M t in 2005. In the same period, the pearl millet productivity increased from 590 to 800 kg ha^{-1}, thus significantly contributing to the total production.

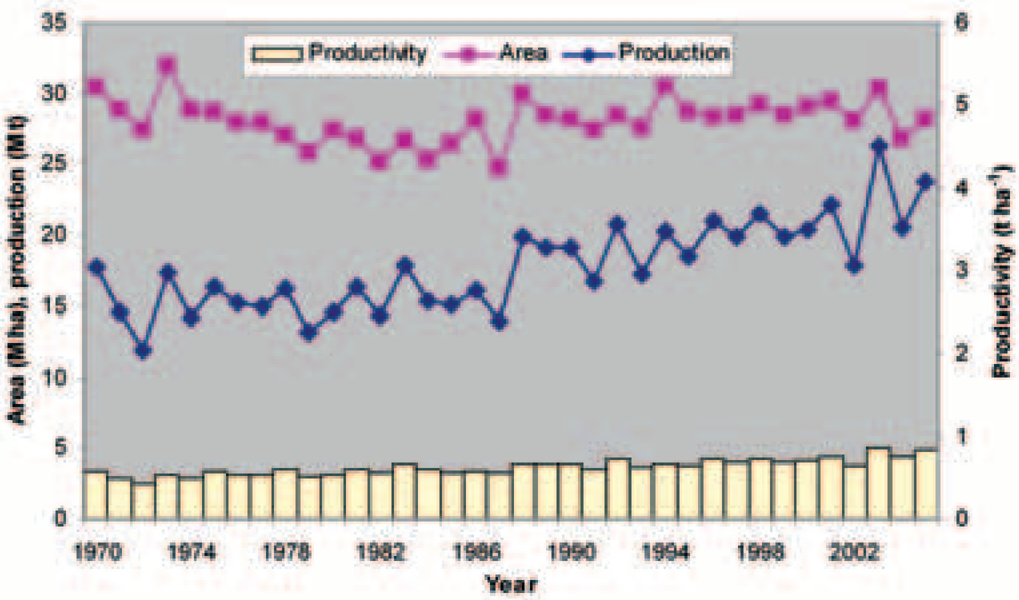

Figure 9. Global trends in area, production and productivity of pearl millet.

Table 31. Area, production and productivity of pearl millet in different countries during 2003-05.				
Country	Area (M ha)	Per cent of total area	Production (M t)	Productivity (kg ha^{-1})
India	9.81	35	9.30	940
Niger	7.92	28	2.48	310
Nigeria	4.61	16	6.71	1450
Sudan	2.03	7	0.60	300
Mali	1.61	6	1.13	700
Burkina Faso	1.27	5	1.11	870
Senegal	0.78	3	0.52	670
Total	28.03		21.85	780

Source: FAOSTAT, 2007; For India data: Ministry of Agriculture, Govt. of India, 2006.

Out of 28.0 M ha of area in the world, India has the largest area (about 35 per cent) under pearl millet cultivation. India and Nigeria put together have about 63 per cent of the global area under millets (Table 31). Among the seven countries, Nigeria has the highest productivity (1450 kg ha^{-1}), followed by India (940 kg ha^{-1}), Burkina Faso (870 kg ha^{-1}), Mali (700 kg ha^{-1}) and Senegal (670 kg ha^{-1}). Sudan and Niger have the lowest productivity (300 to 310 kg ha^{-1}). All these major countries grow millets in predominantly rainfed systems on marginal soils. Rainfall regimes are very low and practically no chemical fertilizers are applied.

6.2 Pearl Millet Production in India

Although, there are year-to-year variations in area sown to pearl millet, total area under pearl millet has decreased from about 13 M ha in 1970 to about 9.6 M ha in the year 2005 (Fig. 10). Variability in total production across the years is large. It varied from 12.1 M t to about 4 M t. Major reason for the variability in the production and productivity is the high variability of rainfall. Drought is the main factor for the lack of yield stability.

Rajasthan is the largest producer with about 42.1 per cent of total cultivated area of pearl millet in India. It contributes about 45.5 per cent of total pearl millet production in the country (2001-03 statistics). Gujarat, Maharashtra, Uttar Pradesh and Haryana together contribute about 39.5 per cent of total area and 46.4 per cent of total production. Productivity of pearl millet in the country has increased since 1970s. Mean productivity during the 1970-75 period was 450 kg ha^{-1}, which increased to 860 kg ha^{-1} during 2000-05. This indicates 90% increase in productivity over the 36 years.

7.0 Yield Gap Analysis of Pearl Millet

7.1 Abstract

In India, pearl millet is grown on the most marginal and least fertile soils in the arid and semi-arid regions. Using crop simulation approach and review of existing crop yield data of research station experiments, frontline demonstrations and farmers' current yields, the potential yields and yield gaps of pearl millet were assessed for increasing productivity to meet the future food and fodder needs.

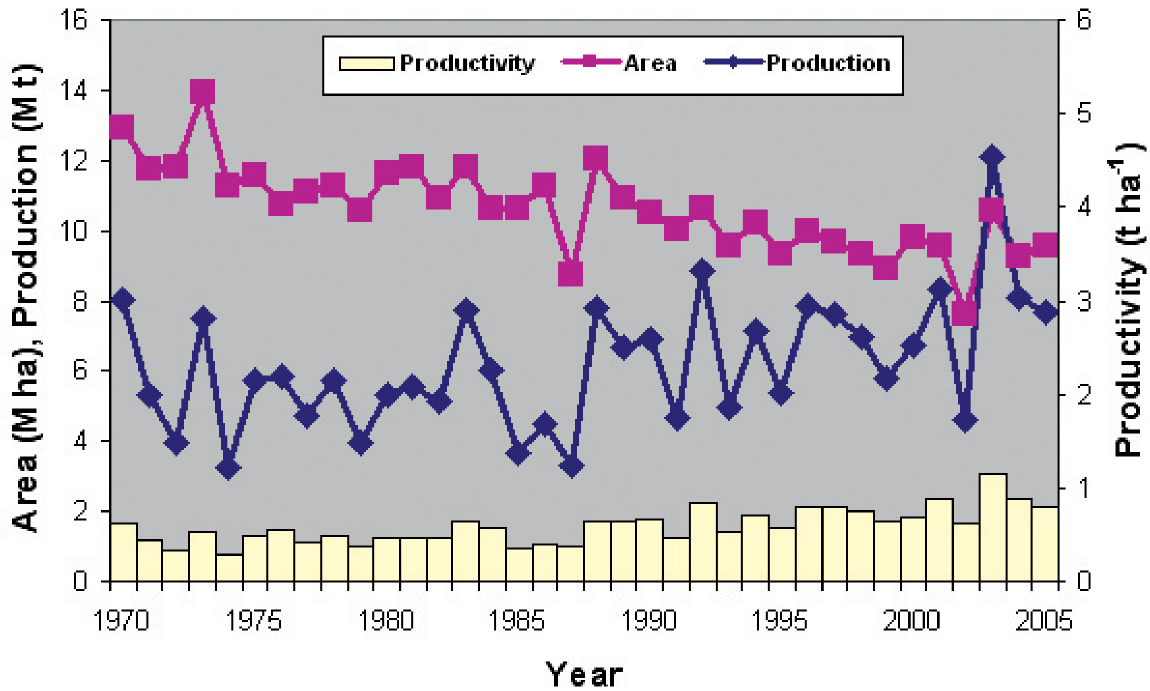

Figure 10. Area, production and productivity of pearl millet in India (Source: Ministry of Agriculture, Govt. of India, 2006).

Based on concentration of the crop in each district, the pearl millet growing area was classified into primary, secondary and tertiary zones. The primary production zone had the lowest productivity of 580 kg ha^{-1}, followed by secondary (1020 kg ha^{-1}) and tertiary (1030 kg ha^{-1}) zone. The overall district level mean yield of farmers across the three production zones was 770 kg ha^{-1}. Mean simulated rainfed potential yield was the lowest at 1430 kg ha^{-1} for the primary production zone, 1960 kg ha^{-1} for the secondary and 2090 kg ha^{-1} for the tertiary zone. Long-term simulated rainfed mean yield of the three production zones was 1830 kg ha^{-1}. Front line demonstrations (FLDs) with improved technology in farmers' fields characterize the rainfed achievable yields. Mean FLD yield across the production zones was 1870 kg ha^{-1}, which is similar to the simulated rainfed mean yield. The gap between long-term simulated rainfed mean yield and the district level farmers mean yield across all the production zones was 950 kg ha^{-1}. Primary production zone had the lowest yield gap of 880 kg ha^{-1}, followed by the secondary zone with 940 kg ha$^{-1;}$ and the tertiary zone with 1060 kg ha^{-1}. These yield gaps indicate the need to scale up the available pearl millet production technologies. Mean simulated water surplus (runoff plus deep drainage) was 140 mm for the primary, 180 mm for the secondary and 270 mm for the tertiary zones.

The above analysis shows that pearl millet productivity can be increased 1.8 to 2.3 times the current levels of productivity. This is possible by growing improved cultivars with improved soil fertility and crop management practices and efficient use of rainfall.

7.2 Introduction

Pearl millet (*Pennisetum glaucum* (L.) R.Br) is the most drought tolerant warm-season cereal crop grown as staple food grain and source of feed and fodder on about 30 M ha in the arid and semi-arid tropical regions of Asia and Africa. Along with barley, it is specifically adapted to grow on the most marginal, driest and the least fertile cereal growing environments (Bidinger et al. 2004). Pearl millet is largely grown on light textured soils in the annual rainfall regime of 400-750 mm, where sorghum and maize often fail to produce any yield (Harinarayana et al. 1999). Pearl millet is the most important cereal crop in India, both in terms of area (9.4 M ha) and production (8.5 M t), with an average productivity of 900 kg ha^{-1} (Database: 2001-03). India is also the largest producer of pearl millet in the world in terms of area and production. In spite of increase in production and productivity of pearl millet in India over the years, its productivity is still much below the potential levels that can be achieved with improved management and high yielding cultivars.

This study was aimed at quantifying productivity potential and yield gap of pearl millet. Spatial and temporal variations in yield gap at various technological levels (i.e., yield gaps between simulated rainfed potential yields, experimental station rainfed yields, frontline demonstration yields and actual farmers' yields) have been presented to assess the scope for enhancing pearl millet production in India. Constraints that limit pearl millet production and the opportunities available to enhance its productivity are also discussed.

7.3 Production Zones and Soil Resources of Pearl Millet

Pearl millet is grown in 327 districts in India with a total area of 9.4 M ha. The primary zone has 4.8 M ha spread out in 14 districts. Out of these 14 districts, 9 districts are in Rajasthan (Table 33). The secondary zone has 3.2 M ha covered by pearl millet. A total of 36 districts come under this zone. Pearl millet area in tertiary zone is distributed in 124 districts. The remaining 153 districts fall in the "others" category with pearl millet cultivation.

Most of the primary production zone is in Rajasthan and with some parts in Gujarat and Maharashtra. Secondary and tertiary zones are rather spread out in other states (Fig. 11). Entisols occupy major portion (about 59%) of the primary zone and most of these are Psamments. These soils are generally loamy fine sands to coarse textured soils. These soils are not saturated for long periods during crop growth periods. Large tracts of these soils are shifting or established sand dunes primarily in Rajasthan. The suborder Orthents forms about 22% area in this zone. These are usually very fine sands or fine textured soils. After Entisols, Aridisols form a major fraction (about 31% of area) of soils in the primary zone. These soils are mostly found in dry desert areas predominantly in Rajasthan and Gujarat and they are very low in organic matter content. The soil profile of this soil order remains moist for a very short period of the year. The suborder Orthids, which are characterized by the absence of argillic horizon and without sodic horizons are common in this zone. Vertisols and Inceptisols comprise about four per cent each in the primary zone. Secondary zone also is dominated with Entisols with 39.8 per cent area. Aridisols are next with 23.2 per cent area. But unlike the primary zone, this zone has 18.7 per cent of area with more productive Vertisols and 15.2 per cent under Inceptisols. The tertiary zone is dominated by Alfisols (28.3 per cent), followed by Entisols occupying about 26.6% of the area, Vertisols 24.9 per cent and 15.1 per cent under Inceptisols (Table 32).

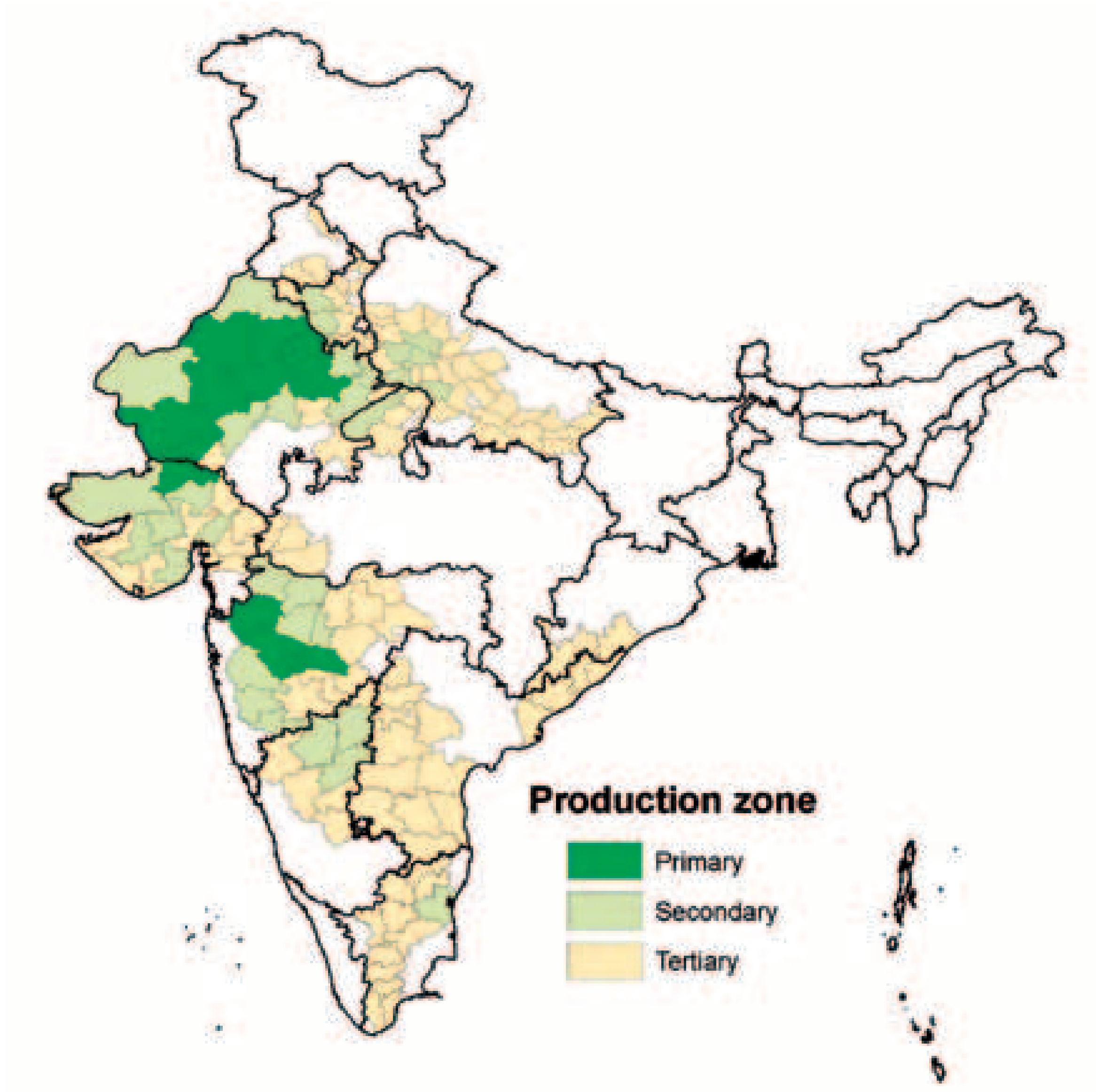

Figure 11. Area-wise production zones of pearl millet in India.

Table 32. Relative distribution of soil resources in pearl millet growing environments.

Primary zone		Secondary zone		Tertiary zone	
Soil type	Area (%)	Soil type	Area (%)	Soil type	Area (%)
Entisols	59.1	Entisols	39.8	Alfisols	28.3
Aridisols	30.9	Aridisols	23.2	Entisols	26.6
Vertisols	4.4	Vertisols	18.7	Vertisols	24.9
Inceptisols	4.1	Inceptisols	15.2	Inceptisols	15.1
		Alfisols	0.8	Aridisols	3.7
				Mollisols	0.1

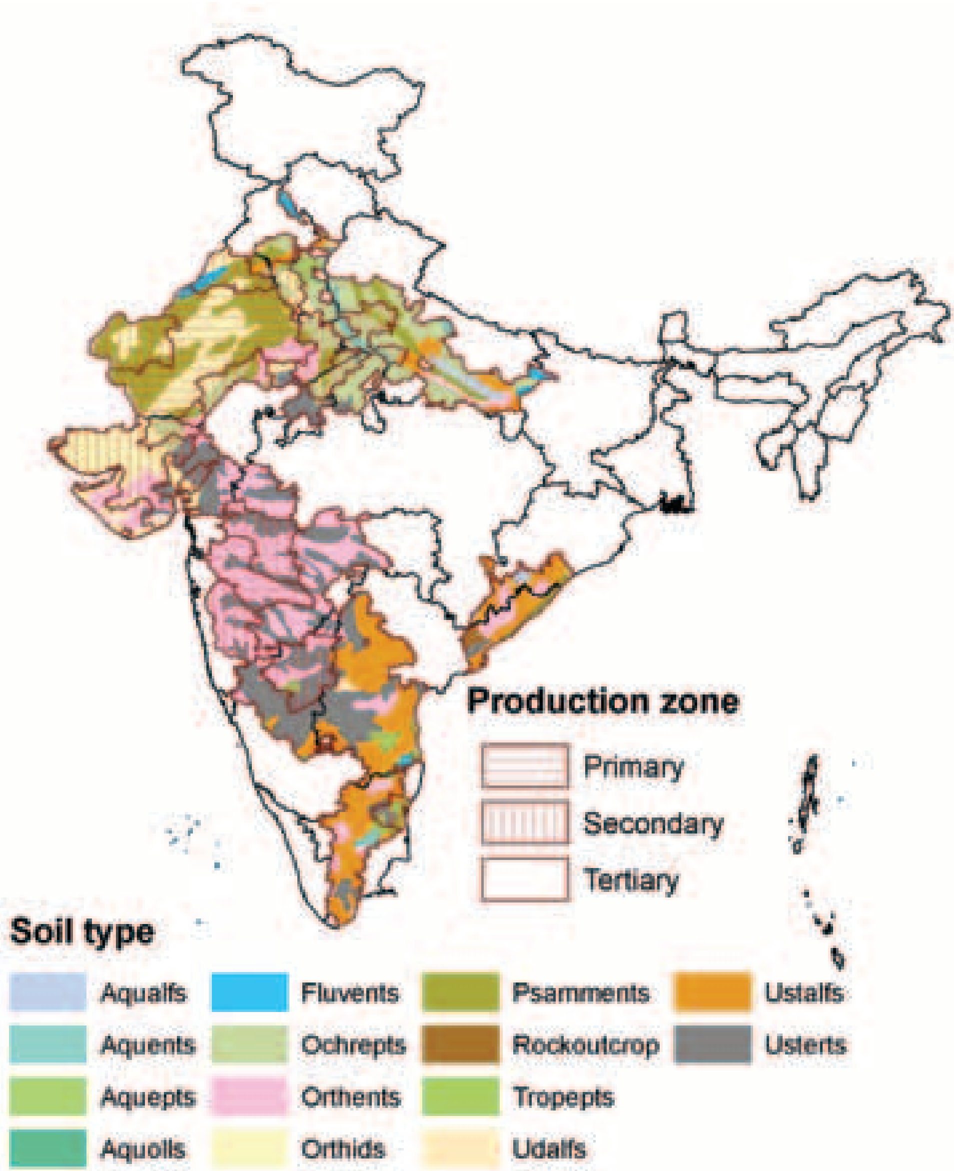

Figure 12. Soil resources in different production zones of pearl millet in India.

7.4 Pearl Millet Productivity in Production Zones, AEZs and States of India

Pearl millet productivity of production zones: The primary zone has 4.8 M ha spread out in 14 districts. Out of these 14 districts, 9 districts are in Rajasthan. Average productivity is 750 kg ha^{-1} with a CV of 36 per cent (Table 33). The secondary zone has 3.2 M ha covered by pearl millet and 36 districts come under this zone. The average productivity is 1060 kg ha^{-1} with a CV of 38 per cent. Pearl millet area in the tertiary zone is distributed in 124 districts having an average productivity of 1050 kg ha^{-1} with a CV of 41 per cent indicating high variability in productivity among districts in this zone. With diverse agroclimatic conditions in the districts classified as "others" the average pearl millet yield is 950 kg ha^{-1} with a CV of 50 per cent. Increase in yield of pearl millet from primary to tertiary zone could be attributed to the better moisture regime as one moves away from the primary zone.

Table 33. **Area, production and productivity of different production zones of pearl millet in India (Database: 2001-03).**

Production zones	No. of districts	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	CV* (%)
Primary	14	4.8	3.6	750	36
Secondary	36	3.2	3.4	1060	38
Tertiary	124	1.4	1.5	1050	41
Others	153	0.033	0.031	950	50
Total	327	9.4	8.5	900	45

* Coefficient of variation among districts.

Area, production and productivity in the agroecological zones: Pearl millet is grown in 13 agroecological zones from arid ecosystem (AEZ 2) to sub-humid ecosystem (AEZ 14) with progressive increase in moisture availability. However, the major area and production is in AEZs 2, 4 and 6 (Fig. 13 & Table 34). AEZ 2 comprises of Western Plain, parts of Rajasthan and Gujarat, which is hot and arid ecoregion with desert and saline soils. The length of the growing period (LGP) is 60-90 days. An area of about 4.52 M ha is under pearl millet cultivation in AEZ 2. The mean productivity of this zone is 730 kg ha^{-1}. Variability of productivity across districts in this zone is very high with a CV of 40 per cent. Because of the extent of area under pearl millet, this zone is the most important zone for pearl millet production in India. AEZ 4 is the second largest with 2.47 M ha under the crop and average productivity of 1280 kg ha^{-1}. AEZ 4 comprises of Northern Plains and Central Highlands that have hot arid climate, light alluvium derived soils and LGP of 90 to 150 days. Pearl millet in AEZ 4 is spread in parts of Rajasthan, Uttar Pradesh, Haryana, Punjab, Madhya Pradesh and Gujarat. AEZ 6 has the third largest area under pearl millet encompassing Deccan Plateau with shallow and medium deep black soils. This is the hot semi-arid zone with a LGP of 90-150 days. Pearl millet in this AEZ is cultivated mostly in Maharashtra and parts of Karnataka and in Nizamabad district in Andhra Pradesh. Total area under pearl millet is 1.58 M ha with an average productivity of 660 kg ha^{-1}. Pearl millet is grown up to AEZ 19. However, the major concentration of the crop is confined to the arid and semi-arid regions (AEZs 2-9) only.

Pearl millet productivity in different states of India: Rajasthan is the major state with an area of 4.74 M ha under pearl millet production (Table 35). Out of the total 8.49 M t produced in the country, 3.74 M t is produced in Rajasthan. Average productivity in the state is one of the lowest at 790 kg ha^{-1} with a CV of 34%. High variability in productivity is due to the fact that most of the area is in the arid zones with low seasonal rainfall. Maharashtra is the second largest state with 1.42 M ha under the crop with a mean productivity of 670 kg ha^{-1}. Gujarat follows with an area of 1.08 M ha and a mean productivity of 1280 kg ha^{-1}. Variability in productivity across districts in Gujarat is high with a CV of 29 per cent. Productivity of pearl millet in Tamil Nadu is high (1070 kg ha^{-1}) but the area under pearl millet is negligible at 0.13 M ha.

Table 34. Area, production and productivity of pearl millet in different agroecological zones of India (Database: 2001-03).

AEZ	No. of districts	Area (M ha)	Production (M t)	Productivity** (kg ha^{-1})	CV* (%)
2	27	4.520	3.301	730	40
3	5	0.129	0.062	480	28
4	72	2.472	3.162	1280	26
5	29	0.367	0.573	1560	49
6	30	1.576	1.038	660	39
7	11	0.072	0.063	870	51
8	32	0.136	0.144	1060	38
9	24	0.084	0.089	1060	44
10	21	0.002	0.001	690	54
11	11	0.011	0.012	1140	46
12	14	0.022	0.018	830	31
13	20	0.003	0.004	1340	30
14	15	0.016	0.010	630	31
Others	16	0.009	0.013	1460	39
Total	327	9.419	8.490	900	45

* Coefficient of variation among districts within AEZ.
** Yield is the mean of districts

Table 35. Area, production and productivity of pearl millet in different states of India (Database: 2001-03).

State	No. of districts	Area (M ha)	Production (M t)	Productivity (kg ha^{-1})	CV* (%)
Andhra Pradesh	20	0.11	0.09	880	55
Gujarat	23	1.08	1.39	1280	29
Haryana	19	0.57	0.72	1260	40
Karnataka	16	0.28	0.14	510	32
Madhya Pradesh	40	0.18	0.20	1150	49
Maharashtra	22	1.42	0.96	670	36
Rajasthan	32	4.74	3.74	790	34
Tamil Nadu	26	0.13	0.14	1070	31
Uttar Pradesh	70	0.88	1.09	1240	26
Others	59	0.03	0.02	670	24
Total	327	9.42	8.49	900	35

* Coefficient of variation among districts within a state.

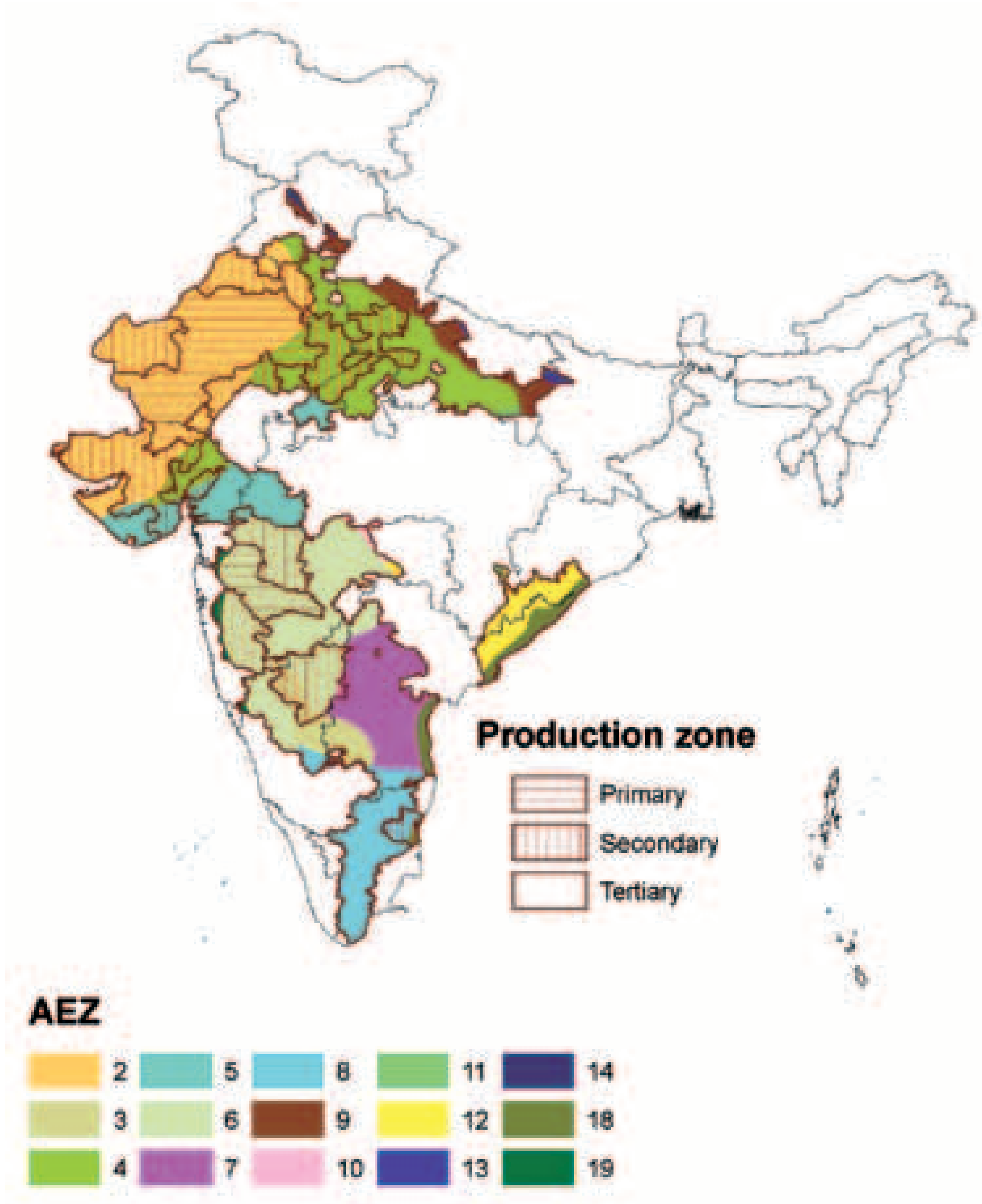

Figure 13. Agroecological zones of pearl millet in India.

7.5 Rainfed Yield Potential of Pearl Millet

Experimental station yields and yield gaps: Experimental station mean yield of the primary zone was 1700 kg ha^{-1} (Table 36). The only district of Jaipur in the primary zone had a mean FLD yield of 1810 kg ha^{-1}. The higher FLD yield than the experimental yield could be attributed to spatial variability in soil or rainfall. The corresponding district mean yield was 610 kg ha^{-1}. As the FLD mean yield of Jaipur was higher than the experimental yield, the yield gap was taken as nil. Because of insufficient number of FLD sites in the primary zone, we could not have a good estimate of the yield gaps I and II. However, the total yield gap for the zone was 1090 kg ha^{-1}.

Mean experimental station yield for the secondary production zone was 2070 kg ha^{-1}. There was a lot of variation in the FLD mean yields of corresponding districts. It ranged from 940 kg to 2520 kg ha^{-1} with a mean of 1600 kg ha^{-1}. The variation among district yields was also high, which averaged to 930 kg ha^{-1}. Mean total yield gap calculated for this zone was 1140 kg ha^{-1}. Because of the lack of FLD data for some locations in the secondary zone, the estimates of mean yield gap I and II were approximate, which were 610 and 790 kg ha^{-1}, respectively.

Experimental station mean yield of the tertiary zone was 2440 kg ha^{-1}. There were only two corresponding districts having FLD data. Mean FLD yield for this zone was 2190 kg ha^{-1}. Jamnagar in Gujarat showed a higher FLD mean yield than the experimental station mean yield. Because of insufficient FLD data, it was difficult to have a reasonable estimates of yield gap I and yield gap II for this zone. Total yield gap for this zone was 1590 kg ha^{-1} (Table 36). Total yield gap as observed for the three production zones indicated the potential to increase the farmers yield through transfer of technology from research stations to the farmers field and its subsequent scaling up for larger areas.

Table 36. Experimental station, FLD and district average yields and yield gaps (kg ha^{-1}) of rainfed pearl millet in India.

Location	State	Expt. station	FLD	District	Yield gap I	Yield gap II	Total yield gap
Primary Zone							
Mandore	Rajasthan	1400	–	430	–	–	960
Jaipur	Rajasthan	1410	1810	810	0	1000	600
Rahuri	Maharashtra	2280	–	590	–	–	1690
Mean	–	1700	1810	610	0	1000	1090
Secondary Zone							
Anand	Gujarat	2720	–	1400	–	–	1330
Aurangabad	Maharashtra	2360	940	740	1430	190	1620
Kothara	Gujarat	1310	–	830	–	–	490
Hisar	Haryana	2180	2520	1120	0	1400	1060
Bijapur	Karnataka	1770	1360	580	410	780	1190
Mean	–	2070	1600	930	610	790	1140
Tertiary Zone							
Jamnagar	Gujarat	2110	2300	850	0	1450	1260
Gwalior	Madhya Pradesh	3380	2080	1540	1300	530	1830
Buldhana	Maharashtra	2230	–	600	–	–	1620
Ahmedabad	Gujarat	2260	–	1140	–	–	1120
Palem	Andhra Pradesh	2660	–	440	–	–	2220
Anantapur	Andhra Pradesh	1990	–	550	–	–	1440
Mean	–	2440	2190	850	650	990	1590
Others							
Coimbatore	Tamil Nadu	3550	–	1190	–	–	2360
Mahuva	Gujarat	2570	–	790	–	–	1780
Mean	–	3060	–	990	–	–	2070

7.6 Simulated Potential Rainfed Yields

Potential yield of locations: The simulated rainfed mean yield of the primary production zone was 1430 kg ha^{-1}. Long-term simulations under rainfed situation showed that the CV in yield for all the three locations of Jodhpur, Jaipur and Rahuri exceeded 40 per cent. This clearly demonstrates that because of large variability in yields of pearl millet across years, farmers have to face a high degree of risk in pearl millet production in this zone. Mean yield in the secondary zone was 1960 kg ha^{-1}. Except Pune in Maharashtra, all other locations had shown a CV greater than 40 per cent in pearl millet yields. The tertiary zone was fairly well spread across India. Mean long-term yield across the locations in this zone was 2090 kg ha^{-1}. The mean yield increased from primary to tertiary zones. There was a large variation in CV of yields across the locations in the tertiary zone. Belgaum and Dharwad showed a lower CV indicating a relatively stable yield across years in Karnataka. All other locations had a high degree of variation across years (Table 37).

Potential yields of production zones: Primary production zone had the lowest mean yield of 1430 kg ha^{-1} (Table 38). This production zone had the highest area under pearl millet. Yield variability across locations was also evident from the high coefficient of variation, which was greater than 30 per cent. Seasonal rainfall in this zone was the lowest at a mean of 320 mm. The secondary zone had a higher mean yield of 1960 kg ha^{-1} with a CV of 48 per cent across locations. The increase in the mean yield could be explained by a higher mean crop season rainfall of 430 mm. The highest mean yield of 2090 kg ha^{-1} was observed in the tertiary zone. Similarly, this zone had the highest mean crop season rainfall of 520 mm.

Potential yields of major states: Rajasthan is the major state growing pearl millet. Mean simulated rainfed yield in this state was 1460 kg ha^{-1} (Table 38). Variability across locations was very high as evidenced by a high coefficient of variation of 32 per cent. The lower yields were due to low mean crop season rainfall of 420 mm. Madhya Pradesh had the highest mean yields by 2530 kg ha^{-1}. Mean crop season rainfall at locations in Madhya Pradesh was also higher at 700 mm. Karnataka had a mean yield of 2170 kg ha^{-1}. Even though, the yields were better than Rajasthan, variability across locations was very high with a CV of 50 per cent. This was due to a high degree of variability (CV = 41%) of crop season rainfall. Maharashtra had a mean yield of 2000 kg ha^{-1}. Variability across locations was high with a CV of 33 per cent.

Potential yields of agroecological zones: The highest mean yield of 2470 kg ha^{-1} was simulated for AEZ 10 (Table 38). This zone had good crop season rainfall of 700 mm. However, pearl millet was grown in a very limited area in this zone. Major pearl millet area falls in AEZ 2 and 3. These zones had low mean yields of 950 and 710 kg ha^{-1}. This was because of low crop season rainfall of 300 and 230 mm in these zones. A major portion of the pearl millet area was concentrated in these unfavorable zones with low rainfall, poor soils and a high degree of variability of rainfall across the years.

Table 37. Seasonal rainfall and simulated grain yield of pearl millet at different locations across India.

			Rainfall (mm)				Grain yield (kg ha^{-1})				District	Yield
		No. of		CV				CV			yield	gap
Location	Soil series	years	Mean	(%)	Min	Max	Mean	(%)	Min	Max	(kg ha^{-1})	(kg ha^{-1})
Primary Zone												
Rahuri	Annapur	17	250	55	70	650	1490	41	540	2860	690	800
Jodhpur	Chirai	26	300	61	30	720	950	45	0	1650	380	570
Jaipur	Chomu	9	420	43	140	660	1850	57	450	3160	740	1110
Mean	–	–	323	–	–	–	1430	–	–	–	603	827
Secondary Zone												
Pune	Otur	15	460	31	270	700	3320	24	1300	4100	750	2570
Gulbarga	Hungund	20	420	45	100	860	1110	59	110	2620	710	400
Gulbarga	Huguluru	22	470	40	150	930	1520	33	740	2610	710	810
Bijapur	Hungund	12	230	34	100	340	710	59	130	1370	640	70
Jalgaon	Jambha	23	510	25	210	760	2110	51	400	3770	1040	1070
Jalgaon	Linga	23	520	22	280	760	1990	54	280	3700	1040	950
Aurangabad	Otur	27	450	35	150	800	2970	44	440	5920	850	2120
Mean	–	–	437	–	–	–	1960	–	–	–	820	1141
Tertiary Zone												
Akola	Jambha	26	580	27	260	870	2410	39	470	4770	580	1830
Akola	Annapur	26	570	31	150	850	2900	32	730	4850	580	2320
Akola	Otur	26	570	31	150	870	2370	42	490	4790	580	1790
Akola	Umbraj	26	570	31	150	870	2180	45	440	4690	580	1600
Amravati	Jambha	18	570	32	270	950	2510	45	730	5270	610	1900
Belgaum	Achmatti	16	740	33	400	1350	2300	37	710	3670	230	2070
Belgaum	Huguluru	16	740	32	450	1350	2920	26	1540	4530	230	2690
Dharwad	Achmatti	18	360	28	200	570	3040	32	780	4700	470	2570
Dharwad	Huguluru	18	360	28	200	570	3560	19	2510	4990	470	3090
Kota	Chambal	35	530	38	180	1040	1590	69	140	4720	510	1080
Parbhani	Jambha	26	570	37	280	1080	1320	55	480	3370	590	730

Table 37. *Continued*

Location	Soil series	No. of years	Rainfall (mm) Mean	CV (%)	Min	Max	Grain yield (kg ha^{-1}) Mean	CV (%)	Min	Max	District yield (kg ha^{-1})	Yield gap (kg ha^{-1})
Parbhani	Otur	26	590	41	280	1150	1460	44	530	3190	590	870
Parbhani	Annapur	26	580	37	280	1080	1620	41	930	3510	590	1030
Parbhani	Umbraj	26	570	37	280	1080	1400	51	520	3390	590	810
Sholapur	Barsi	19	310	36	80	460	1260	67	140	2590	480	780
Sholapur	Otur	19	310	36	80	460	1390	63	140	2890	480	910
Sholapur	Umbraj	19	310	36	80	460	1230	64	110	2630	480	750
Mean	–	–	519	–	–	–	2090	–	–	–	509	1578
Others												
Rajgarh	Jamra	24	730	40	310	1660	2290	44	290	3720	–	0
Indore	Sarol	27	680	34	330	1200	2710	39	460	4780	–	0
Guna	Saunther	18	660	32	240	970	2200	49	130	3570	1200	1000
Guna	Jamra	19	710	30	240	990	2920	33	740	4130	1200	1720
Mean	–	–	695	–	–	–	2530	–	–	–	1200	680

Table 38. **Simulated rainfed potential yields of pearl millet and seasonal rainfall in different production zones, states and AEZs.**

Zones	No. of locations	Simulated yields (kg ha^{-1})				Rainfall (mm)			
		Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)
Crop Zones									
Primary	3	950	1850	1430	32	250	420	320	27
Secondary	7	710	3320	1960	48	230	520	430	22
Tertiary	17	1230	3560	2090	35	310	740	520	27
Others	4	2200	2920	2530	14	660	730	690	4
States									
Rajasthan	3	950	1850	1460	32	300	530	420	28
Madhya Pradesh	4	2200	2920	2530	14	660	730	700	4
Karnataka	7	710	3560	2170	50	230	740	470	41
Maharashtra	17	1230	3320	2000	33	250	590	490	24
AEZs									
6	23	1110	3560	2100	36	250	740	495	27
10	3	2200	2920	2470	16	660	730	700	5
2	1	0	1650	950	45	30	720	300	61
3	1	130	1370	710	59	100	340	230	34
4	1	450	3160	1850	57	140	660	420	43
5	2	300	4750	2150	54	255	1120	605	36

7.7 Yield Gaps

Yield gap of production zones: Because of progressive increase in mean rainfall from primary to tertiary production zone, the simulated mean yields, experimental station mean yields, FLD yields and district average yields increased from primary to the tertiary zone (Table 39). Experimental station yields in all production zones were somewhat higher than the mean simulated yields but remained below the simulated maximum possible yields. This was because simulations were carried out for many years, whereas the experimental data was available only for ten years. Yield gap I across production zones ranged from nil to 470 kg ha^{-1} with mean of 200 kg ha^{-1}. Yield gap II was higher than the yield gap I, which ranged from 540 to 1140 kg ha^{-1} with a mean of 920 kg ha^{-1} for the production zones. Yield gap II formed a larger part of the total yield gap (yield gap between the experimental and district mean yield), indicating greater scope for adopting the already available technologies by farmers for productivity enhancement. Yield gap between the simulated potential and mean district yield increased from 680 kg ha^{-1} for the primary zone to 1040 kg ha^{-1} for the tertiary zone with a mean of 880 kg ha^{-1}. The data indicates that the productivity of pearl millet could be increased 1.8 to 2.3 times from the current level of productivity in the three production zones.

Table 39. Yield gap of pearl millet in production zones.

	Primary	Secondary	Tertiary	Mean
	(kg ha^{-1})			
Rainfed yields				
Simulated mean yield	1430	1960	2090	1830
Simulated maximum yield	1850	3320	3560	2910
Exp. stn. mean yield	1700	2070	2440	2070
FLD mean yield	1810	1600	2190	1870
District mean yield*	750	1060	1050	950
Yield gaps				
Expt. stn. – FLD yield (YG I)	0	470	250	200
FLD yield - district mean (YG II)	1060	540	1140	920
Exp. stn. mean - district mean	950	1010	1390	1120
Simulated mean - district mean	680	900	1040	880

* Taken from Table 33

Yield gap of agroecological zones: As the experiment station mean yields for the agroecological zones were generally higher than the simulated mean yields, the total yield gaps estimated based on the experiment station yields were wider than those estimated with simulated mean yields. These yield gaps in general increased from AEZ 2 to AEZ 8. AEZ 2 had the lowest yield gap of 1020 kg ha^{-1} and AEZ 8 had the maximum yield gap of 2490 kg ha^{-1} (Table 40). This is because of increase in rainfall amount and decrease in its variability as one moves from AEZ 2 to AEZ 8. Based on the simulated yields, the total yield gap ranged from 220 to 1440 kg ha^{-1} for the AEZs. In most cases, the yield gap II was larger than the yield gap I, indicating greater need to transfer existing pearl millet production technologies from demonstration sites to the farmers' fields.

Table 40. Yield gap of pearl millet in different AEZs of India.

	AEZs						
	2	3	4	5	6	7	8
	(kg ha^{-1})						
Rainfed yields							
Simulated mean yield	950	710	1850	2150	2100	–	–
Experimental station mean yield	1750	1990	2350	2720	2160	2660	3550
FLD mean yield	2410	–	1940	–	1150	–	–
District mean yield*	730	480	1280	1560	660	870	1060
Yield gaps							
Experimental station-FLD yield (YG I)	0	–	410	–	1010	–	–
FLD-district mean (YG II)	1680	–	660	–	490	–	–
Exp. mean – district mean	1020	1510	1070	1160	1500	1790	2490
Simulated mean – district mean	220	230	570	590	1440	–	–

* Taken from Table 34.

Yield gap of major states: Simulated yields for Andhra Pradesh, Gujarat, Haryana and Tamil Nadu were not available because of the lack of input data for executing the pearl millet model. Similarly, total yield gap based on the experiment station data was wider in Andhra Pradesh, Karnataka, Madhya Pradesh, Maharashtra and Tamil Nadu as compared to other states (Table 41). Such comparison between states for total yield gap based on simulated yields was not possible because of lack of simulated data for some states. Except for Madhya Pradesh and Maharashtra, yield gap II was larger than yield gap I. For Gujarat, Haryana and Rajasthan, the FLD yields were higher than the experiment station yields, indicating that on-farm trials at some sites in these states might have been conducted under more favorable environments or provided with supplemental irrigation. Nevertheless, larger total yield gaps indicate the scope of enhanced productivity of pearl millet by proper crop and nutrient management practices.

Table 41. Yield gap of pearl millet in major states of India.

	Andhra Pradesh	Gujarat	Haryana	Karnataka	Madhya Pradesh	Maharashtra	Rajasthan	Tamil Nadu
					(kg ha^{-1})			
Rainfed yields								
Simulated mean yield	–	–	–	2170	2530	2000	1460	–
Experimental station mean yield	2320	2100	2180	1770	3380	2290	1400	3550
FLD mean yield	–	2300	2520	1360	2080	940	1810	–
District mean yield*	880	1280	1260	510	1150	670	790	1070
Yield gaps								
Experimental station - FLD yield (YG I)	–	0	0	410	1300	1350	0	–
FLD yield - district mean (YG II)	0	1020	1260	850	930	270	1020	–
Experimental stn. mean – district mean	1440	820	920	1260	2230	1620	610	2480
Simulated mean – district mean	–	–	–	1660	1380	1330	670	–

* Taken from Table 35

7.8 Water Balance Components of Pearl Millet

Rainfall: Mean seasonal rainfall across locations and years was 320 mm in the primary zone, 420 mm in the secondary zone and 520 mm in the tertiary zone. All the three locations in the primary zone had a very high CV of rainfall with Jodhpur being the highest (61%) (Tables 42 & 44). High variability in rainfall was the main reason for unstable yields across years. Secondary zone had about 25 per cent more rainfall than the primary zone. A clear reflection of this could be seen in the increase of mean yield of this zone. However, all the other locations except Jalgaon exhibited a high CV in rainfall. The tertiary zone had almost 100 mm more rainfall than the secondary zone. Although, the mean yields of this zone were higher than those in the secondary zone, the quantum of increase in yields did not match with the increase of rainfall. The reason could be the high CV, indicating a high degree of variability across years or poor crop management. Dharwad was an exception, with a CV less than 30 per cent.

Table 42. Simulated water balance components of rainfed pearl millet during the season.

		No. of	Rainfall (mm)				Runoff (mm)				Deep drainage (mm)			
Station	Soil	years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone														
Rahuri	Annapur	17	250	55	70	650	40	100	0	160	50	113	0	210
Jodhpur	Chirai	25	300	61	30	720	50	15	0	290	100	95	0	300
Jaipur	Chomu	9	420	43	140	660	70	132	0	320	100	85	0	280
Mean	–	–	320	–	–	–	50	–	–	–	90	–	–	–
Secondary Zone														
Pune	Otur	15	460	31	270	700	110	56	50	220	110	60	0	250
Gulbarga	Hungund	20	420	45	100	860	140	71	20	460	90	68	0	270
Gulbarga	Huguluru	22	470	40	150	930	100	81	10	370	100	72	0	220
Bijapur	Hungund	12	230	34	100	340	60	68	10	140	30	96	0	80
Jalgaon 1	Jambha	23	510	25	210	760	50	72	0	180	200	38	10	330
Jalgaon 2	Linga	23	520	22	280	760	150	40	60	310	110	40	40	200
Aurangabad	Otur	27	450	35	150	800	100	55	10	240	80	85	0	240
Mean	–	–	420	–	–	–	90	–	–	–	100	–	–	–
Tertiary Zone														
Akola	Jambha	26	580	27	260	870	60	55	10	140	230	47	40	440
Akola	Annapur	26	570	31	150	850	110	52	10	220	170	53	20	330
Akola	Otur	26	570	31	150	870	170	45	20	310	120	65	0	290
Akola	Umbraj	26	570	31	150	870	170	45	20	310	120	62	0	300
Amravati	Jambha	18	570	32	270	950	60	84	10	210	220	57	10	520
Belgaum	Achmatti	16	740	33	400	1350	260	60	80	690	200	42	50	330
Belgaum	Huguluru	16	740	32	450	1350	230	63	80	660	200	45	60	340
Dharwad	Achmatti	18	360	28	200	570	60	63	10	160	80	49	10	160
Dharwad	Huguluru	18	360	28	200	570	50	73	10	140	80	53	10	170
Kota	Chambal	35	530	38	180	1040	160	61	20	470	120	71	0	300
Parbhani	Jambha	26	570	37	280	1080	70	80	0	250	280	55	60	590
Parbhani	Otur	26	590	41	280	1150	200	66	30	580	180	59	40	400
Parbhani	Annapur	26	580	37	280	1080	120	71	10	370	220	55	60	480

Table 42. *Continued*

Station	Soil	No. of years	Rainfall (mm)				Runoff (mm)				Deep drainage (mm)			
			Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Parbhani	Umbraj	26	570	37	280	1080	190	60	30	480	160	60	40	370
Sholapur	Otur	19	310	36	80	460	70	57	10	150	40	76	0	110
Sholapur	Umbraj	19	310	36	80	460	70	57	10	150	50	72	0	120
Mean	–	–	520	–	–	–	120	–	–	–	150	–	–	–
Others														
Rajgarh	Jamra	24	730	40	310	1660	260	64	70	820	190	63	40	560
Indore	Sarol	27	680	34	330	1200	240	56	60	490	160	55	30	390
Guna	Saunther	18	660	32	240	970	210	53	60	430	180	50	20	330
Guna	Jamra	19	710	30	240	990	220	48	60	420	200	50	10	330

Table 43. Simulated long-term water balance components of rainfed pearl millet.

			Evapotranspiration (mm)				Extractable soil water (mm)			
Station	Soil	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone										
Rahuri	Annapur	17	190	15	140	230	70	45	20	120
Jodhpur	Chirai	25	160	20	80	240	140	21	90	200
Jaipur	Chomu	9	250	24	150	340	130	19	80	160
Mean	–	–	200	–	–	–	110	–	–	–
Secondary Zone										
Pune	Otur	15	280	10	220	310	90	31	60	140
Gulbarga	Hungund	20	200	21	100	280	110	25	70	190
Gulbarga	Huguluru	22	280	17	190	380	210	17	120	270
Bijapur	Hungund	12	160	23	110	250	90	23	60	120
Jalgaon 1	Jambha	23	260	17	170	340	270	6	230	290
Jalgaon 2	Linga	23	260	17	160	340	140	12	100	160
Aurangabad	Otur	27	280	18	150	400	100	28	30	150
Mean	–	–	250	–	–	–	140	–	–	–
Tertiary Zone										
Akola	Jambha	26	280	15	220	410	260	12	190	290
Akola	Annapur	26	290	15	220	420	90	43	20	140
Akola	Otur	26	280	16	210	410	110	30	50	150
Akola	Umbraj	26	280	16	200	400	140	22	80	180
Amravati	Jambha	18	270	17	210	380	270	7	220	300
Belgaum	Achmatti	16	270	16	220	330	180	9	140	200
Belgaum	Huguluru	16	290	14	230	350	230	11	180	270
Dharwad	Achmatti	18	250	14	170	300	160	14	130	190
Dharwad	Huguluru	18	260	12	190	310	190	12	170	230

Table 43. *Continued*

			Evapotranspiration (mm)				Extractable soil water (mm)			
Station	Soil	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Kota	Chambal	35	240	30	90	380	190	19	80	230
Parbhani	Jambha	26	210	13	150	280	280	5	250	300
Parbhani	Otur	26	210	11	170	270	130	13	90	150
Parbhani	Annapur	26	220	12	170	280	120	20	80	170
Parbhani	Umbraj	26	210	12	150	280	160	9	130	180
Sholapur	Barsi	19	210	23	120	280	160	14	120	190
Sholapur	Otur	19	210	22	120	280	100	24	60	140
Sholapur	Umbraj	19	210	23	110	270	130	17	90	170
Mean	–	–	250	–	–	–	170	–	–	–
Others										
Rajgarh	Jamra	24	260	21	160	400	150	19	80	170
Indore	Sarol	27	270	17	160	380	180	12	110	200
Guna	Saunther	18	250	20	130	300	80	16	50	90
Guna	Jamra	19	280	22	190	410	140	18	80	170

Runoff: Runoff is determined by soil hydraulic properties, amount and more importantly the intensity of rainfall. Mean simulated runoff in the primary zone was 50 mm during the cropping season, which is rather low. Mean runoff in the secondary zone was 90 mm. Tertiary zone had a mean runoff of 120 mm during the crop season (Tables 42 & 44). Although, there was a large variation among locations within a production zone to produce surface runoff, tertiary zone had the highest runoff potential for water harvesting and its use as supplemental irrigation to increase crop yields.

Deep drainage: A fraction of the rainfall during the crop season, which enters the soil profile is lost through deep drainage. However, this helps increasing the groundwater levels through recharge. Deep drainage was more than runoff for all the production zones. Simulated runoff was 90 mm for the primary zone, 100 mm for the secondary zone and 150 mm for the tertiary zone, respectively (Tables 42 & 44).

Evapotranspiration: Evapotranspiration (ET) is a combined term representing soil evaporation and plant transpiration during the crop growth period. Primary zone had mean ET of 200 mm, which ranged from 120 to 270 mm across locations (Tables 43 & 44). Simulated mean ET for the secondary zone was 250 mm, which was 20% more than that simulated for the primary zone. Simulated ET for the tertiary zone was the same as for the secondary zone.

Extractable water: Extractable water left in the soil profile at the end of the season gives an indication for the potential to grow second crop or to extend the crop growth period of the current crop for greater yield potential at a given site or production zone. Amount of water left in the soil profile on an average was 110 mm for the primary zone, 140 mm for the secondary zone and 170 mm for the tertiary zone, respectively, indicating increase in production (Table 43).

Table 44. Water balance components of pearl millet during the season in different production zones of India.

	Primary zone		Secondary zone		Tertiary zone	
Water balance components	Mean	Range	Mean	Range	Mean	Range
Rainfall (mm)	320	80-680	420	180-700	520	250-910
Runoff (mm)	50	0-260	90	20-230	120	20-330
Deep drainage (mm)	90	0-260	100	0-220	150	20-330
Evapotranspiration (mm)	200	120-270	250	170-330	250	170-340

7.9 Constraints and Opportunities to Pearl Millet Production

Major pearl millet growing area is in the arid region of India (Rajasthan and Northern Gujarat) where rainfall is low and erratic. Therefore, drought is the most common constraint. Low inherent soil fertility and low nutrient input due to high rainfall variability is another constraint. Among the biotic constraints, downy mildew is the most destructive disease causing severe economic losses. Other minor diseases affecting pearl millet are smut, ergot and rust (ICRISAT 2002). Improved millet hybrids resistant to downy mildew and drought-tolerant have increasingly become available, which need to be adopted for increasing productivity. In some areas, significant amount of water is lost and surface runoff and deep drainage, which needs to be harvested and used as supplemental irrigation. In other dry areas, *in-situ* moisture conservation practices need to be adopted. Integrated nutrient management practices are required to enhance the pearl millet productivity and increase the water use efficiency. Many of these technologies are available on the shelve and need to be refined and adopted for different agroecologies of pearl millet.

7.10 Summary

Pearl millet production is an essential component of rainfed agriculture in the arid and semi-arid regions of India. In this report, we determined the potential yields and yield gaps of pearl millet to estimate future food production possibilities. Pearl millet growing area was classified into primary, secondary and tertiary zones based on the concentration of the crop in each district. Primary production zone has about 4.8 M ha concentrated in just 14 districts. Majority of this area is in Rajasthan, Gujarat and Maharashtra. These areas are characterized by low annual rainfall and marginal soils and a high degree of variation in productivity within the production zones. Primary production zone had the lowest productivity of 750 kg ha^{-1} followed by secondary (1060 kg ha^{-1}) and tertiary (1050 kg ha^{-1}) zone. Mean yield of farmers in the production zones was only 950 kg ha^{-1}. To assess the potential yields and yield gaps, the districts from each production zone were taken up, where the required input data for crop simulation were available. Mean simulated potential yields was the lowest at 1430 kg ha^{-1} in the primary production zone. Secondary and tertiary zones had a mean simulated yield of 1960 and 2090 kg ha^{-1}, respectively.

Long-term simulated rainfed mean yield of all the production zones was 1830 kg ha^{-1}. The gap between long-term simulated rainfed mean yields and the mean district level farmers yields from all the production zones was 880 kg ha^{-1}. Primary production zone had the lowest gap of 680 kg ha^{-1}, followed by secondary production zone with a gap of 900 kg ha^{-1} and tertiary zone with a gap of 1040 kg ha^{-1}. Mean FLD yields of all the production zones was 1870 kg ha^{-1}. The mean yield gap between FLD and the district level farmers yields among all the production zones was 920 kg ha^{-1}.

All the water balance components like rainfall, runoff and deep drainage were the lowest in the primary zone and progressively increased from primary to tertiary production zones. Mean seasonal rainfall in the primary zone was the lowest at 320 mm, followed by 420 mm in the secondary zone and 520 mm in the tertiary zone. Simulated long-term mean runoff in the primary production zone was 50 mm, followed by 90 mm in the secondary zone and 120 mm in the tertiary zone. Mean simulated long-term deep drainage in the primary production zone was 90 mm followed by 100 mm in the secondary production zone and 150 mm in the tertiary production zone. These results show that the growing environment of the primary production zone, which has about 50 per cent of the total area under pearl millet concentrated in just 14 districts, has least favorable natural resources to support pearl millet production.

Drought is the major constraint across all the production zones of pearl millet. Low and erratic rainfall is the major cause for the water stress faced by the crop. Due to the risk factor of crop failures, farmers resort to low to no nutrient inputs. However, this study has shown a significant scope for increasing crop yields of pearl millet in all the three production zones of India.

References

Bidinger FR and **Hash CT.** 2004. Pearl millet. Chapter 5 (pages 225–270) *in* Physiology and Biotechnology Integration for Plant Breeding (Nguyen HT and Blum A, eds.). Marcel Dekker, New York, USA.

Bristow RL and **Campbell GS.** 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. Agr. For. Meteorol. 31:159-166.

Harinarayana G, Anand Kumar A and **Andrews DJ. 1999.** Pearl millet in global agriculture. *In* (Khairwal IS, Rai KN, Andrews DJ & Harinarayana G, Eds.). Pearl Millet Breeding. New Delhi: Oxford and IBH. pp. 479-506.

Hoogenboom G, Wilkens PW, Thornton PK, Jones JW, Hunt LA and **Imamura DT.** 1999. Decision support system for agrotechnology transfer v3.5. *In* DSSAT version 3, vol. 4 (ISBN 1-886684-04-9) (Hoogenboom G, Wilkens PW and Tsuji GY, eds.). University of Hawaii, Honolulu, USA. pp. 1-36.

ICRISAT. 2002. Medium-term plan: 1994-98, Volume 1, Main Report, Patancheru, AP, India: ICRISAT. Pages 80.

Jones JW, Tsuji GY, Hoogenboom G, Hunt LA, Thornton PK, Wilkens PW, Imamura DT, Bowen WT and **Singh U.** 1998. Decision Support System for Agrotechnology Transfer DSSAT v3.

Kerr JM. 1996. Sustainable development of rainfed agriculture in India. Environment and Production Technology Division (EPTD) Discussion Paper No. 20, IFPRI, Washington DC, USA. 177 pp.

Lal S, Deshpande SB and **Sehgal J** (Eds.)**.** 1994. Soil Series of India. Soils Bulletin 40. Nagpur, India: National Bureau of Soil Survey and Land Use Planning. Pp. 684.

Rosegrant M, Cai X, Cline S and **Nakagawa N.** 2002. The role of rainfed agriculture in the future of global production. Environment and Production Technology Division (EPTD) Discussion Paper No.90, IFPRI, Washington DC, USA. Pp. 105.

Sehgal JL, Mandal DK, Mandal C and **Vadivelu S.** 1995. Agroecological subregions of India. Technical Bulletin, NBSS Publication No. 43, Nagpur, India: National Bureau of Soil Survey and Land Use Planning. Pp. 35.

Umakanth AV and **Seetharama N.** 2003. Importance of economically significant constraints for *Kharif* Sorghum in different regions of India. International Sorghum and Millets Newsletter. 44: 8-11.

Virmani SM and **Alagarswamy G.** 1993. Characterizing the yield gap of sorghum for peninsular India. Annual report 1992, Resource Management Program, ICRISAT Center. pp. 13-17.

Annexures

Annexure I. Simulated rainfed biomass and grain yields of rainy season (*kharif*) sorghum in different production zones of India.

				Total biomass (kg ha^{-1})				Grain yield (kg ha^{-1})			
Station	State	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone											
Akola	Maharashtra	Jambha	26	11540	14	6590	14540	3650	14	2280	4600
Akola	Maharashtra	Annapur	26	11670	12	8000	14300	3560	19	1540	4590
Akola	Maharashtra	Otur	26	11190	15	6530	14420	3420	20	1730	4520
Akola	Maharashtra	Umbraj	26	10900	17	5640	14400	3320	21	1940	4510
Amravati	Maharashtra	Jambha	18	10890	26	3470	15550	3610	25	1240	5250
Dharwad	Karnataka	Achmatti	18	9890	23	1630	12430	3450	23	580	4420
Dharwad	Karnataka	Huguluru	18	10600	8	9500	12620	3670	9	3240	4530
Jalgaon	Maharashtra	Jambha	23	9890	31	2590	13160	3230	29	870	4210
Parbhani	Maharashtra	Jambha	26	7380	22	3890	10520	2510	22	1410	3770
Parbhani	Maharashtra	Otur	26	8000	18	5340	10860	2680	17	1850	3850
Parbhani	Maharashtra	Annapur	26	8520	12	6660	10950	2810	13	2140	3870
Parbhani	Maharashtra	Umbraj	26	7770	19	4710	10740	2610	19	1700	3820
Rajgarh	Madhya Pradesh	Jamra	24	10360	30	590	13430	3210	30	160	4290
Mean	–	–	–	9892	–	–	–	3210	–	–	–
Secondary Zone											
Jodhpur	Rajasthan	Chirai	26	5240	41	100	9070	1570	46	0	2830
Dhar	Madhya Pradesh	Sarol	22	13550	21	3350	16220	4430	23	1260	5340
Kota	Rajasthan	Chambal	35	7930	51	80	15160	2440	53	0	4880
Shajapur	Madhya Pradesh	Sarol	23	9910	31	2070	14140	3230	29	650	4500
Shajapur	Madhya Pradesh	Saunther	23	10240	28	1300	13860	3210	31	420	4470
Aurangabad	Maharashtra	Otur	27	11740	23	6250	14800	3840	28	870	5040
Belgaum	Karnataka	Achmatti	16	10310	33	2190	13820	3510	33	770	4900
Belgaum	Karnataka	Huguluru	16	11720	17	7220	14300	3910	17	2470	5070
Guna	Madhya Pradesh	Saunther	19	8880	30	4880	13710	2910	27	1710	4300
Guna	Madhya Pradesh	Jamra	18	12500	19	5490	14790	4000	24	1600	4910
Nagpur	Maharashtra	Linga	26	9260	28	3830	12420	3030	25	1390	3960
Wardha	Maharashtra	Sukali	16	12410	16	7790	15290	4010	18	2500	5330
Betul	Madhya Pradesh	Jambha	20	12240	11	8830	14430	4040	14	3110	5180
Mean	–	–	–	10456	–	–	–	3395	–	–	–

Annexure I. *Continued*

				Total biomass (kg ha^{-1})				Grain yield (kg ha^{-1})			
Station	State	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Tertiary Zone											
Indore	Madhya Pradesh	Sarol	27	11780	21	4210	14130	3780	20	1550	4470
Ujjain	Madhya Pradesh	Sarol	26	11770	23	1660	14120	3790	22	580	4650
Rahuri	Maharashtra	Annapur	17	8160	26	3540	11230	2520	38	960	3750
Sholapur	Maharashtra	Barsi	19	9750	39	2660	13710	3130	41	570	4530
Sholapur	Maharashtra	Otur	19	9120	47	340	13710	2910	49	30	4530
Sholapur	Maharashtra	Umbraj	19	8660	47	660	13580	2730	50	190	4330
Pune	Maharashtra	Otur	15	13120	14	7310	14560	4380	16	2050	4870
Bhopal	Madhya Pradesh	Jamra	33	12230	8	10200	13930	3870	11	2600	4450
Bhopal	Madhya Pradesh	Saunther	33	11390	15	6910	13680	3520	22	1120	4420
Mean	–	–	–	10664	–	–	–	3403	–	–	–
Others											
Kannod	Madhya Pradesh	Sarol	19	10450	32	1810	14660	3340	30	500	4870

Annexure II. Simulated rainfed biomass and grain yields of postrainy season (*Rabi*) sorghum in different production zones of India.

				Total biomass (kg ha^{-1})				Grain yield (kg ha^{-1})			
Station	State	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone											
Rahuri	Maharashtra	Annapur	18	4490	29	2240	7330	1180	46	360	2670
Sholapur	Maharashtra	Barsi	19	6170	51	1460	11790	1850	58	350	4070
Sholapur	Maharashtra	Otur	19	4320	42	1030	9050	1200	49	160	2980
Sholapur	Maharashtra	Umbraj	19	3740	44	1110	8430	1010	48	210	2550
Mean	–	–	–	4680	–	1460	9150	1310	–	270	3070
Secondary Zone											
Aurangabad	Maharashtra	Otur	26	1270	56	210	3490	1270	56	210	3490
Belgaum	Karnataka	Achmatti	15	3180	35	1100	5140	1000	35	390	1590
Belgaum	Karnataka	Huguluru	15	7560	16	5960	9920	2150	23	1480	2800
Dharwad	Karnataka	Achmatti	18	4860	30	2610	8020	1530	27	1080	2500
Dharwad	Karnataka	Huguluru	18	6560	21	4670	9450	1890	27	1050	3200
Parbhani	Maharashtra	Jambha	26	2930	43	380	5760	930	42	30	2010
Parbhani	Maharashtra	Otur	26	3850	23	2080	5520	1220	24	780	1830
Parbhani	Maharashtra	Annapur	26	4480	17	3160	6270	1260	31	810	2380
Parbhani	Maharashtra	Umbraj	26	3310	24	1650	5060	1010	25	590	1520
Mean	–	–	–	4220	–	2420	6510	1360	–	710	2370
Tertiary Zone											
Wardha	Maharashtra	Sukali	16	7280	18	5880	10110	2050	31	1280	3330
Akola	Maharashtra	Jambha	26	2640	41	280	3950	810	42	20	1500
Akola	Maharashtra	Annapur	26	4340	22	3000	6680	1120	42	740	2610
Akola	Maharashtra	Otur	26	3570	27	1410	5410	1090	32	450	2270
Jalgaon	Maharashtra	Jambha	23	1460	54	210	2650	510	61	10	970
Jalgaon	Maharashtra	Linga	23	1330	55	200	2510	450	62	10	870
Mean	–	–	–	3440	–	1830	5220	1000	–	410	1930
Others											
Amravati	Maharashtra	Jambha	18	2590	55	900	6530	850	53	320	1960

Annexure III. Simulated rainfed biomass and grain yields of pearl millet in different production zones of India

				Total biomass (kg ha^{-1})				Grain yield (kg ha^{-1})			
Station	State	Soil series	No. of years	Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Primary Zone											
Rahuri	Maharashtra	Annapur	17	5640	28	2910	8560	1490	41	540	2860
Jodhpur	Rajasthan	Chirai	26	3910	35	0	6170	950	45	0	1650
Jaipur	Rajasthan	Chomu	9	7530	45	2160	11950	1850	57	450	3160
Mean	–	–	–	5693	–	–	–	1430	–	–	–
Secondary Zone											
Pune	Maharashtra	Otur	15	10430	13	7930	12130	3320	24	1300	4100
Gulbarga	Karnataka	Hungund	20	4120	49	1060	7990	1110	59	110	2620
Gulbarga	Karnataka	Huguluru	22	5260	25	3030	8280	1520	33	740	2610
Bijapur	Karnataka	Hungund	12	3430	60	750	7420	710	59	130	1370
Jalgaon 1	Maharashtra	Jambha	23	7830	40	1780	12320	2110	51	400	3770
Jalgaon 2	Maharashtra	Linga	23	7500	43	1160	11910	1990	54	280	3700
Aurangabad	Maharashtra	Otur	27	10190	34	3190	18140	2970	44	440	5920
Mean	–	–	–	6966	–	–	–	1961	–	–	–
Tertiary Zone											
Akola	Maharashtra	Jambha	26	8850	32	2310	15330	2410	39	470	4770
Akola	Maharashtra	Annapur	26	10390	23	3760	15460	2900	32	730	4850
Akola	Maharashtra	Otur	26	9040	31	2470	15380	2370	42	490	4790
Akola	Maharashtra	Umbraj	26	8530	33	2250	15150	2180	45	440	4690
Amravati	Maharashtra	Jambha	18	8670	41	2570	17640	2510	45	730	5270
Belgaum	Karnataka	Achmatti	16	7840	36	2770	12300	2300	37	710	3670
Belgaum	Karnataka	Huguluru	16	9720	24	5520	14750	2920	26	1540	4530
Dharwad	Karnataka	Achmatti	18	8550	30	2510	12700	3040	32	780	4700
Dharwad	Karnataka	Huguluru	18	9850	17	7000	13080	3560	19	2510	4990
Kota	Rajasthan	Chambal	35	6430	64	570	15860	1590	69	140	4720
Parbhani	Maharashtra	Jambha	26	4460	42	1890	9550	1320	55	480	3370
Parbhani	Maharashtra	Otur	26	4850	36	2150	9470	1460	44	530	3190
Parbhani	Maharashtra	Annapur	26	5360	31	3410	9890	1620	41	930	3510

Annexure III. *Continued*

Station	State	Soil series	No. of years	Total biomass (kg ha^{-1})				Grain yield (kg ha^{-1})			
				Mean	CV (%)	Min	Max	Mean	CV (%)	Min	Max
Parbhani	Maharashtra	Umbraj	26	4690	38	2130	9650	1400	51	520	3390
Sholapur	Maharashtra	Barsi	19	5210	58	560	9690	1260	67	140	2590
Sholapur	Maharashtra	Otur	19	5800	53	1030	10710	1390	63	140	2890
Sholapur	Maharashtra	Umbraj	19	5270	55	850	9910	1230	64	110	2630
Mean	–	–	–	7265	–	–	–	2086	–	–	–
Others											
Rajgarh	Madhya Pradesh	Jamra	24	8420	38	1100	12500	2290	44	290	3720
Indore	Madhya Pradesh	Sarol	27	9180	35	1480	14910	2710	39	460	4780
Guna	Madhya Pradesh	Saunther	18	7460	44	450	11420	2200	49	130	3570
Guna	Madhya Pradesh	Jamra	19	10070	30	2850	12990	2920	33	740	4130
Mean	–	–	–	8783	–	–	–	2530	–	–	–

Annexure IV. Experimental station, FLD and district yields (kg ha^{-1}) of *kharif* sorghum.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Primary Zone													
Akola, Maharashtra	**Lat. 19.33°N**	**Long. 74.01°E**											
Experimental	2219	3414	3705	3080	3122	4310	–	2886	3841	–	5648	3598	–
FLD	–	–	–	–	–	2100	–	2100	2200	–	1600	–	–
District	1612	994	2104	1707	1471	1770	2160	1495	1470	–	1655	1421	1955
Buldana, Maharashtra	**Lat. 20.32°N**	**Long. 76.11°E**											
Experimental	3141	2837	4434	3341	4403	3168	–	3572	3581	–	3988	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1998	729	2598	1509	1975	1473	2508	1203	1779	–	1509	1320	1585
Parbhani, Maharashtra	**Lat. 19.16°N**	**Long. 76.46°E**											
Experimental	2169	3835	4842	4055	4126	3259	–	3324	1624	–	1845	–	–
FLD	–	–	–	–	–	2900	–	1800	700	1050	830	–	–
District	1105	741	1884	1403	1389	1439	1620	1399	1115	–	1250	1292	1440
Yavatmal, Maharashtra	**Lat. 20.23°N**	**Long. 78.08°E**											
Experimental	3371	6012	3133	3359	2600	3604	–	1625	1231	–	4206	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1553	1324	1633	1177	988	1012	1652	720	1427	–	1102	1094	1181
Jalgaon, Maharashtra	**Lat. 21.03°N**	**Long. 75.34°E**											
Experimental	–	4303	5074	5060	3903	2384	–	3778	2609	–	3341	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1594	1229	2190	1885	1953	1717	2213	2025	2032	–	1176	1499	2115
Dharwad, Karnataka	**Lat. 15.27°N**	**Long. 75.00°E**											
Experimental	–	4445	6863	5279	4525	6219	–	5905	6562	–	5458	–	–
FLD	–	–	–	–	–	–	–	–	2400	2100	3260	–	–
District	859	1321	1029	1273	1303	1421	1776	–	–	–	1105	568	795
Palem, (Mahabubnagar), Andhra Pradesh			**Lat. 16.73°N**		**Long. 77.98°E**								
Experimental	–	2179	3172	2877	3688	3973	–	3086	3525	–	3610	-	-
FLD	–	–	–	–	–	–	–	700	–	1700	1200	-	-
District	731	331	627	585	669	741	629	608	600	–	760	709	917

Annexure IV. *Continued*

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Secondary Zone													
Aurangabad, Maharashtra Lat. 19.92°N Long. 75.33°E													
Experimental	1549	3995	–	2001	2890	2059	–	1422	2261	–	1754	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1118	674	1629	1396	1265	1069	1801	1125	1344	–	897	1062	1410
Dhule, Maharashtra Lat. 20.90°N Long. 74.78°E													
Experimental	–	1271	4373	–	4684	2016	–	3205	3482	–	–	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	–	–	–	–	–	1037	1492	1253	1630	–	523	1398	1113
Adilabad, Andhra Pradesh Lat. 19.67°N Long. 78.53°E													
Experimental	–	3737	5268	3936	3752	2386	–	2730	3618	–	4514	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	603	344	1207	1317	945	731	1097	552	1200	–	1599	1675	1538
Bailhonga (Belgaum), Karnataka Lat. 15.82°N Long. 74.87°E													
Experimental	–	5101	1725	3972	2338	–	–	3352	4855	–	3218	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1125	1312	1324	1442	1356	1159	1540	–	–	–	1305	1205	1370
Surat, Gujarat Lat. 21.12°N Long. 72.50°E													
Experimental	–	4850	3801	3746	3992	4124	–	3357	3834	–	3392	–	–
FLD	–	–	–	–	–	–	2100	2100	2600	1600	980	–	–
District	1473	546	1218	1507	–	–	1362	1562	1416	–	1150	1101	1597
Karad (Satara), Maharashtra Lat. 17.17°N Long. 74.11°E													
Experimental	4857	1718	3041	3682	1767	6591	–	4515	5906	–	4634	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1530	1476	1672	1471	1101	1843	1750	1426	1829	–	1756	1528	1615
Tertiary Zone													
Gandhinglaj (Kolhapur), Maharashtra Lat. 16.13°N Long. 74.21°E													
Experimental	–	2176	6073	3862	880	3852	–	2987	4114	–	3254	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	2404	1538	2602	2052	1816	2591	2251	1438	2133	–	1581	2066	1824

Annexure IV. *Continued*

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Somnath (Chandrapur), Maharashtra			**Lat. 19.95°N**		**Long. 79.28°E**								
Experimental	3071	4740	6326	4776	4069	3668	–	4286	2259	–	2408	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	611	611	846	1116	802	664	1378	636	935	–	1751	1099	1158
Indore, Madhya Pradesh			**Lat. 22.43°N**		**Long. 75.48°E**								
Experimental	–	4470	3039	3042	2106	3278	–	2039	4420	–	3917	–	–
FLD	–	–	–	–	–	–	–	–	2300	2200	1850	–	–
District	1151	1051	1154	1081	852	1217	1200	1176	1143	–	1400	909	1118
Deesa (Banaskantha), Gujarat			**Lat. 24.25°N**		**Long. 72.17°E**								
Experimental	–	3988	2049	4835	3318	2571	–	1864	4112	–	2826	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	398	219	408	251	–	–	530	22	184	–	153	749	219
Kanpur, Uttar Pradesh			**Lat. 26.26°N**		**Long. 80.22°E**								
Experimental	–	2588	2672	2004	2398	2787	–	1720	–	–	1809	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	1333	1515	1654	1545	1180	1353	1144	1285	895	–	1291	1057	1376
Navsari, Gujarat		**Lat. 20.85°N**		**Long. 72.92°E**									
Experimental	–	3564	3501	3023	3863	3482	–	2514	3718		3496	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	–	–	–	–	–	–	864	783	960	–	1000	1000	1000
Udaipur, Rajasthan			**Lat. 24.35°N**	**Long. 73.42°E**									
Experimental	–	3083	2478	1518	4234	3688	–	4227	4312	–	2519	–	–
FLD	–	–	–	–	–	–	2140	1800	1400	1100	1390	–	–
District	611	142	591	197	480	–	557	656	–	–	170	610	528

Annexure V. Experimental station, FLD and district yields (kg ha^{-1}) of *rabi* sorghum.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Primary Zone													
Sholapur, Maharashtra		**Lat. 17.40°N**		**Long. 75.54°E**									
Experimental	1197	813	–	–	867	–	–	1141	687	–	2674	–	–
FLD	–	–	–	–	–	–	–	–	–	2100	1170	–	–
District	534	313	425	577	327	651	632	216	467	–	448	440	335
Bijapur, Karnataka		**Lat. 16.67°N**		**Long. 75.92°E**									
Experimental	4419	2493	1751	2161	2370	1938	–	1365	1002	–	1486	–	–
FLD	–	–	–	–	–	–	–	–	–	–	1225	1900	–
District	388	457	593	707	565	684	789	–	–	–	657	740	671
Rahuri (Ahmednagar), Maharashtra			**Lat. 19.38°N**		**Long. 74.65°E**								
Experimental	2669	3107	1645	3578	2445	2250	–	1441	1518	–	1795	–	–
FLD	–	–	–	–	–	–	–	1500	1010	1206	1270	–	–
District	505	267	418	442	334	469	537	363	503	–	310	331	237
Gulbarga, Karnataka		**Lat. 17.21°N**		**Long. 76.51°E**									
Experimental	2684	2426	3183	2168	2657	2101	–	1946	1838	–	2264	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	394	413	832	852	661	778	612	–	–	–	712	756	776
Secondary Zone													
Karad (Satara), Maharashtra			**Lat. 17.17°N**		**Long. 74.11°E**								
Experimental	3342	2843	2337	2616	3643	2608	–	1638	2684	–	–	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	838	721	588	764	699	714	847	604	1021	–	510	642	434
Parbhani, Maharashtra		**Lat. 19.16°N**		**Long. 76.46°E**									
Experimental	1695	–	1792	2326	1739	934	–	981	1525	–	–	–	–
FLD	–	–	–	–	–	–	–	–	1213	–	1360	–	–
District	661	643	670	854	802	768	789	339	486	–	705	827	764

Annexure V. *Continued*

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Dharwad, Karnataka Lat. 15.27°N Long. 75.00°E													
Experimental	977	2621	2232	2405	2612	3324	–	1353	3355	–	4135	–	–
FLD	–	–	–	–	–	–	–	–	–	–	1400	–	–
District	276	560	546	939	559	668	835	–	–	–	670	327	325
Annigeri (Dharwad), Karnataka Lat. 15.43°N Long. 75.43°E													
Experimental	–	–	1219	2421	2108	1027	–	604	891	–	4716	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	276	560	546	939	559	668	835	–	–	–	670	327	325
Nandyal (Kurnool), Andhra Pradesh Lat. 15.30°N Long. 78.30°E													
Experimental	2504	4828	2925	2672	1877	1462	–	1865	3111	–	–	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	971	1104	1293	1055	746	921	839	945	1068	–	1221	1526	1337
Tertiary Zone													
Hagari (Belgaum), Karnataka Lat. 15.15°N Long. 77.08°E													
Experimental	–	2340	2395	2093	–	2791	–	3996	3154	–	1553	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	656	617	844	899	671	819	1037	–	–	–	862	1212	578
Madhira (Khammam), Andhra Pradesh Lat. 16.92°N Long. 80.37°E													
Experimental	3462	2968	3677	3698	2350	3815	–	2844	–	–	–	–	–
FLD	–	–	–	–	–	–	–	–	–	–	–	–	–
District	523	648	625	674	567	538	522	727	636	–	595	687	625

Annexure VI. Experimental station, FLD, district and simulated yields of pearl millet.

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Primary Zone													
Mandore, Rajasthan		**Lat. 26.35°N**	**Long. 73.03°E**										
Station	1739	–	1289	–	1559	585	1545	1783	–	–	–	1273	–
District	387	–	480	–	534	–	368	389	–	–	–	–	–
Jaipur, Rajasthan		**Lat. 26.5°N**		**Long. 75.5°E**									
Station	1306	–	–	1798	2722	–	1458	791	1639	–	742	862	698
FLD	–	–	–	–	–	–	–	–	2077	–	1693	1656	–
District	801	–	–	556	916	–	678	809	1110	–	–	–	–
Simulated					1469	2361	3090	1353	439	1321	3156	529	
Rahuri, Maharashtra		**Lat. 19.38°N**	**Long. 74.65°E**										
Station	2662	4303	–	2716	2815	1380	1794	2015	702	–	–	2114	–
District	429	607	–	618	369	522	790	558	808	–	–	–	–
Simulated	2092	1065	1671	1874	1681	1000	–	–	–	–	–	–	–
Secondary Zone													
Aurangabad, Maharashtra			**Lat. 19.92°N**		**Long. 75.33°E**								
Station	812	2916	–	2461	2601	2040	2222	3297	2467	–	2894	1923	2034
FLD	–	–	–	–	–	–	–	–	–	–	880	992	–
District	621	406	–	1005	603	634	1158	786	854	–	746	631	–
*-Simulated from 1956 to 1982													
Anand, Gujarat		**Lat. 22.33°N**		**Long. 72.58°E**									
Station	1796	2384	2252	3982	761	3029	2672	2603	–	–	4022	3710	4006
District	1216	1217	1872	1336	1093	–	1466	1562	–	–	1255	1542	–
Kothara, Gujarat		**Lat. 23.13°N**		**Long. 68.93°E**									
Station	–	1493	–	1342	534	117	2467	–	–	190	3061	402	–
District	–	1123	–	991	–	407	1178	–	–	444	809	–	–
Hissar, Haryana			**Lat. 29.09°N**	**Long. 75.44°E**									
Station	2373	3160	1491	2050	3109	1112	–	2051	2006	–	1891	2547	3494
FLD	–	–	–	–	–	–	–	–	2419	–	2892	2235	–
District	830	560	1174	607	1266	–	–	1137	1385	–	1595	1504	–

Annexure VI. *Continued*

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Bijapur, Karnataka			**Lat. 16.67°N**		**Long. 75.92°E**								
Station	783	1195	940	2315	1529	1571	–	–	2071	–	2990	2543	3012
FLD	–	–	–	–	–	–	–	–	1935	–	1050	1100	
District	519	524	575	710	398	689	–	–	659	–	–	–	–
Simulated	518	604	126	505	261	–	–	–	–	–	–	–	–
Tertiary Zone													
Buldhana, Maharashtra			**Lat. 20.32°N**		**Long.76.11°E**								
Station	2072	–	2865	–	1794	2237	2879	2403	1447	–	2140	2223	2191
District	602	–	619	–	703	744	757	444	500	–	620	448	–
Jamnagar, Gujarat		**Lat. 22.47°N**		**Long. 70.07°E**									
Station	1836	2481	1143	–	1476	1951	2715	2979	825	–	2814	2858	1828
District	261	388	1031	–	1104	–	1004	1274	689	–	741	1164	–
Palem, Andhra Pradesh			**Lat. 16.73°N**		**Long. 77.98°E**								
Station	3678	2110	2041	2375	2824	3281	2251	–	–	–	2332	3078	3269
District	501	249	271	357	364	583	571	–	–	–	611	–	–
Anantapur, Andhra Pradesh					**Lat. 14.41°N**	**Long. 77.37°E**							
Station	1938	2059	1843	2648	2904	–	1261	1151	2119	–	1671	2261	1252
District	376	353	638	400	333	–	667	1000	667	–	500	–	–
Gwalior, Madhya Pradesh			**Lat. 26.0°N**	**Long. 78.0°E**									
Station	1697	3139	3288	2995	4067	3244	3818	4451	3942	–	2945	3539	3718
District	1206	1253	1729	1231	1462	1857	1471	1667	2000	–	–	–	–
Others													
Coimbatore, Tamil Nadu			Lat. 11.0°N	Long. 76.0°E									
Station	3265	4177	1185	4551	3600	3953	2560	4215	4651	–	3559	3283	2794
District	927	866	1078	1500	1315	1193	1095	1514	–	–	–	–	–
Mahuva, Gujarat				**Lat. 21.08°N**	**Long. 71.8°E**								
Station	1159	1464	4024	2806	1779	3022	–	3089	2531	–	2554	3226	2317
District	750	429	1176	385	1000	–	–	1000	–	–	–	–	–

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