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Report no. 43

Quantification of Yield Gaps in Rain-fed Rice, Wheat, Cotton and Mustard in India

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Abstract

In order to meet increasing demands of food due to rising population and income, food production in India and other south Asian countries need to be increased. Rain-fed agriculture in India, practiced on 94 million hectares (M ha), is considered a major source of production increase in future. This report analyses the magnitude of rain-fed potential yield gaps of rice, wheat, mustard and cotton crops, considering the spatial and temporal variation in climatic features. These yields can be interpreted as the upper limit that can be achieved by the current varieties in a rain-fed scenario with soil and weather as the only yield reducing factors. InfoCrop, a generic dynamic crop simulation model with sensitivity to variety, agronomic management, soil, weather, flooding, frost and pests and calibrated and validated in typical rain-fed and irrigated cultivating areas of these crops was used for quantification of rain-fed potential yields in different regions. Yields in technology maximization experiments (Plant Breeder's fields) and on-farm technology demonstration plots (Front-line demonstrations) have also been used as additional measures of potential yield. Yield gaps were calculated as the difference between these yield levels and the region's average measured yields. The results showed that irrespective of the definition of potential yield, there was considerable yield gap across all states in all crops indicating large scope for increasing rain-fed yields in future. On an average, the gap relative to simulated rain-fed potential yields was 2560 kg ha^{-1} for rice, 1120 kg ha^{-1} for cotton and 860 kg ha^{-1} for mustard. Such national average rain-fed yield gaps could not be estimated in wheat because of large percent of irrigated area in all states. The mean yield gap based on the average of simulated, experimental and on-farm rain-fed potential yields was 1670 kg ha^{-1} for rice, 770 kg ha^{-1} for cotton, 460 kg ha^{-1} for mustard and 70 kg ha^{-1} for wheat. It remains to be quantified if these biophysical estimates of yield gaps can be bridged economically.

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COMPREHENSIVE Assessment of water management in agriculture

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Contents

Executive Summary

In order to meet increasing demands of food due to increasing population and income, food production in India and other South Asian countries need to be increased. However, lately there has been a significant slow-down in the growth rate in the cultivated area, production and yield. Potential yields in experimental areas are also stagnating. It is, therefore, important to secure the past yield gains and further increase the potential yield of major food crops. It is also very important to know how much additional food can be produced in different regions to meet the increasing demand. In view of such stagnations, we need to know if the genetic yield ceiling have been reached for critical crops or are there some other factors that are not allowing yields to increase. Estimates of these potentials can assist in quantifying the carrying capacity of agro-ecosystems.

Rain-fed agriculture in India is practiced on 94 million hectares (M ha). These regions have low grain yields and are, therefore, considered to have great potential for increasing production in future. The main objective of this analysis is, therefore, to estimate the rain-fed potential yields of rice, wheat, mustard and cotton crops in different regions, considering the spatial and temporal variation in climatic features and available agricultural technology. These yields can be interpreted as the upper limit that can be achieved by the current varieties in a rain-fed scenario with soil and weather as the only yield reducing factors. In this analysis, we have used InfoCrop, a generic dynamic crop simulation model with sensitivity to variety, agronomic management, soil, weather, flooding, frost and pests, for quantification of rain-fed potential yields in different regions. The model has been calibrated and validated in typical rain-fed and irrigated areas' cultivating crops considered in this analysis. Yields in technology maximization experiments (plant breeder's fields) and on-farm technology demonstration plots (frontline demonstrations) have also been used as additional measures of potential yield. Yield gaps have been quantified by comparing these yield levels with the region's average yield. The difference between potential rain-fed yields and measured regional yields is considered as the biophysical yield gap.

In rice, the results showed that irrespective of the definition of potential yield, there is considerable yield gap across all states, indicating a large scope for increasing rain-fed yields in future. On an average, the yield gap relative to simulated rain-fed potential was close to 2500 kg ha^{-1}. The all India mean gap for rain-fed rice was at least 1670 kg ha^{-1}. Overall, the gaps were generally smaller in West Bengal and it was the highest in Uttar Pradesh.

In cotton, the mean yield gap between simulated rain-fed potential yield and state average yield was 1120 kg ha^{-1}. This yield gap at the experimental station level was only 640 kg ha^{-1}. At the on-farm level, the gap was somewhat similar to that of the experimental stations. In the main rain-fed cotton producing states, there is sufficient gap that can possibly be bridged by improved management in future. To summarize, yield gap is high in Gujarat and Maharashtra, modest in Andhra Pradesh and relatively low in Karnataka and Madhya Pradesh.

The results showed that in mustard the gaps between simulated rain-fed potential yield and the state average yield was 860 kg ha^{-1}. Uttar Pradesh and West Bengal having large mustard cultivation showed considerable yield gap due to their large simulated rain-fed potential yields. The gap was, however, generally small at the experimental station level as well as on-farm.

In wheat, since the measured yields were significantly large due to confounding effect of irrigation, the calculated yield gaps were either nil or rather small. Karnataka, West Bengal and Madhya Pradesh showed a gap of 80 kg ha^{-1} to 800 kg ha^{-1} at different scales.

These studies have shown that there are still considerable yield gaps in rain-fed crops that can be bridged in future to meet the increasing food requirements. In all the crops, these gaps would be larger than our calculations if the yield data from irrigated areas could be separated from the measured state data.

1. Introduction

The production of food grains in India increased considerably since 1960s due to increase in arable area, large-scale cultivation of high yielding semi-dwarf varieties and increased applications of irrigation, fertilizers and pesticides. India became food secure in the last three decades, at gross level, because of increase in food production. The food security of India and other countries in South Asia is, however, now at risk due to increase in population. By 2050, India's population is expected to grow to 1.6 billion people from the current level of 1.1 billion. This implies a greater demand for food. Although, the world as a whole may have sufficient food for everyone, it would need to be produced in the region itself due to socio-economic and political compulsions (Rabbinge 1999). The cereal requirement of India by 2020 will be between 257 and 296 million tons (Mt) depending on income growth (Kumar 1998; Bhalla et al. 1999). The demand for rice and wheat is expected to increase to 122 and 103 Mt, respectively, by 2020 assuming a medium income growth (Kumar 1998). This will have to be produced from the same or even shrinking land resource. Thus, by 2020 the average yields of rice and wheat need to be increased by about 60%. Similar is the scenario for many other crops.

Although, there is a pressure to increase production, lately, there has been a significant slow-down of the growth rate in the cultivated area, production and yield. The annual rate of growth of cereal production and yield showed a peak during the early years of the green revolution but since 1980s there has been a decline (Sinha et al. 1998). Adding to the worry of food planners, is the stagnant grain yields in experimental farms. The potential yield of rice in the tropics has not increased above 10 t ha^{-1} since IR 8 was released 30 years ago, despite making significant achievements in attaining yield stability, increasing per day productivity and improving grain quality (Aggarwal et al. 1996). In wheat, some studies have shown an increase in yield potential with time (Nagarajan 1998; Rajaram 1998). However, a review of data of the regional statistics, agronomists' experiments, long-term field trials, breeders' variety evaluation trials and simulation studies also showed stagnation of yields in rice and wheat in northern India (Aggarwal et al. 2000).

The gradual increase in environmental degradation through intensive cropping systems is further compounding the problem. There is now a great concern about decline in soil fertility, change in water table depth, rising salinity, resistance of harmful organisms to many pesticides and degradation of quality of irrigation water in north-western India (Sinha et al. 1998).

Thus, there is a tremendous challenge facing agricultural scientists to develop technologies to increase food production in the coming decades. There is an urgent need to increase the potential yield of major food crops. It is very important to know how much additional food can be produced in different regions to meet the increasing demand. In view of such stagnations, we need to know if the genetic yield ceiling has been reached for critical crops or if there are some other factors that are not allowing yields to increase. Estimates of these potentials can assist in quantifying the carrying capacity of agro-ecosystems.

Rain-fed agriculture in India is practiced on 94 million hectares (M ha). These areas generally have bypassed from the benefits of green revolution and as a result, grain yields remain low. These areas are considered to have vast untapped potential for increasing production in future by upgrading rain-fed agriculture (Rockstrom et al. 2007). For population rich and low-income rain-fed regions, it is important to know where and at what cost the additional food can be produced with current technology and/or what alternative technologies will be needed to meet the desired production targets. The main objective of this analysis is, therefore, to estimate the rain-fed potential yields of rice, wheat, mustard and cotton crops in different regions, considering the spatial and temporal variation in climatic features and available agricultural technology. These yields can be interpreted as the upper limit that can be achieved by the current varieties in a rain-fed scenario with soil and weather as the only yield reducing factors.

Determination of potential productivity of a crop requires thorough understanding of crop growth and development. The latter, in turn, are dependent upon several climatic, edaphic, hydrological, physiological and management factors. The major factors affecting crop growth and development are radiation, temperature (yield determining), water, nutrition (yield limiting) and pests and diseases (yield reducing). In addition, productivity is also determined by many other factors such as cultivar, its physiology and crop management that interact with weather and soils to influence yield level. In irrigated and well-managed crops, productivity is primarily determined by radiation and temperature whereas in rain-fed areas, precipitation and soil moisture storage are considered important. A large number of experiments have been done to understand these interactions and their results can be used to quantify potential yields. The results of such experiments conducted in different locations/experiments/seasons are, however, often confounded because of inadequate consideration of interactions with genotype, climatic factors and their variability, and agronomic management. Crop growth models by integrating the effects of different factors on yield provide a unique opportunity to supplement the results of field trials. Such models have been used in the past for identifying options related to technology generation, technology evaluation and technology extension and for understanding the reasons for adoption (or no adoption) of technology (Penning de Vries et al. 1993; Teng et al. 1992; Kropff et al. 1996). In this paper, we have used such a crop growth simulation model for quantification of rain-fed potential yields in different regions. Yields in technology maximization experiments (plant breeder's fields) and on-farm technology demonstration plots (frontline demonstrations) have also been used as additional measures to know potential yield. Yield gaps have been quantified by comparing these yield levels with the region's average yield.

2. Materials and Methods

2.1 Potential rain-fed yields

There are several ways to estimate potential yields. Dynamic simulation models are very commonly used for this purpose (Penning de Vries et al. 1993; Aggarwal et al. 1995, Bhatia et al. 2006, Murty et al. 2007). In addition, there are several experimental approaches that can also provide knowledge about the genetic potential of varieties. Plant breeders typically do their experiments in small plots in ideal conditions of management and pest control to find the best genotype. The selected varieties are further assessed for their performance in large plots in farmer's fields (frontline demonstrations). These trials are used for technology demonstration to farmers. In general, it is expected that simulated potential yields will be the highest since there is total control of yield regulating factors. Plant breeder's trials come close to these simulated yields but are often lower due to some location-specific yield regulating factors. In front-line demonstrations done in farmer's fields, there are invariably some uncontrolled yield-reducing factors and hence these yields are generally lower than the other two methods. In our study, we have used simulated rain-fed potential yields, experimental potential yields (plant breeder's trials in rain-fed environment) as well as on-farm potential yields (frontline demonstrations in rain-fed environment) as the three different expressions of potential rain-fed yields.

2.2 Simulated rain-fed potential yields

InfoCrop model (Aggarwal et al. 2004) was used for simulating potential rain-fed yields. This is a generic dynamic crop simulation model with sensitivity to variety, agronomic management, soil, weather, flooding, frost and pests. The model simulates all major processes of crop growth, soil water and nutrient balances, greenhouse gases emission and crop-pest interactions. It is used to estimate potential yields and yield gaps, assess impact of climatic variability, optimize management - dates of planting, variety, irrigation and nitrogen fertilizer, assessing interactions among genotype, environment, management and pests, yield forecast, yield loss assessment due to pests and greenhouse gases emission. The model has been calibrated and validated in typical rain-fed and irrigated areas' cultivating crops considered in this analysis (data not shown, for details refer to Aggarwal et al. 2006; Hebbar et al. 2004).

Several representative locations in different states for which weather data was available and which have reasonable cultivation of rain-fed crops were selected. Care was taken to select stations from different meteorological sub divisions in each state (Fig. 1). The required soil profile data for each of these locations was collected from the National Bureau of Soil Survey and Land Use Planning and other available reports. Simulations were done using the weather data for 10 to 20 years of each location. Standard sowing dates, varieties and other management practices were considered in these simulations. The average of the yields of all years was used as the simulated rain-fed potential yield for a location. The simulated rain-fed potential yield for the state was the arithmetic mean of all locations in that state.

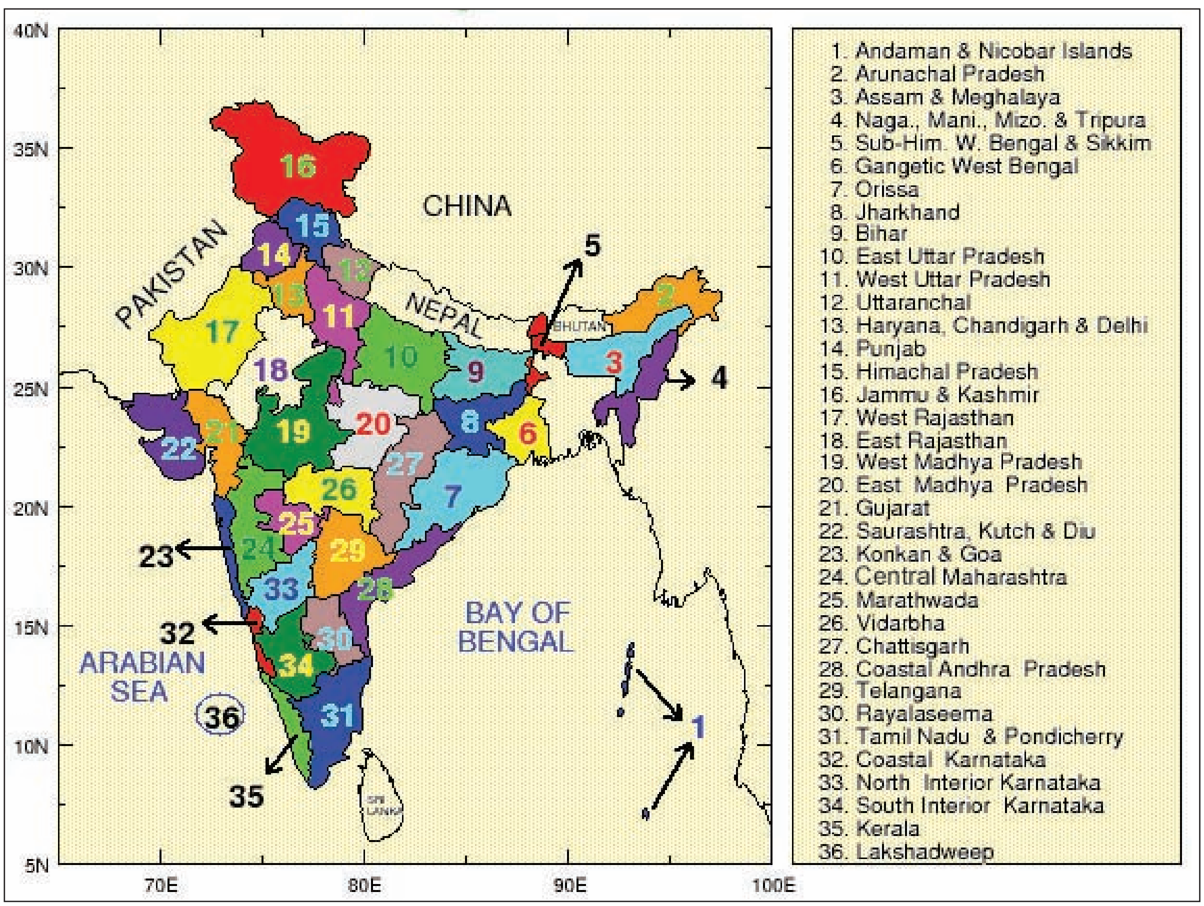

Figure 1. Meteorological subdivisions of India.

2.3 Experimental potential yields

The available data from several breeders' trials was collected from the recently published reports of the All India Coordinated Improvement Projects of the respective crops. Only those locations and trials were considered that were totally rain-fed. The values used in this paper are the averages of all such data, which include different seasons, varieties and locations within a state (note that individual varieties and locations may have higher values than the ones used in the present analysis).

2.4 On-farm potential yields

The on-farms yields were obtained from the frontline demonstrations data, available for different crops over the recent years. These yields are also average across different locations, seasons and varieties within the state. However, such data was available only for a few years and sites.

2.5 Measured yields

The cultivated area, production and yield of different crops were obtained from the published data of the Ministry of Agriculture, Government of India. These yields were considered as the measured yields to calculate yield gaps. It may be noted that state averages are the means of irrigated and rain-fed areas and hence rain-fed yields will be overestimated, especially in crops such as wheat where irrigated areas are large.

2.6 Yield gaps

The yield gaps were calculated from all three expressions of potential yields as follows:

1. Simulated rain-fed potential yield gap = simulated mean rain-fed potential yield – measured yield (state average).
2. Experimental yield gap = experimental potential yield (plant breeder's trials) – measured yield (state average).
3. On-farm yield gap = on-farm potential yields – measured yield (state average).

The average of these yield gaps was also calculated as the expression of overall gap.

2.7 Options to bridge yield gaps

There could be several approaches that can be used to bridge yield gaps. We have used simulation model to evaluate three major options for this purpose:

Supplementary irrigation: From the simulation results, the maximum simulated potential yield in any given year was noted for each location. These yields were generally of those years when rainfall was well distributed and adequate to meet crop water requirements. A comparison of these with the mean rain-fed potential yields indicates the gap that can be bridged by additional water availability.

Ensuring timely planting: Farmers of rain-fed areas have a problem in sowing seeds on time due to delay in onset of monsoon. Simulations were done for each location in which sowing date (transplanting date in case of rice) was determined by the onset of monsoon (implemented by ensuring sufficient moisture at planting). A comparison of the mean yields across different years of such simulations with the simulated mean rain-fed potential yields (this considers timely planting all the times) indicates the gap that can be bridged by ensuring timely planting. The latter is possible by providing irrigation at the sowing time.

Improved nitrogen management practices: Additional simulations were done for each location in which the nitrogen management was according to the current practices of farmers in the rain-fed areas. The difference of these yields with the simulated mean rain-fed potential yields (calculated with the assumption of no nitrogen stress at any given time) was considered to develop a strategy to bridge yield gap due to improved nitrogen management, including quantity and time of application.

In addition to nitrogen management, recent studies have shown existence of widespread deficiencies of micronutrients such as zinc and boron and secondary nutrients such as sulfur in 80-100% farmers' fields in rain-fed areas of different states in India (Rego et al. 2007; Sahrawat et al. 2007). Application of balanced nutrients (micro-and macro nutrients) in farmers' fields increased crop yields up to 100 per cent (Rego et al. 2007).

3. Results and Discussion

3.1 Rice

Current distribution and yields

Rice in India is grown almost throughout the country except in the arid eastern parts of Rajasthan (Fig. 2). It is grown in extremely diverse hydrological environments such as irrigated, rain-fed uplands, lowlands, as well as under deep-water conditions. Of the 44 million hectares (M ha) of harvested rice area, almost 54% is irrigated. Most of the rice producing areas of Punjab, Haryana, Andhra Pradesh and Tamil Nadu are irrigated (Table 1). Rain-fed rice is grown in several states such as West Bengal, Uttar Pradesh, Orissa, Bihar, Assam, Karnataka, Maharashtra, Madhya Pradesh and Jharkhand (Fig. 2).

The production of rice in India has increased from 20 million tons (M t) in 1950 to 93 M t in 2002. This has been due to an increase in area under rice in the first few decades and later due to increase in irrigation coverage as well as yield per hectare (Fig. 3). Today, West Bengal, Uttar Pradesh, Andhra Pradesh, Punjab and Orissa alone account for 60% of the total rice production and almost 50% of the total rice cultivated area in India (Table 1).

The average yield of rice is more than 3000 kg ha^{-1} in several districts of Punjab, Haryana, Andhra Pradesh and Tamil Nadu (Fig. 4). In some areas of these districts, yields have increased by 50-100% in the past two decades due to higher input use. Farmers in these states have much higher per capita income than the traditional rice-growing states of eastern India. The yields are generally less than 2000 kg ha^{-1} in central Indian states such as Madhya Pradesh and in eastern Indian states such as Orissa, Bihar and Jharkhand (Table 1 and Fig. 4). Since rice is mostly rain-fed in these states, the production is strongly dependent on distribution of rainfall. The transplanting is largely dependent upon the date of onset of monsoon. In some eastern states, erratic rainfall leads to drought during the vegetative period, but later on, the crop may be damaged by submergence due to high rainfall. Other constraints are soil acidity in southern and eastern India, salinity and alkalinity in northern India.

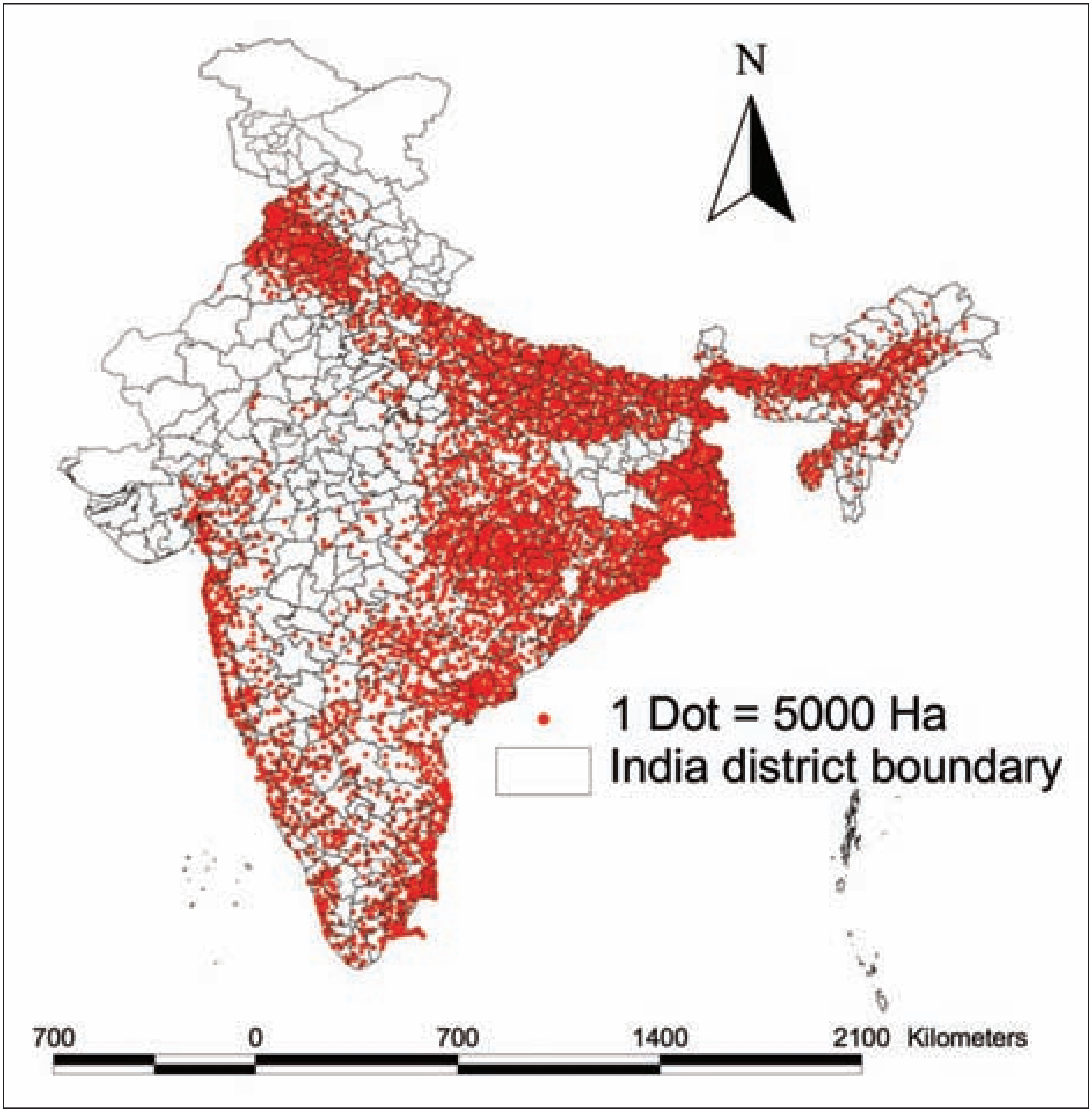

Figure 2. Distribution of rice area by district in India. Almost 80% of the rice in eastern India is rain-fed whereas the entire rice in northern India is irrigated.

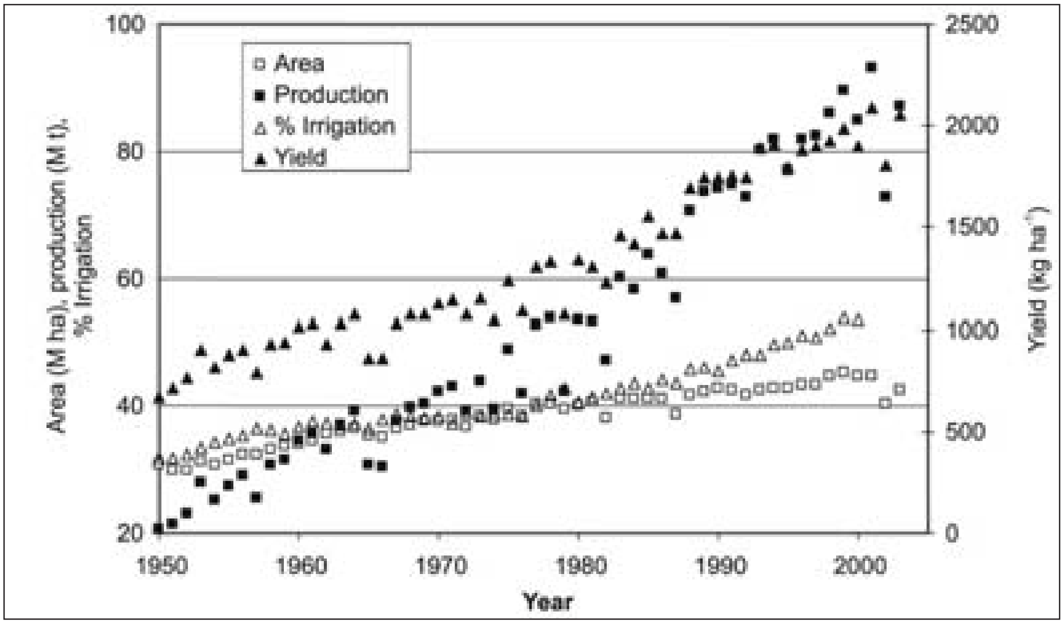

Figure 3. Change in area, production and yield of rice in India (average) with time.

Table 1. Area, production, yield and irrigation coverage for the rice producing states of India. All data except irrigation relates to the 2001-02 season.

States	Area (M ha)	Production (M t)	Yield (kg ha^{-1})	% coverage under irrigation during 1999-2000
West Bengal	6.07	15.26	2510	42
Uttar Pradesh	5.88	12.46	2120	66
Andhra Pradesh	3.83	11.39	2980	96
Punjab	2.49	8.82	3550	99
Orissa	4.5	7.15	1590	41
Tamil Nadu	2.11	6.87	3260	93
Bihar	3.57	5.28	1480	42
Chhatisgarh	3.73	5.13	1370	-
Assam	2.53	3.85	1520	8
Karnataka	1.42	3.17	2240	72
Haryana	1.03	2.72	2650	100
Maharashtra	1.51	2.65	1750	28
Madhya Pradesh	1.76	1.66	950	25
Jharkhand	1.48	1.64	1110	-
Gujarat	0.66	1.03	1550	65
Kerala	0.32	0.72	2220	60
Others	1.75	3.28	-	-
All India	44.62	93.08	2090	54

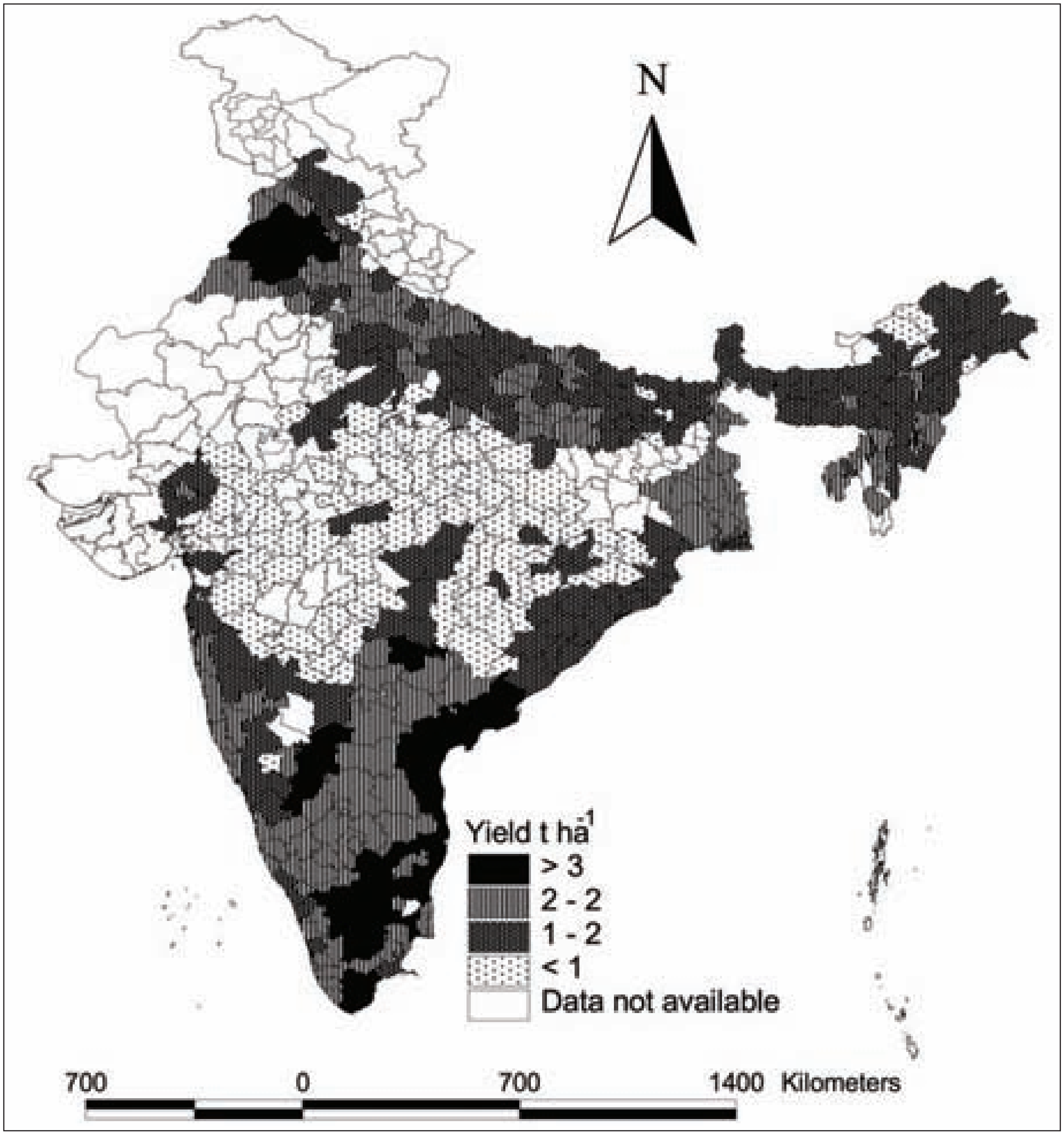

Figure 4. Variation in rice yields across districts of India.

Simulated rain-fed potential yields

The simulation results showed that the yield across different locations in major rain-fed states could vary considerably depending upon rainfall, soil and other location specific factors. At all locations, mean rain-fed potential yield appeared to be reasonably large. The mean yield across different years varied from a low of 2700 kg ha^{-1} in Indore and Nagpur to more than 5000 kg ha^{-1} at several locations in Bihar, Karnataka, Maharashtra, West Bengal and Uttar Pradesh (Table 2). The variance in yields ranged from 16 to 38% depending upon location. There was a small trend of variance being low in high rainfall areas but this relationship was not strong (Table 2).

In some years, the yield could go very low. For example, the minimum yield was less than 1500 kg ha^{-1} in Bangalore and several locations in Madhya Pradesh (Table 2). In fact, in some years, when the rainfall was low, delayed or erratic, crops failed altogether in many locations (data for individual years is not shown). The maximum yield across different locations varied from 4250 kg ha^{-1} in Indore to 7320 kg ha^{-1} in Bangalore. These yields were obtained when rainfall was good and well distributed.

Table 2. Simulated maximum, mean and minimum rain-fed yield for some important locations in rain-fed states. Also shown is the coefficient of variation (CV) of these yields and the mean rainfall during the crop season.

State	Location	Met sub division	Simulated rain-fed potential yield (kg ha^{-1}) Maximum	Mean	Minimum	CV (%)	Mean seasonal rainfall (mm)
Bihar	Patna	9	5660	3690	1480	36.5	650
Bihar	Sabour	9	6130	5620	2200	25.8	930
Karnataka	Bangalore	33	7320	5770	1380	28.3	670
Karnataka	Dharwad	32	4550	3250	2130	25.8	520
Madhya Pradesh	Indore	19	4250	2780	1060	37.5	870
Madhya Pradesh	Jabalpur	19	5290	3480	1250	25.6	1210
Madhya Pradesh	Jhabua	19	5600	4650	1930	25.9	740
Madhya Pradesh	Raipur	19	4420	3230	2010	15.8	980
Maharashtra	Akola	26	6410	4270	1480	28.4	640
Maharashtra	Nagpur	26	5030	2760	1120	37.7	900
Maharashtra	Nanded	25	8540	5680	2430	26.3	760
Orissa	Bhubaneswar	7	4820	3830	2420	17.6	990
Orissa	Cuttack	7	4890	3600	1730	27.9	1090
Uttar Pradesh	Faizabad	10	6810	4600	1730	29.6	830
Uttar Pradesh	Lucknow	10	6270	5360	3680	15.3	660
Uttar Pradesh	Saharanpur	11	6550	5070	1590	21.0	920
Uttar Pradesh	Varanasi	10	5960	4850	2660	19.1	850
West Bengal	Barrackpore	6	5300	3740	2830	18.0	1050
West Bengal	Calcutta	6	6580	4110	1760	30.7	1120
West Bengal	Mohanpur	6	6780	5600	4880	11.2	1030

At the state level, the mean rain-fed potential rice yield as simulated by InfoCrop varied from 3500 kg ha^{-1} in Madhya Pradesh to 5000 kg ha^{-1} in Uttar Pradesh (Fig. 5). The simulated rain-fed potential yields were intermediate in other states. The average rain-fed potential for India was calculated to be 4550 kg ha^{-1}.

The experimental potential yields showed a large variation. It was only 1400 kg ha^{-1} in states such as Maharashtra whereas it was as high as 4300 kg ha^{-1} in Uttar Pradesh. In other states, the average yield in breeder's plots varied from 2500 kg ha^{-1} to 3700 kg ha^{-1} (Fig. 5). On an all India basis, these yields were 3300 kg ha^{-1}.

The on-farm potential yields showed relatively less variation across states, possibly because of large plot size of the demonstrations and the data being the average of several trials. The yields in Bihar and Madhya Pradesh were 2300 kg ha^{-1} and 2550 kg ha^{-1}, respectively. In Uttar Pradesh, Orissa and West Bengal, these yields varied from 3500 kg ha^{-1} to 3750 kg ha^{-1}. On an all India basis, these yields were 3000 kg ha^{-1}. In some states such as West Bengal and Orissa, the on-farm potential yields were more

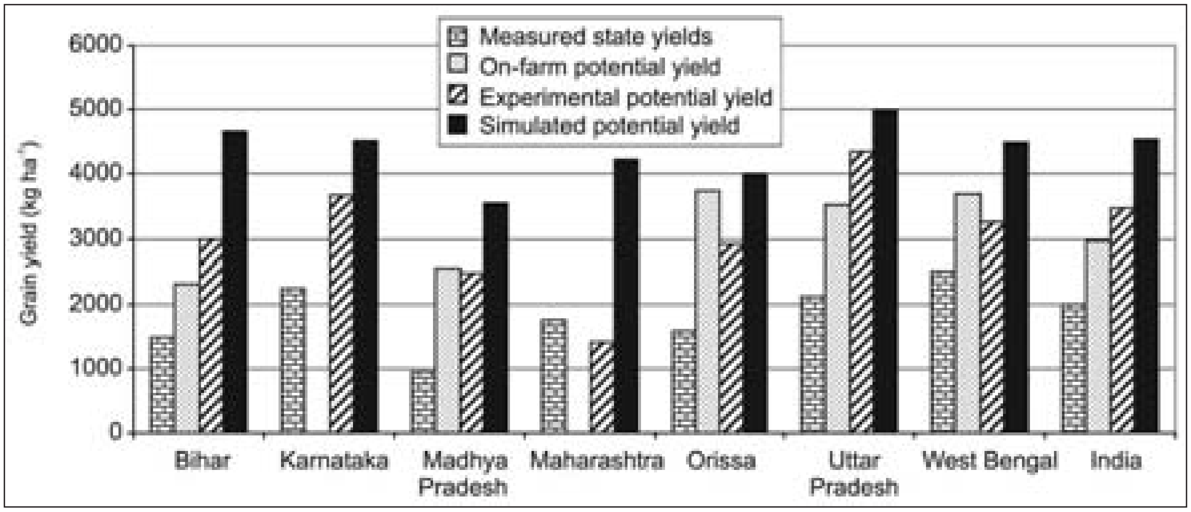

Figure 5. Comparison of simulated, experimental and on-farm rain-fed potential yields and the measured state average yields of rice. Please note that the measured yields are average of irrigated as well as rain-fed areas.

than those obtained in the breeder's plots (Fig. 5). Such differences could be due to the variety of sources used in the present calculations, For example, differences associated with genotypes, planting dates and management used in different trials.

Measured yields

The mean yields at the state level showed considerable variation (Fig. 5). These were the lowest in Madhya Pradesh and was followed by Bihar and Orissa. All these states are largely rain-fed (Table 1). By comparison, the average yields in Karnataka, Uttar Pradesh and West Bengal were more than 2000 kg ha^{-1}. It is difficult to draw any meaningful conclusion from such states' average yields because a considerable fraction of these were from irrigated areas. Nevertheless, rain-fed yields in these states shall be still lower than the values presented here. On an all India basis, measured yields were 2000 kg ha^{-1}.

Yield gaps

The results showed that irrespective of the definition of potential yield, there is considerable yield gap across all states, indicating large scope for increasing rain-fed rice yields in future. On an average, the gap relative to simulated potential was close to 2500 kg ha^{-1} (Table 3). It was more than 3000 kg ha^{-1} for Bihar and less than 2000 kg ha^{-1} for West Bengal. At the experimental station level, the gap varied from 740 kg ha^{-1} (in West Bengal) to 2230 kg ha^{-1} (in Uttar Pradesh). This value was around 1500 kg ha^{-1} in all other states. On-farm yield gaps were surprisingly nil in Maharashtra. Possibly, the on-farm trials have always experienced some constraint. In Orissa, however, the gap was more than 2000 kg ha^{-1}, almost close to the gap with simulated rain-fed potential yields. Overall, the gaps were generally smaller in West Bengal at all levels and the highest in Uttar Pradesh. The average yield gap was the smallest (1240 kg ha^{-1}) in Maharashtra and the highest in Uttar Pradesh (2160 kg ha^{-1}). The all India mean gap for rain-fed rice was at least 1670 kg ha^{-1}.

Table 3. Calculated yield gaps of rice from simulated rain-fed, experimental and on-farm potential yields[1].

	Yield gap (kg ha^{-1})			
State	Simulated potential	Experimental potential	On-farm potential	Average
Bihar	3170	1510	820	1830
Karnataka	2280	1440		1860
Madhya Pradesh	2590	1540	1600	1910
Maharashtra	2480		0	1240
Orissa	2410	1320	2160	1960
Uttar Pradesh	2850	2230	1400	2160
West Bengal	1970	740	1190	1300
India	2560	1480	970	1670

1. Gaps calculated would be higher than the actual for rain-fed conditions in all cases because the measured yields included data from irrigated areas as well.

Options to bridge yield gaps

In rain-fed areas, water resources can be augmented through rainwater harvesting and by adopting community watershed management approach (Wani et al. 2003). The result showed that the main strategy required to increase rain-fed yields is to provide supplementary irrigation. This was evident in all states when the mean rain-fed potential yields were compared with the maximum yields obtained in a specific year (Fig. 6). The later were generally obtained in those years where rainfall was well distributed throughout the rainy season. Ensuring timely planting at the beginning of the season by providing irrigation for transplanting when monsoon is delayed can also bridge yield gaps to some extent. Improvement in nitrogen management, which includes providing optimal amounts at the desired times, can also bridge the yield gap to considerable extent.

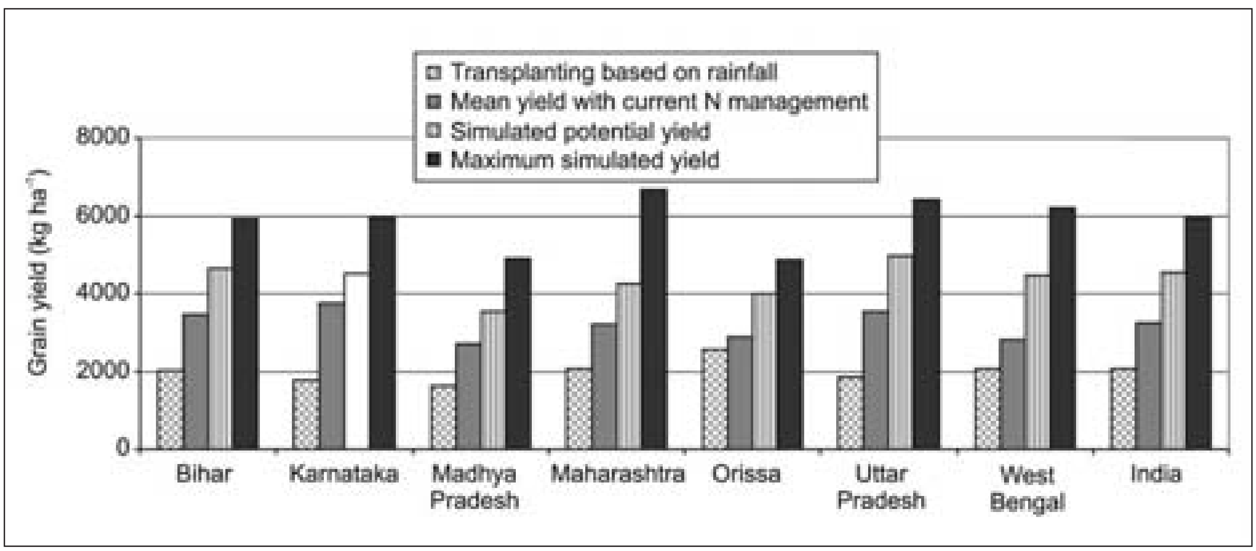

Figure 6. Simulated options to increase rain-fed yields in different states.

3.2 Cotton

Current distribution and yields

Cotton in India is grown in rainy season in semi-arid regions (Fig. 7). The crop is grown in Maharashtra, Andhra Pradesh and Gujarat followed by Punjab, Haryana, Karnataka and Madhya Pradesh. In north Indian states of Punjab, Haryana and Rajasthan, the crop is irrigated whereas in other states, it is partially irrigated or rain-fed (Table 4). Almost the crop is rain-fed in Maharashtra, that accounts for 34% of the cotton area and 27% of national production. The total production of cotton in India is 10 million bales (170 kg each) from nine million hectare area. As is therefore obvious, the productivity of seed cotton is very low, ranging between 300 kg ha^{-1} and 1200 kg ha^{-1} among states. However, in a few districts of Punjab, Haryana, Andhra Pradesh and Karnataka, the seed cotton yield exceeds 1200 kg ha^{-1} (Fig. 8), although the state averages are much lower (Table 4).

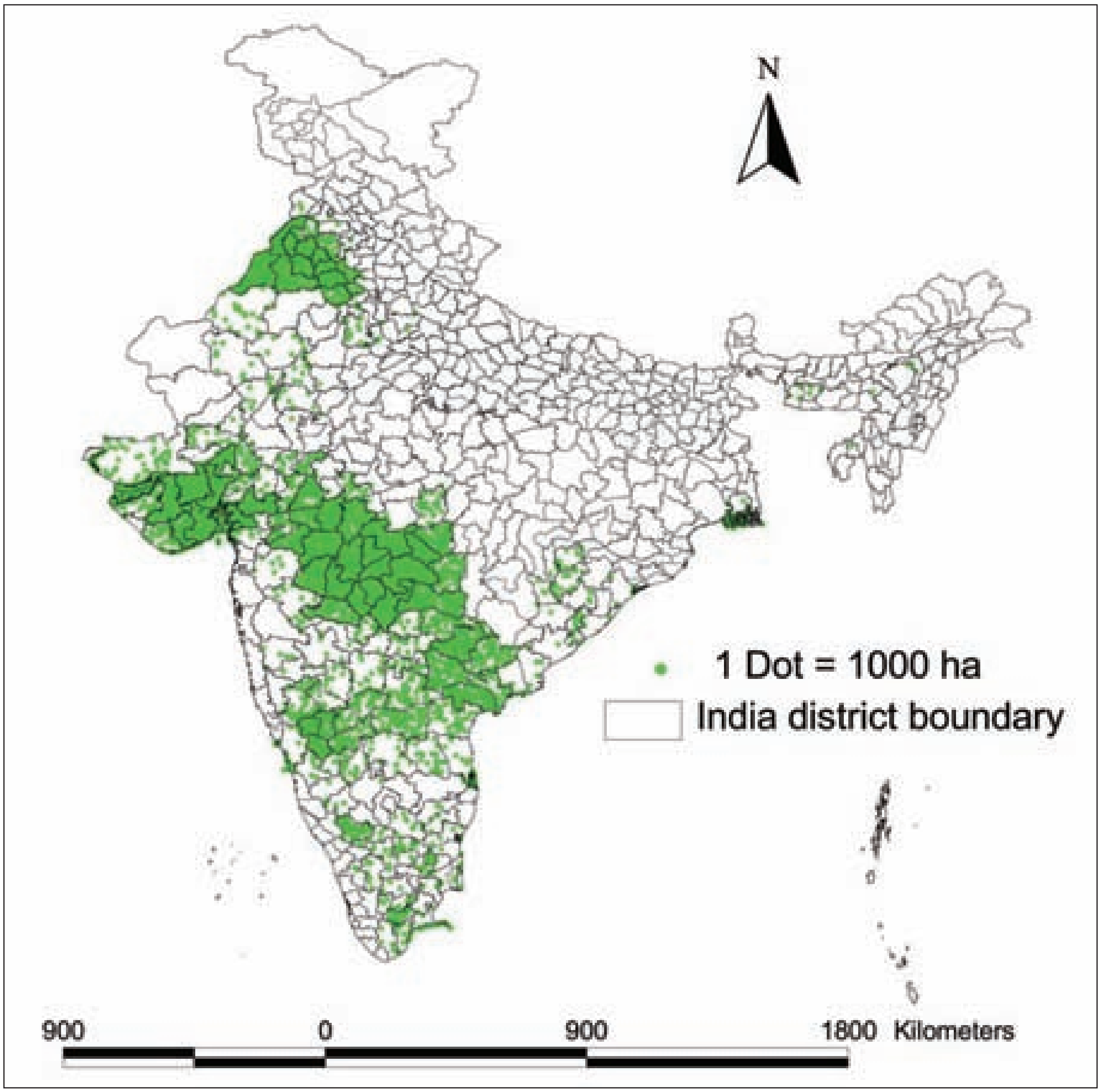

Figure 7. Distribution of cotton area by district in India.

Table 4. Area, production, yield and irrigation coverage for the cotton producing states of India. All data except irrigation relates to the 2001-02 season.

States	Area (M ha)	Production (M bales of 170 kg each)	Yield, (kg ha^{-1})	% coverage under irrigation during 1999-2000
Maharashtra	3.1	2.69	490	4.0
Andhra Pradesh	1.1	1.87	950	18.0
Gujarat	1.75	1.7	550	42.0
Punjab	0.61	1.31	1210	100.0
Haryana	0.63	0.72	640	100.0
Karnataka	0.61	0.72	670	14.0
Madhya Pradesh	0.54	0.39	400	40.0
Tamil Nadu	0.19	0.33	970	35.0
Rajasthan	0.51	0.28	310	100.0
Others	0.06	0.08	750	-
All India	9.1	10.09	620	35.0

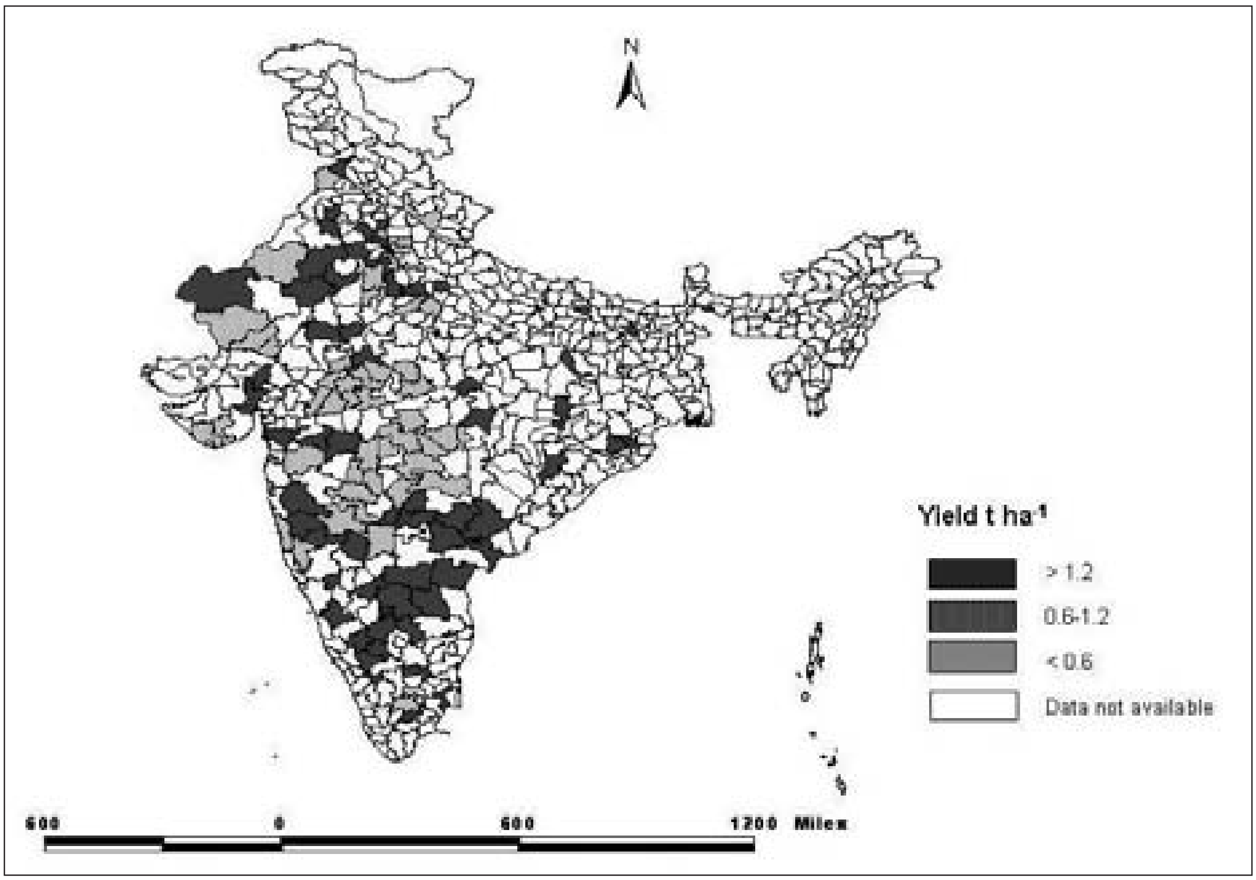

Figure 8. Seed cotton yields in districts of India.

The production of cotton during the last 50 years has increased from three million bales to almost 15 million bales today (Fig. 9). The major reason for this increase has been the coverage under irrigation, which changed from 8% to 35% by 2000 (Fig. 9). As a consequence, the seed cotton yield increased from 300 kg ha^{-1} to 1000 kg ha^{-1}. The total area under cultivation has remained by and large constant during the last five decades.

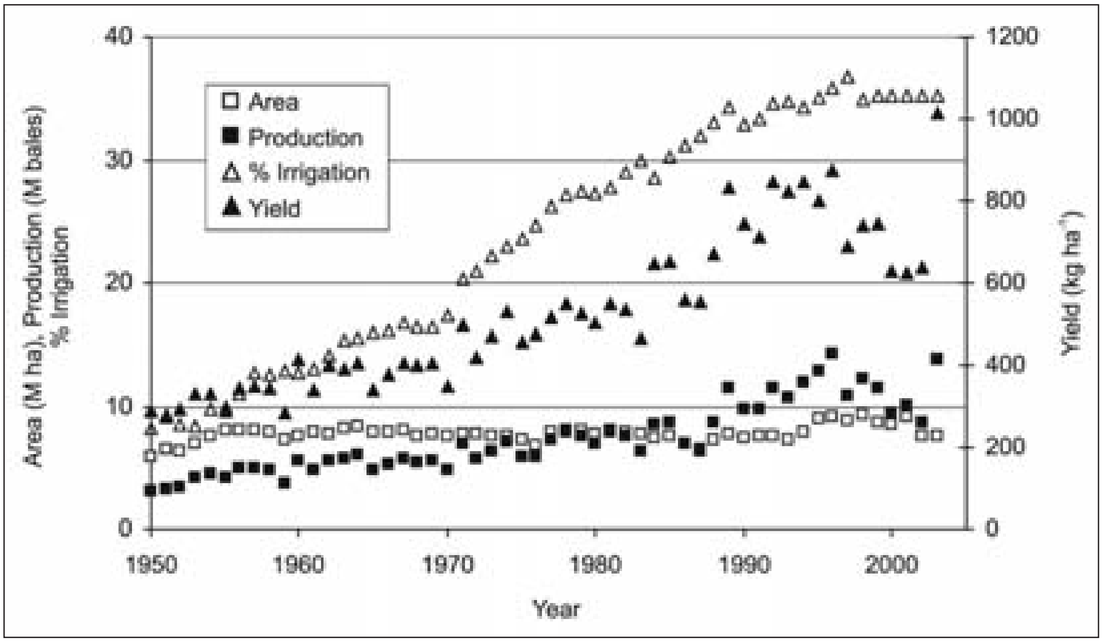

Figure 9. Change in area, production and yield of seed cotton in India with time.

In the rain-fed areas, the cotton yield is strongly dependent on the date of onset of monsoon, which affects planting date. The cotton soils are generally clayey and rainfall is modest. The crop is exposed to drought as well as floods. Both of these reduce crop yields depending upon the stage of growth. Pests and diseases, especially bollworms, are the other major yield-reducing factors.

Simulated rain-fed potential yields

Simulation results showed reasonable rain-fed potential yields of rain-fed cotton in different regions. The mean potential yield varied from 900 kg ha^{-1} to 2400 kg ha^{-1}. There were large variations within the same state as is evident from Table 5. For example, in Andhra Pradesh yields varied from 1080 kg ha^{-1} to 2410 kg ha^{-1}.

The maximum yields across different locations varied from 1730 to 2750 kg ha^{-1}. In most locations, except in a few places in Madhya Pradesh, the maximum yields were always above 2000 kg ha^{-1}. Such high yields were obtained in those seasons when rainfall was well distributed and the onset of monsoon was timely. The minimum yields in rain-fed situations were highly variable across locations. At times, the crops failed altogether in some areas such as in Karnataka, Madhya Pradesh in Maharashtra (Table 5). In a few locations in Andhra Pradesh, Gujarat and Madhya Pradesh where rainfall was relatively higher, the minimum rain-fed potential yields in any given year were also more than 1000 kg ha^{-1}.

At the state level, the simulated rain-fed potential yields varied from 1400 kg ha^{-1} to 1800 kg ha^{-1}. The lowest potential was in Karnataka and Madhya Pradesh, whereas the highest yield was in Andhra Pradesh (Fig. 10). All India average potential yield was 1648 kg ha^{-1}. The coefficient of variation in yields ranged from 12 to 74%. There appears to be a negative correlation of this with rainfall in general, CV was less than 20% when seasonal rainfall was 1000 mm or more (Table 5).

Table 5. Simulated maximum, mean and minimum yield for some important locations in predominantly rain-fed states. Also shown is the coefficient of variation (CV) of these yields and the mean rainfall during the season.

State	Location	Met sub division	Simulated rain-fed potential yield (kg ha^{-1})			CV (%)	Mean seasonal rainfall (mm)
			Maximum	Mean	Minimum		
Andhra Pradesh	Anakapalli	27	2730	2360	1570	14.8	950
Andhra Pradesh	Rajahmundry	27	2750	2410	1870	16.7	1100
Andhra Pradesh	Hyderabad	28	2500	1680	510	35.5	850
Andhra Pradesh	Anantapur	29	2520	1080	50	58.0	540
Gujarat	Bharuch	21	2320	1360	450	45.9	790
Gujarat	Surat	21	2380	2090	1930	12.2	880
Gujarat	Junagadh	22	2570	1690	410	36.5	770
Karnataka	Bijapur	32	2240	1220	0	74.2	610
Karnataka	Dharwad	32	2230	1490	930	26.6	660
Karnataka	Bangalore	33	2190	1480	0	37.6	750
Madhya Pradesh	Gwalior	19	2700	1840	1320	22.9	800
Madhya Pradesh	Indore	19	1730	940	300	50.2	990
Madhya Pradesh	Jabalpur	19	1790	1390	920	17.6	1310
Madhya Pradesh	Raipur	19	2450	1720	1150	18.2	1100
Madhya Pradesh	Sagar	19	2150	1100	0	61.6	840
Maharashtra	Nanded	25	2580	1390	20	58.0	870
Maharashtra	Akola	26	2320	1580	200	33.7	720
Maharashtra	Nagpur	26	2530	1770	760	31.2	1030

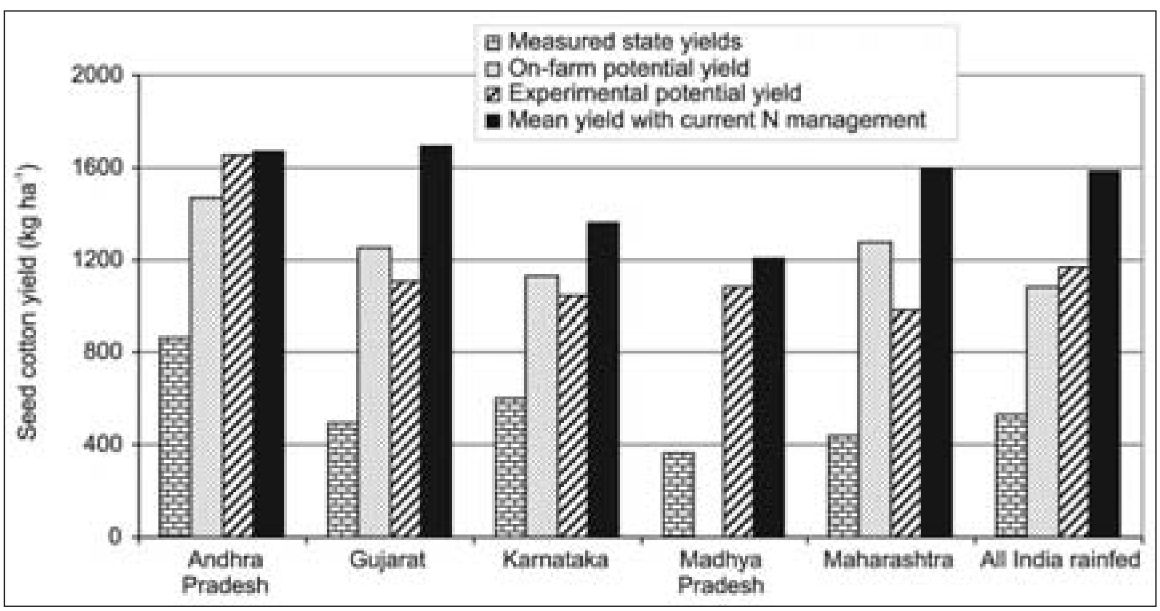

Figure 10. Comparison of simulated, experimental and on-farm rain-fed potential yields and the measured state average yields of cotton. Note that the measured yields are average of irrigated and rain-fed areas.

The experimental potential yields also showed considerable variation. On an average, the yields were between 1000 and 1100 kg ha^{-1} in all states except in Andhra Pradesh where the yields were more than 1600 kg ha^{-1} (Fig. 10).

The on-farm potential yields also showed a similar trend. Surprisingly, in many states these yields were slightly higher than the yields obtained in breeder's trials (Fig. 10). These differences could possibly be due to different data and sources used in this calculation, especially related to locations, seasons, varieties and planting dates in two types of data.

Measured yields

The mean cotton seed yield at the state level was the lowest in Madhya Pradesh (366 kg ha^{-1}). This was followed by Maharashtra and Gujarat, where the yield level reached up to 500 kg ha^{-1} (Fig. 10). In Karnataka, the average yield was 600 kg ha^{-1} and was the highest in Andhra Pradesh. However, the actual rain-fed yields in Andhra Pradesh, Gujarat and Madhya Pradesh were lower than these figures because the reported yields also included the data from irrigated regions.

Yield gaps

The results showed that mean yield gap between simulated rain-fed potential yield and the state average yield was 1120 kg ha^{-1}. The lowest gap of 790 kg ha^{-1} was recorded in Karnataka while the maximum was in Gujarat with 1220 kg ha^{-1}.

At the experimental station level, the gap was maximum in Andhra Pradesh and Gujarat while Karnataka had the lowest gap (Table 6). The mean gap at this scale was only 640 kg ha^{-1}.

Table 6. Calculated yield gaps of cotton from simulated, experimental and on-farm potential yields[1].

	Yield gap (kg ha^{-1})			
State	Simulated potential	Experimental potential	On-farm potential	Average
Andhra Pradesh	970	780	600	780
Gujarat	1220	610	760	860
Karnataka	790	440	520	580
Madhya Pradesh	1030	710	0	580
Maharashtra	1140	540	830	840
India	1120	640	550	770

1. Gaps calculated would be higher than the actual for rain-fed conditions because the measured yields include data from irrigated areas as well.

At the on-farm level, the gap was somewhat similar to that of the experimental stations (Table 6). There was no gap in Madhya Pradesh whereas all other states had a gap between 500 and 850 kg ha^{-1}. Thus, in the main rain-fed cotton producing states, there is sufficient gap that can possibly be bridged by improved management. The yield gap is high in the states of Gujarat and Maharashtra, modest in Andhra Pradesh and relatively low in Karnataka and Madhya Pradesh.

Options to bridge yield gaps

As in the case of rice, the results showed that the main strategy to increase rain-fed yield is to provide supplementary irrigation when rainfall is deficit. This is illustrated by a comparison of simulated mean rain-fed potential yield (with average distribution of rainfall) and maximum simulated yield with well-distributed rainfall (Fig. 11). Nutrient management and ensuring irrigation for timely planting of cotton were relatively minor options to bridge yield gap.

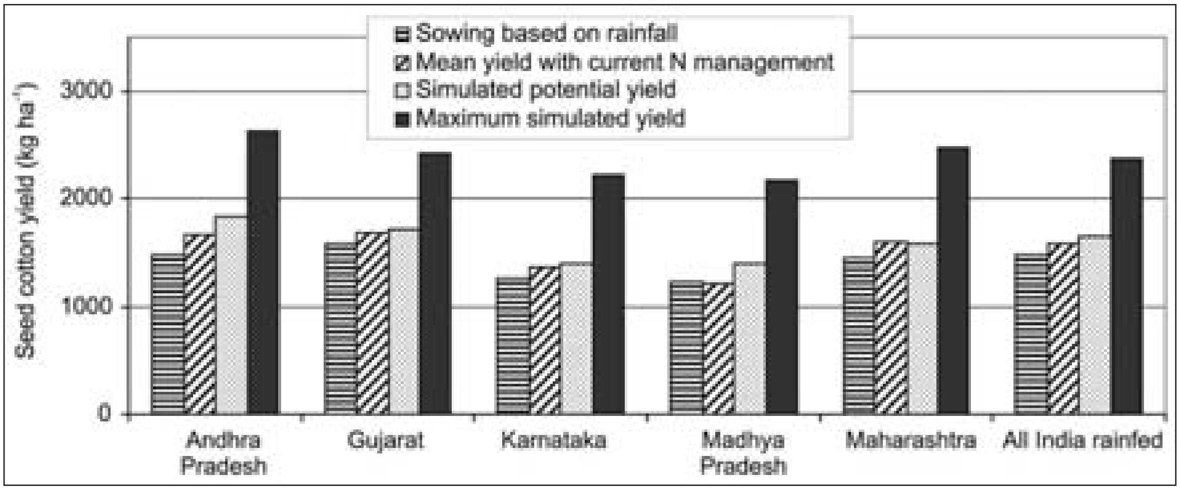

Figure 11. Simulated options to increase rain-fed yields in different states.

3.3 Mustard

Current distribution and yields

Mustard in India is grown mainly in the northern and eastern India (Fig. 12). It is grown in *rabi* season on stored soil moisture with 2-3 supplementary irrigations, whenever and wherever possible. Rajasthan, Uttar Pradesh and Haryana are the main mustard producing states (Table 7). These states account for 63% of the total area under India and 70% of the total production. Only 1/3rd of the total mustard area (1.7 M ha) in India is rain-fed. The major area under rain-fed cultivation is in Rajasthan, Madhya Pradesh, Assam and Uttar Pradesh (Table 7).

Table 7. Area, production, yield and irrigation coverage for the mustard producing states of India. All data except irrigation relates to the 2001-02 season.

States	Area (M ha)	Production (M t)	Yield (kg ha^{-1})	% coverage under irrigation during 1999-2000
Rajasthan	1.84	1.94	1060	81
Uttar Pradesh	0.85	0.85	1000	71
Haryana	0.54	0.8	1490	86
West Bengal	0.44	0.34	770	75
Madhya Pradesh	0.51	0.46	910	35
Gujarat	0.25	0.29	1180	98
Assam	0.27	0.44	500	1
Bihar	0.09	0.08	840	34
Punjab	0.05	0.06	1200	84
Others	0.23	0.12	-	-
All India	5.07	5.08	1000	66

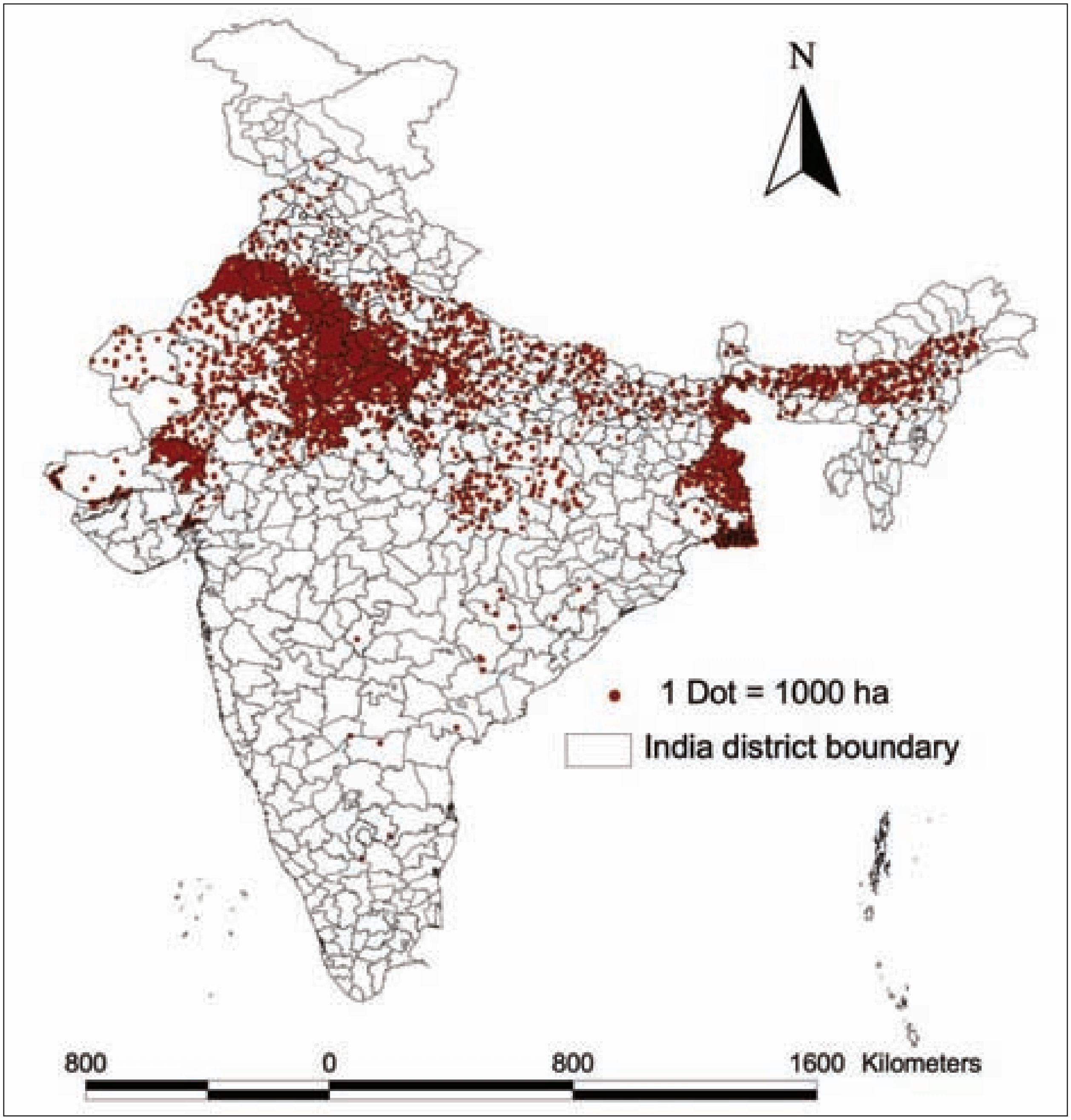

Figure 12. Distribution of mustard area by district in India.

Mustard yields vary considerably across different states (Table 7). The highest yields were recorded in the largely irrigated state of Haryana (1490 kg ha^{-1}) and the lowest yields were reported from eastern Indian states, where a reasonable proportion of area is rain-fed. The yields in other states were between 900 kg ha^{-1} and 1200 kg ha^{-1}.

There is considerable difference in district yields within the states. For example, in some districts of Punjab and Haryana, district yields were much higher than 1000 kg ha^{-1} whereas in some districts the yields were between 500 kg ha^{-1} and 1000 kg ha^{-1} (Fig. 13). In other states, the differences across districts were generally smaller.

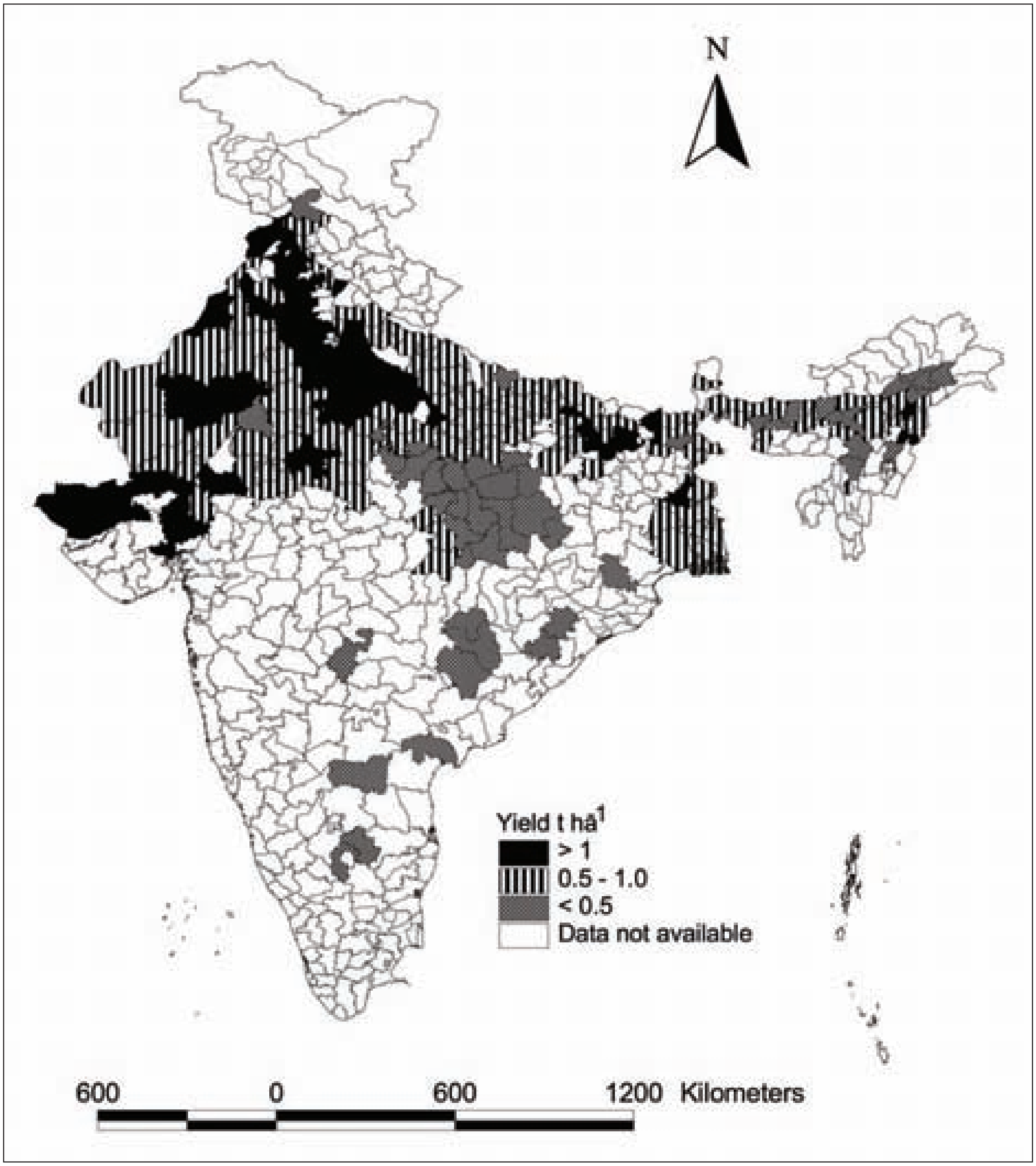

Figure 13. Variation in mustard yields across districts of India

Over the last 50 years, mustard area has gradually increased from 2 M ha to 5 M ha. There has been considerable expansion of irrigation in mustard since 1950s. From a low of 10 percent irrigated area in 50s, it has become 65 percent in early 90s. Ever since, the area has not increased (Fig. 14). As a direct consequence of this, the grain yields have also improved from 400 kg ha^{-1} to 1000 kg ha^{-1}.

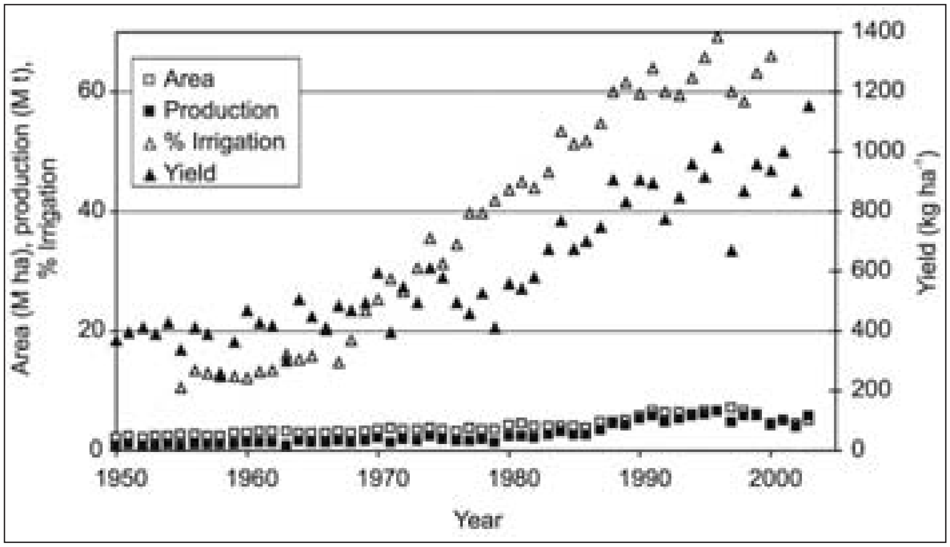

Figure 14. Change in area, production and yield of mustard in India with time.

Simulated rain-fed potential yields

Results showed that the simulated yield across locations in rain-fed area varied between 480 kg ha^{-1} and 3890 kg ha^{-1} depending upon the season (Table 8). The mean simulated yields varied from 960 kg ha^{-1} to 2520 kg ha^{-1} (Table 8). The locations in Madhya Pradesh showed lower potential yield as compared to locations in other states. The locations of West Bengal showed high yields because of relatively lesser drought periods experienced during the crop season. The coefficient of variation in yields ranged from 22% to 72% depending upon locations. However, this had no clear relationship with the mean rainfall during the season (Table 8).

Table 8. Simulated maximum, mean and minimum yield of mustard for some important locations in predominantly rain-fed states. Also shown is the coefficient of variation (CV) of these yields and the mean rainfall during the season.

State	Location	Met sub division	Simulated rain-fed potential yield (kg ha^{-1})			CV (%)	Seasonal rainfall (mm)
			Max	Mean	Min		
Bihar	Patna	9	2910	1250	710	38.9	30
Bihar	Sabour	9	3070	2330	810	13.5	90
Delhi	Delhi	13	3550	2060	630	36.1	70
Haryana	Karnal	13	3890	1800	760	46.3	110
Haryana	Sirsa	13	3330	2110	630	47.7	50
Madhya Pradesh	Gwalior	19	2900	1800	920	38.0	50
Madhya Pradesh	Raipur	19	2550	1090	520	48.9	60
Madhya Pradesh	Ratlam	19	1910	960	620	37.8	30
Madhya Pradesh	Sagar	19	2160	960	480	55.5	50
Uttar Pradesh	Jhansi	11	2920	1820	590	47.8	50
Uttar Pradesh	Lucknow	10	2890	2210	910	24.5	60
Uttar Pradesh	Saharanpur	11	3160	1770	740	44.7	110
Uttar Pradesh	Varanasi	10	3020	1980	1310	27.7	60
West Bengal	Barrackpore	6	3460	2260	1470	25.1	110
West Bengal	Mohanpur	6	3580	2520	1180	31.5	160

The maximum simulated rain-fed yields across locations varied from 1910 kg ha^{-1} to 3890 kg ha^{-1} (Table 8) in comparison to rain-fed rice and cotton, where minimum yields could go very low. At least 400 kg ha^{-1} yield was always recorded at any location in mustard. In both locations of West Bengal, where rainfall during the cropping season was more than 100 mm, the average minimum yields were at least 1180 kg ha^{-1}.

At the state level, the mean simulated rain-fed potential yields varied from 1200 kg ha^{-1} in Madhya Pradesh to 2400 kg ha^{-1} in West Bengal. Rajasthan, Haryana and Uttar Pradesh states with large mustard area followed closely (Fig. 15). The average rain-fed potential yield of mustard was calculated to be 1860 kg ha^{-1}.

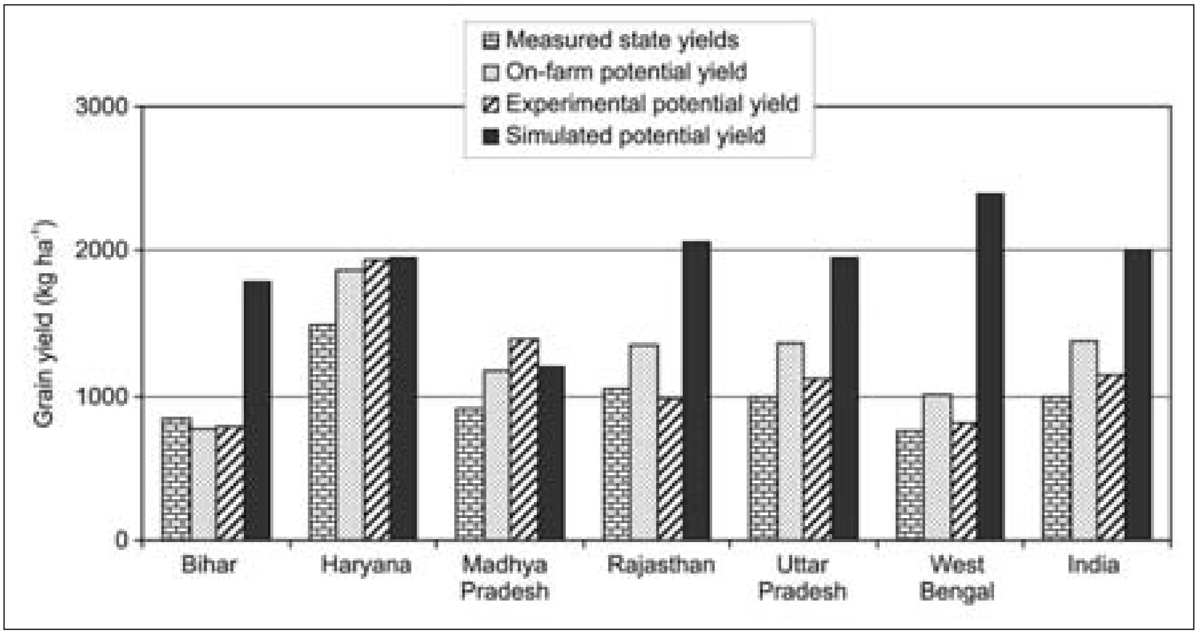

Figure 15. Comparison of simulated, experimental and on-farm rain-fed potential yields and the measured state average yields of mustard. Note that the measured yields are average of irrigated as well as rain-fed areas.

The experimental potential yields also showed a large variation across the states. Bihar, Rajasthan and West Bengal had yields lower than 1000 kg ha^{-1} (Fig. 15). The highest yields in breeder's experiments were reported in Haryana. These were almost similar to the simulated rain-fed potential yields. In Madhya Pradesh, the experimental potential yields were slightly higher than the simulated potential yield. The reasons for this were not clear.

The variation in the on-farm potential yields was as large as in the experimental potential yields. The lowest yields were reported in Bihar and the highest were in the state of Haryana. The other states showed intermediate values.

Measured yields

The mean yields at the state level showed considerable variation. The differences among the states were generally smaller than the experimental yields (Fig. 15). The lowest yields were reported in the state of West Bengal, followed by Bihar and Madhya Pradesh. The mean yields were about 1000 kg ha^{-1} in Rajasthan and Uttar Pradesh, respectively. Haryana reported the highest average at 1490 kg ha^{-1}. It may be noted that the state average is the mean of irrigated and rain-fed areas.

Yield gaps

The results showed that the gap between simulated rain-fed potential yield and the measured state average yield was 860 kg ha^{-1}. It was very low in Madhya Pradesh whereas Rajasthan, Uttar Pradesh and West Bengal having large mustard cultivation showed considerable yield gap due to their large simulated potential yields (Table 9).

Table 9. Calculated yield gaps of mustard from simulated, experimental and on-farm potential yields[1].

	Yield gap (kg ha^{-1})			
State	Simulated potential	Experimental potential	On-farm potential	Average
Bihar	950	0	0	320
Haryana	470	450	380	430
Madhya Pradesh	300	480	260	350
Rajasthan	1000	0	290	430
Uttar Pradesh	950	120	370	480
West Bengal	1630	50	240	640
India	860	150	380	460

1. Note that the gaps calculated would be higher than the actual for rain-fed conditions because the measured yields include data from irrigated areas as well.

The gap was, however, generally small at the experimental station level as well as on-farm (Table 9). In Bihar, in both cases there was no yield gap. West Bengal showed the largest yield gap of 640 kg ha^{-1}. In all other states, the gap was less than 500 kg ha^{-1}. In reality, however, yield gaps would be larger in rain-fed areas than calculated here.

Options to bridge yield gaps

The results showed that the strategy to increase yields like rain-fed rice of cotton is to provide supplementary irrigation. This is illustrated by the difference between maximum simulated yield (when there is sufficient seasonal rainfall) and simulated potential (when rainfall is average overtime). The improved nitrogen management can also bridge yield gap although to a smaller extent only (Fig. 16).

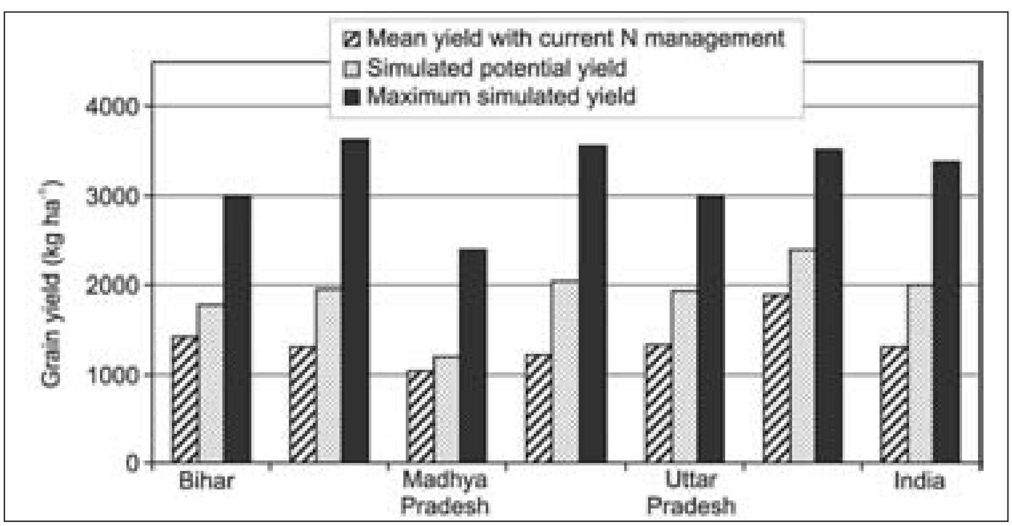

Figure 16. Simulated options to increase rain-fed yields in different states.

3.4 Wheat

Current distribution and yields

Wheat in India is grown on 26 M ha. It is cultivated throughout India except southern and north-eastern states (Fig. 17). Uttar Pradesh, Punjab, Haryana, Rajasthan are the major wheat producing states and account for almost 80% of the total production in India (Table 10). Only 13% of the total wheat area is rain-fed. The major rain-fed wheat areas are in Madhya Pradesh, Gujarat, Himachal Pradesh, Maharashtra, West Bengal and Karnataka.

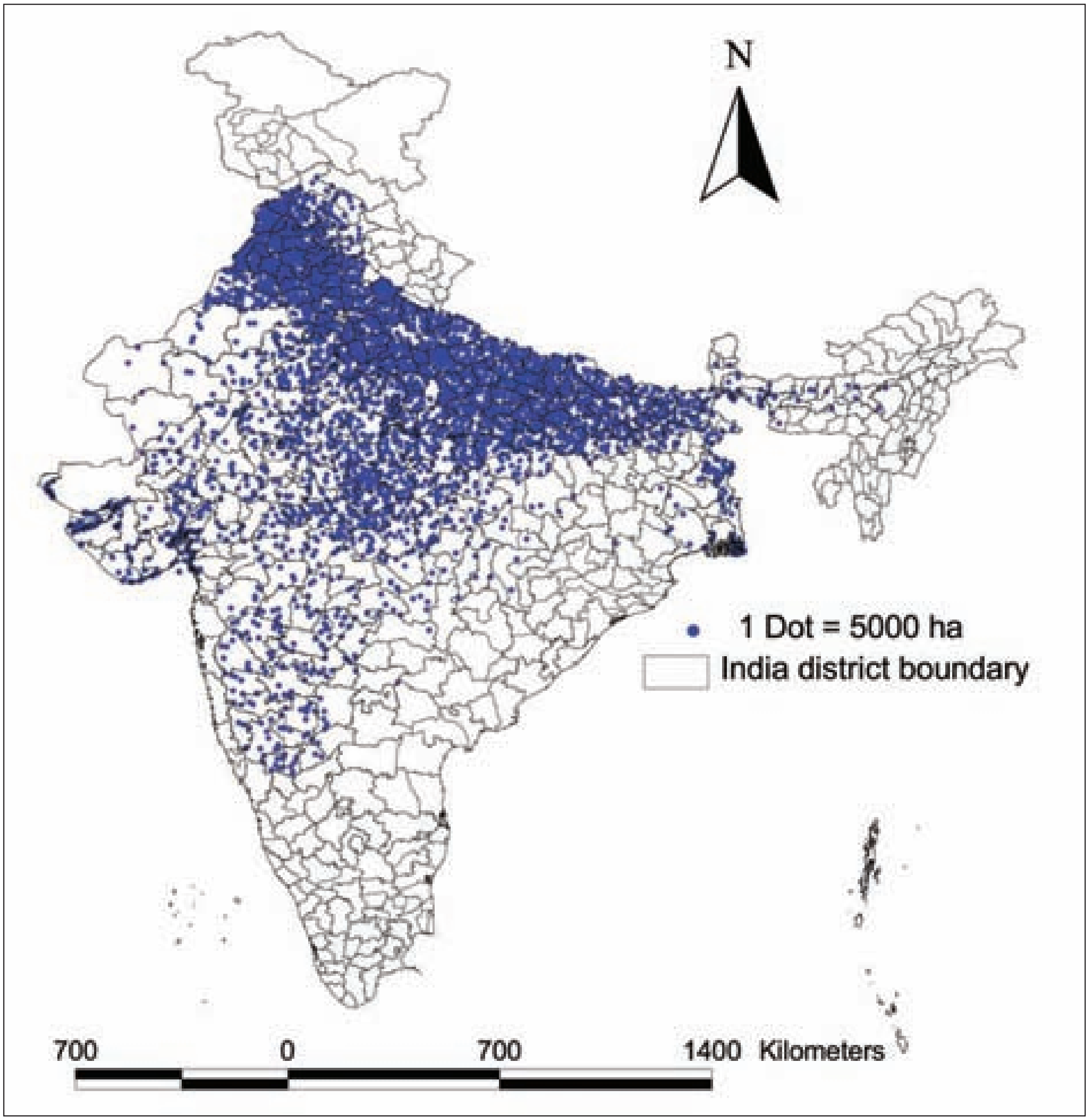

Figure 17. Distribution of wheat area by district in India.

Wheat yields in different states vary tremendously due to different technologies adopted by the farmers and the agro-climatic characteristics of the region. Yields in Karnataka, Maharashtra, Madhya Pradesh, Assam and Uttaranchal were less than 2000 kg ha^{-1} due to relatively higher temperatures in these states, limited irrigation availability and small quantities of fertilizers applied. Comparatively, yields in Punjab and Haryana were more than 4000 kg ha^{-1} due to favorable weather during crop season and recommended applications of irrigation and fertilizers. In Uttar Pradesh, Rajasthan, Bihar and other important wheat producing states, average yields were between 2000 kg ha^{-1} and 3000 kg ha^{-1} due to slightly warmer temperatures, relatively more rain-fed areas and less fertilizer application (Table 10).

Table 10. Area, production, yield and irrigation coverage for the wheat producing states of India. All data except irrigation relates to the 2001-02 season.

States	Area (M ha)	Production (M t)	Yield (kg ha^{-1})	% coverage under irrigation during 1999-2000
Uttar Pradesh	9.08	25.02	2760	92
Punjab	3.42	15.5	4530	97
Haryana	2.3	9.44	4100	99
Rajasthan	2.29	6.39	2790	98
Madhya Pradesh	3.43	5.63	1640	72
Bihar	2.13	4.38	2060	90
Gujarat	0.47	1.14	2440	80
Maharashtra	0.78	1.08	1390	80
West Bengal	0.43	0.96	2220	80
Uttaranchal	0.38	0.73	1930	-
Himachal Pradesh	0.38	0.6	1610	18
Karnataka	0.26	0.2	750	43
All India	25.92	71.81	2770	87

There were large variations within a state in terms of yields especially in states such as Madhya Pradesh, Bihar and Rajasthan. In several districts of these states, yields varied from less than 1000 kg ha^{-1} to as high as 3000 kg ha^{-1} (Fig. 18). The main reason for this variation was availability of irrigation, other management factors and soil type.

Wheat is one of the main crops, which has benefitted tremendously from the green revolution technologies. Over the last 50 years, area under wheat cultivation has increased from 10 million to 26 million hectares. During the same period, irrigated area has increased from 30% to 85% of the total area (Fig. 19). Crop yields have been showing a similar pattern of improvement: from 700 kg ha^{-1} in 1950 to 2800 kg ha^{-1} today. This increase has been due to increased irrigation facilities, application of fertilizers, improved varieties and socio-economic support provided to the farmers.

Simulated rain-fed potential yields

The results showed considerable potential of rain-fed wheat yields in different regions. The mean simulated yields varied from as low as 810 kg ha^{-1} in several locations in Maharashtra to 3340 kg ha^{-1} in West Bengal (Table 11). In general, rain-fed potential yields were lower for most locations in Maharashtra, Madhya Pradesh and Karnataka. The CV in yield across different locations was 19.5% to 86.4%. It was, however, not due to rainfall during the crop season; the latter in any case was very small in most of the locations (Table 11).

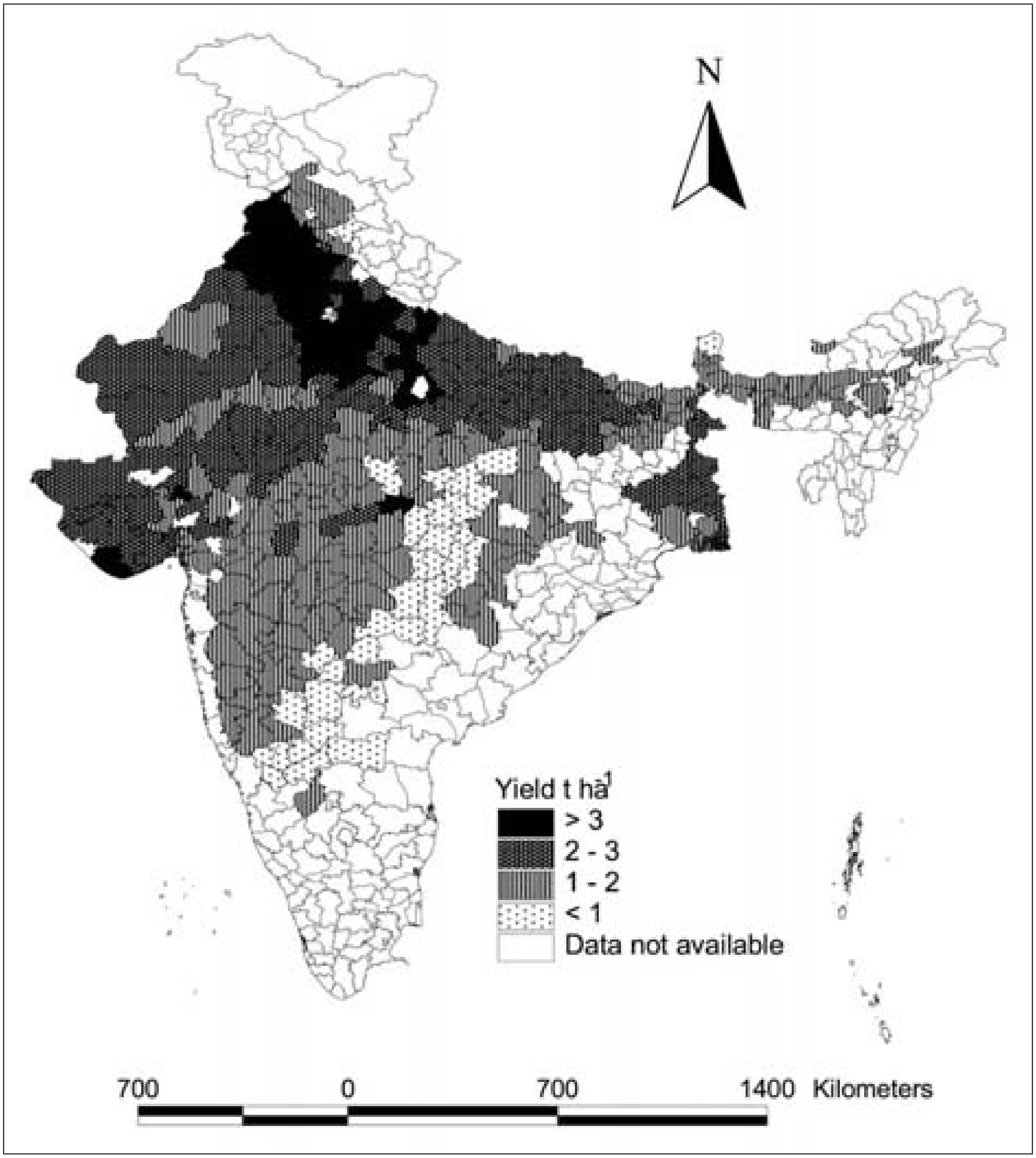

Figure 18. Variation in wheat yields across districts of India.

The minimum yields across different locations also showed considerable variation. These were less than 500 kg ha^{-1} in some locations spread across Maharashtra, Madhya Pradesh, Karnataka and West Bengal (Table 11). Comparatively, the minimum yields were more than 2000 kg ha^{-1} in Gwalior in Madhya Pradesh as well as in Mohanpur and Barrackpore in West Bengal. The maximum rain-fed yields as simulated by the model were as high as 5760 kg ha^{-1} for Gwalior. Within Madhya Pradesh, there was a large variation: Jhabua had the lowest potential whereas Gwalior showed high potential yield. These were possibly related to temperature differences between these sites.

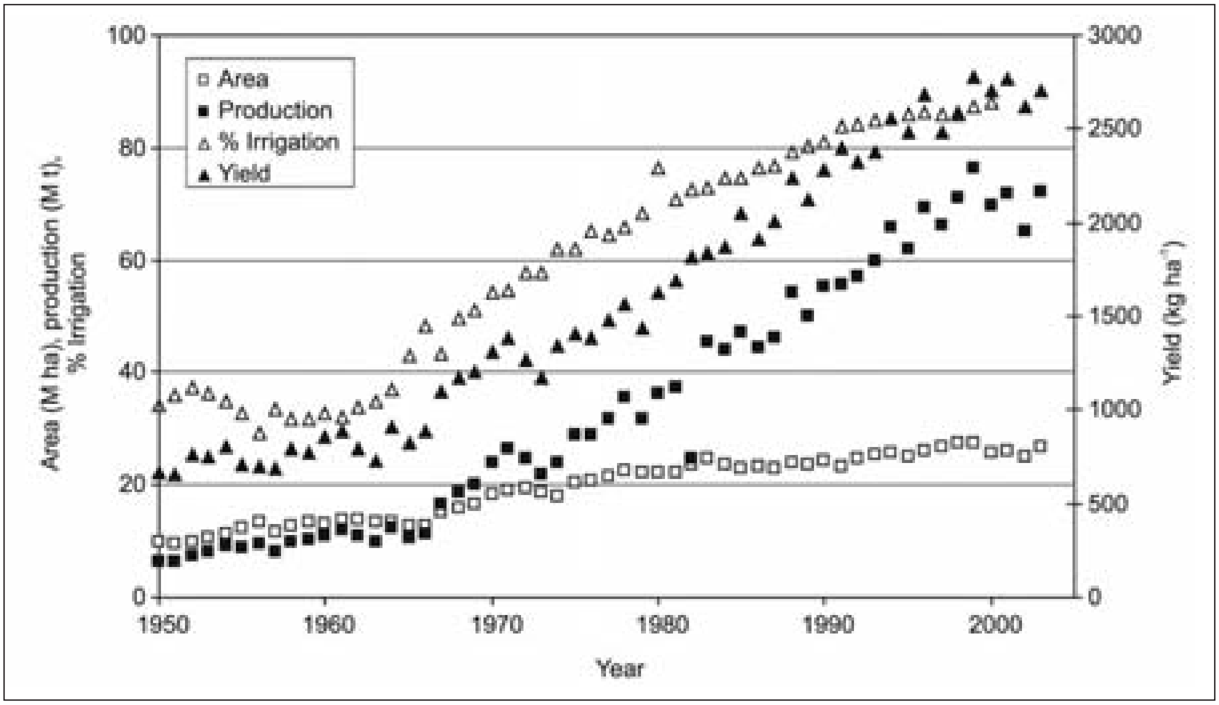

Figure 19. Change in area, production and yield of wheat in India with time.

Table 11. Simulated maximum, mean and minimum yield for some important locations in predominantly rain-fed states. Also shown is the coefficient of variation (CV) of these yields and the mean rainfall during the season.

State	Location	Met sub division	Simulated rain-fed potential yield (kg ha^{-1})			CV (%)	Seasonal rainfall (mm)
			Max	Mean	Min		
Gujarat	Surat	21	2350	1750	1140	34.5	0
Gujarat	Bharuch	21	3070	2280	1800	19.5	10
Gujarat	Junagadh	22	2740	1750	1160	23.3	8
Karnataka	Dharwad	32	3650	1260	460	73.9	50
Karnataka	Bijapur	32	2830	1860	620	37.1	50
Karnataka	Bangalore	33	3680	2310	1360	36.6	80
Karnataka	Bellary	33	3820	2670	1700	26.1	70
Madhya Pradesh	Raipur	19	3060	1530	950	40.4	30
Madhya Pradesh	Indore	19	3250	1570	860	40.4	30
Madhya Pradesh	Jhabua	19	1680	1140	260	24.5	20
Madhya Pradesh	Jabalpur	19	4740	1430	920	60.3	50
Madhya Pradesh	Ratlam	19	3230	1450	870	46.3	30
Madhya Pradesh	Sagar	19	3340	1420	840	55.4	30
Madhya Pradesh	Gwalior	19	5760	3290	2290	27.9	30
Maharashtra	Sholapur	24	3350	1520	970	49.0	50
Maharashtra	Nanded	25	1890	810	370	86.4	30
Maharashtra	Akola	26	2490	1020	500	49.7	40
Maharashtra	Wardha	26	3210	1310	590	54.3	50
Maharashtra	Nagpur	26	3610	1170	680	53.8	40
West Bengal	Mohanpur	6	4360	3340	2290	54.3	80
West Bengal	Barrackpore	6	3700	2830	2180	71.5	70
West Bengal	Calcutta	6	2620	1430	50	23.4	110

At the state level, the simulated wheat rain-fed potential yield was the highest in West Bengal, followed by Gujarat and Madhya Pradesh (Fig. 20). The lowest potential yield of 1180 kg ha^{-1} was in Maharashtra. The overall mean rain-fed potential yield in India was 1720 kg ha^{-1}. The experimental potential yields were also the highest for West Bengal, followed by Madhya Pradesh. The lowest yields were reported in Gujarat (Fig. 20). In the on-farm experiments, the trend was the same.

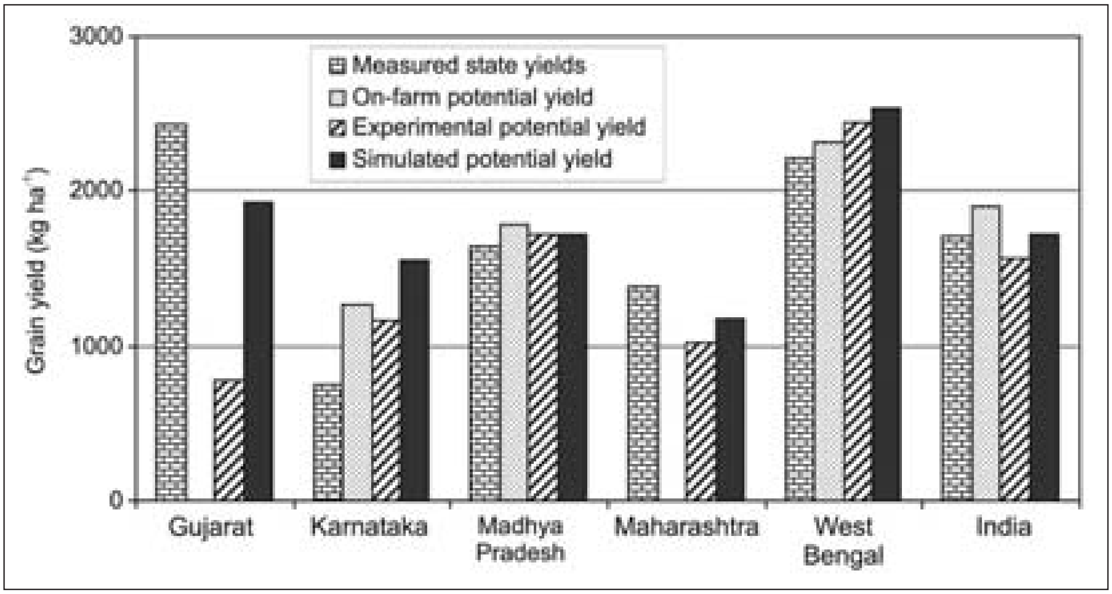

Figure 20. Comparison of simulated, experimental and on-farm rain-fed potential yields and the measured state average yields of wheat. Note that the measured yields are average of irrigated as well as rain-fed areas and a large proportion of wheat is irrigated in most states.

Measured yields

The state average yields were often higher than the simulated rain-fed potential yields (Fig. 20). This was due to the fact that a large proportion of wheat is irrigated in most states that result in higher measured yields compared to experimental and simulated yields in rain-fed environments. Measured yields were the highest in Gujarat and West Bengal and were low in the southern states of Maharashtra and Karnataka due to warmer temperatures, resulting in shorter crop season.

Yield gaps

Since the measured yields were significantly large due to confounding effect of irrigation, in most cases yield gaps were either nil or rather small (Table 12). Karnataka, West Bengal and Madhya Pradesh showed a gap of 100 kg ha^{-1} to 800 kg ha^{-1} whereas Gujarat and Maharashtra showed no gap at all.

Options to bridge yield gaps

The simulation results indicated that the strategy to increase rain-fed yields is to provide supplementary irrigation. This was evident when the mean simulated rain-fed potential yields were compared with the maximum yields (Fig. 21). Improved nitrogen management could reduce yield gaps to a limited extent in most states (Fig. 21).

Table 12. Calculated yield gaps of wheat from simulated, experimental and on-farm potential yields[1].

	Yield gap (kg ha^{-1})			
State	Simulated rain-fed potential	Experimental potential	On-farm potential	Average
Gujarat	0	0	0	0
Karnataka	800	420	510	580
Madhya Pradesh	80	80	150	100
Maharashtra	0	0	0	0
West Bengal	320	230	110	220
India	10	0	200	70

1. Note that the gaps calculated would be higher than the actual for rain-fed conditions because the measured yields include data from irrigated areas as well.

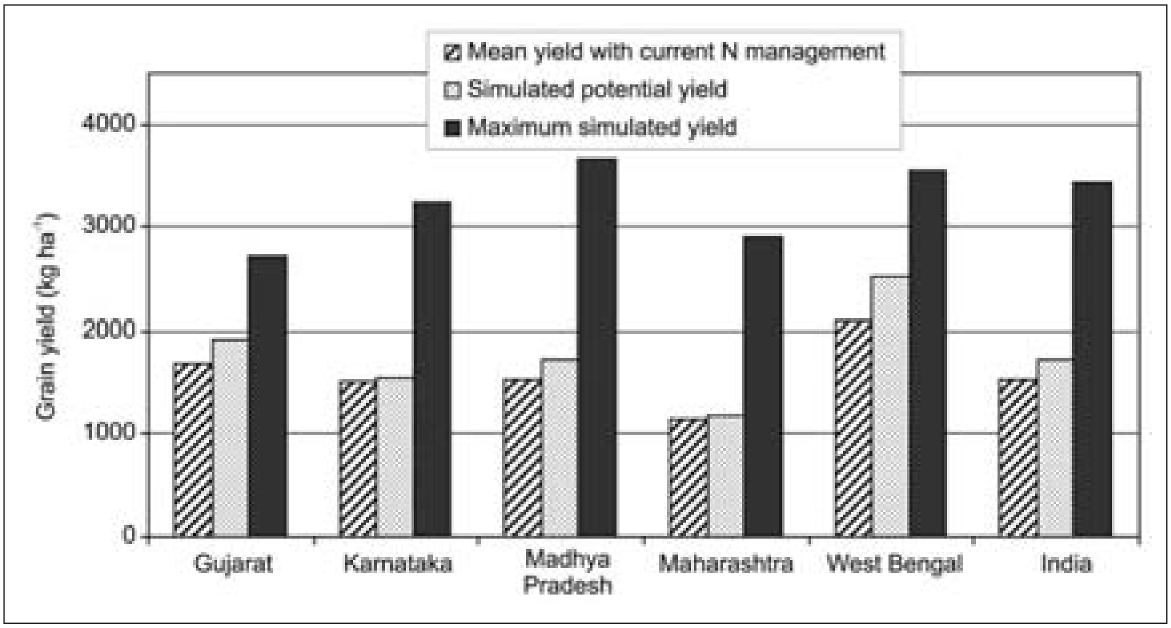

Figure 21. Simulated options to increase rain-fed yields in different states.

4. Conclusions

These studies have shown that there are still considerable yield gaps in rain-fed crops that can be bridged in future to meet the increasing food requirements. At the country level, the gaps appeared to be the smallest in wheat (70 kg ha^{-1}) and the largest in rice (1670 kg ha^{-1}). In all crops, these gaps could be larger than our calculations if the yield data from irrigated areas could be separated in the measured state data. Data on rain-fed yields separately at state level was not available. At the same time, the simulated rain-fed potential yields for the state, as calculated in this report, are the arithmetic mean of all locations/seasons/varieties of that state. This could cause some errors because of the relative differences in the edaphic and climatic conditions among different locations and their distribution in the state. To overcome this, a more detailed analysis using GIS is required. This is currently being done in our laboratory. Nevertheless, these small differences are not likely to cause any major change in the assessment of the magnitude of yield gaps.

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The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a nonprofit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Centers of the Consultative Group on International Agricultural Research (CGIAR).

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