6 Yield Gap Analysis: Modelling of Achievable Yields at Farm Level

P. Singh,[1]* P.K. Aggarwal,[2] V.S. Bhatia,[3]*** M.V.R. Murty,[1]**** M. Pala,[4] T. Oweis,[4]***** B. Benli,[4] K.P.C. Rao[5]****** and S.P. Wani[1]*******

[1]*International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India;* [2]*Indian Agricultural Research Institute (IARI), New Delhi 110 012, India;* [3]*National Research Centre for Soybean (NRCS), Khandwa Road, Indore 452 017, Madhya Pradesh, India;* [4]*International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria;* [5]*International Center for Research on Agroforestry (ICRAF), Nairobi, Kenya;*
*emails: *p.singh@cgiar.org; **pramodag@vsnl.com; ***Bhatia_virender-singh@hotmail.com; ****murtymur@rediffmail.com; *****t.oweis@cgiar.org; ******k.p.c.rao@cgiar.org; *******s.wani@cgiar.org*

Introduction

The world population is expected to reach about 8 billion by 2025 (United Nations, 2006), before it stabilizes at about 10–11 billion towards the end of the 21st century. Most of this increase in population is expected to occur in less-developed countries, where most of the poor live and where rainfed agriculture forms the dominant basis for livelihood security. Asia and Africa will be the major contributors to this increase in population (Table 6.1). More food will be needed in future in view of expected increases in population, the extent to which malnutrition is to be overcome and the changing food habits of people towards more animal-based foods. Many countries in Asia and Africa will have to import more food to meet their food requirements in future (Table 6.1). At least in the foreseeable future, plants, especially the cereals, will continue to supply much of our increased food demand, both for human consumption and as feed for livestock to satisfy the rapidly growing demand for meat, milk and eggs in the newly industrialized countries. It is estimated that an additional 1 billion t of grain will be needed annually by 2025. Most of this increase must be supplied from lands already in production, through yield improvements (Borlaug, 2001).

Much of the past progress in boosting agricultural productivity has taken place in more favourable irrigated areas. Prospects of further irrigation developments are limited in Asia, and despite high development potential in sub-Saharan Africa (SSA), the last decades have shown a decline in irrigation expansion. In the last few decades the emerging evidence indicates that crop productivity growth in irrigated areas has slowed or stagnated due to multiple factors. As sources of growth in irrigated areas decline, rainfed agriculture must increase to fill the gap. Because of population increase and competing demands for land for other sectors of the economy, especially in the South Asian region, most of the increase in food production will have to take place from increase in productivity per unit of land rather than area increase under agriculture.

Table 6.1. Current and expected population increase, food demand and net import in the selected regions of the world[a].

Region	Current population (million)	Expected population in 2025 (million)	Food demand in 1995 (million t)	Expected food demand in 2025 (million t)	Net import in 1995 (million t)	Expected net import in 2025 (million t)
South-east Asia	558	686	113.5	176	7	6.2
South Asia	1646	2146	226.2	376.3	0.2	40.1
Sub-Saharan Africa	769	1194	78.4	172.4	9.8	34.9
West Asia and North Africa	402	548	120.2	202	37.8	83
World	6671	8011	1778.6	2606.4	–	–

[a] Source: Rosegrant *et al.* (2002); United Nations (2006).

The semi-arid regions of Asia and Africa are primarily dependent on rainfed agriculture, where the agricultural productivity of rainfed systems is low. Sub-Saharan Africa and South Asia will remain 'hot spots' of child malnutrition, food insecurity and poverty, where underdevelopment, rapid population increase, land degradation, climate uncertainty and water scarcity, and unfavourable government policies are the major bottlenecks to achieving higher agricultural production and improved rural livelihoods. Future climate change due to global warming will have a negative effect on crop yields, thus making the matter worse in achieving the Millennium Development Goals of food security in the developing world.

While the food production increases in future must occur in the rainfed areas of Asia and Africa, it is also important to know where, how and how much additional food can be produced in different regions to meet the increasing food demand. Estimates of the potential production of regions can assist in quantifying carrying capacity of agroecosystems. The purpose of this chapter is to quantify the potential yields and yield gaps between the potential and the actual yields obtained by the farmers for the major rainfed crops grown in the selected countries in South and South-east Asia (India, Thailand and Vietnam), SSA and the West Asia and North Africa (WANA) region, where food security in future is increasingly threatened because of expected increase in population and degradation of natural resources. This analysis will help identify the opportunities and constraints for yield improvement in future with the implementation of the improved crop production and natural resource management technologies for the rainfed regions.

Data and methods adopted to quantify potential yields and yield gap of crops varied across countries, depending upon the nature of data availability to perform such analyses. Broadly, the potential yields and yield gaps of the crops were estimated based upon the data generated through crop simulation methods, research station yield maximization trials, on-farm technology demonstrations with improved management, and farmers' actual yields reported at state, district or province level by each country.

Yield Gap Analysis of Crops in South and South-east Asia

Yield gap analysis of rainfed crops in India

By 2025, India's population is expected to reach 1.45 billion from the current level of 1.17 billion (United Nations, 2006). The cereal requirement of India by 2020 will be between 257 and 296 million t, depending on income growth (Kumar, 1998; Bhalla *et al*., 1999). It is necessary that food production in India must increase by about 5 million t annually for the next 25 years to ensure food and nutritional security to the burgeoning population (Kanwar, 2000). Irrigated green revolution areas are already showing signs of fatigue due to further increase in crop production. It is believed that rainfed areas, which cover almost 70% of the total land area under agriculture in India, would have a greater share in meeting the future food needs of the country due to increasing population (Kanwar, 2000; Singh *et al.*, 2000). By 2020, about 600 million people would be living in rainfed regions besides an estimated 650 million head of livestock. The current level of productivity of rainfed cereals ranges from 520 to 1320 kg/ha and that of pulses from 540 to 650 kg/ha, which is quite low compared with what can be potentially achieved. The per capita land availability in rainfed areas is expected to fall from 0.28 ha in 1990 to 0.12 ha by 2020 (Singh *et al.*, 2000). It means more food has to be produced from each unit of land to meet the growing food needs in future.

Biophysical environment and production systems of the rainfed areas

The rainfed areas are spread out widely in the country from north to south and east to west. They can be broadly classified into arid, semi-arid (dry), semi-arid (wet) and dry subhumid agroecologies (Fig. 6.1 and Table 6.2). These agroecologies vary substantially in their production potential, cropping systems being followed by the farmers and the constraints limiting production. There are six major soil orders that dominate the rainfed areas of India (Fig. 6.1 and Table 6.2). The soils of the semi-arid tropics (SAT) are poor in fertility, low in organic matter, prone to severe degradation, undulating in physiography and shallow in depth. Vegetative cover is sparse due to the extended period of aridity and over-exploitation for crop production and grazing. Lack of surface cover promotes erosion due to run-off water and wind (Wani *et al.*, 2003a). Most dryland soils are deficient in nitrogen and phosphorus. Vertisols developed on granite and sedimentary rocks are more deficient in phosphorus than those on basalt (Singh and Venkateswarlu, 1985). In the SAT, the deficiency of potassium was noticed in certain coarse-textured soils, some red soils and in soils on which high crop yields were obtained without potassium application for a long period (Venkateswarlu, 1987). In addition to the three critical elements, widespread deficiency of sulfur, zinc, boron and iron have also been reported (Rego *et al.*, 2007). The opportunities for water harvesting increase from arid agroecology to dry subhumid agroecology with an increase in amount of rainfall. Rainfed agriculture in these agroecologies is rarely practised as a single crop or livestock system. Mixed farming and diversity are the main features. The major crop production systems of rainfed agriculture are rainfed rice and wheat, coarse cereals (sorghum, pearl millet and maize), pulses (pigeonpea and chickpea), oilseeds (soybean, groundnut, sunflower, rape seed and mustard) and cotton. These crops have a significant role in the economy of a given area in view of the area and production.

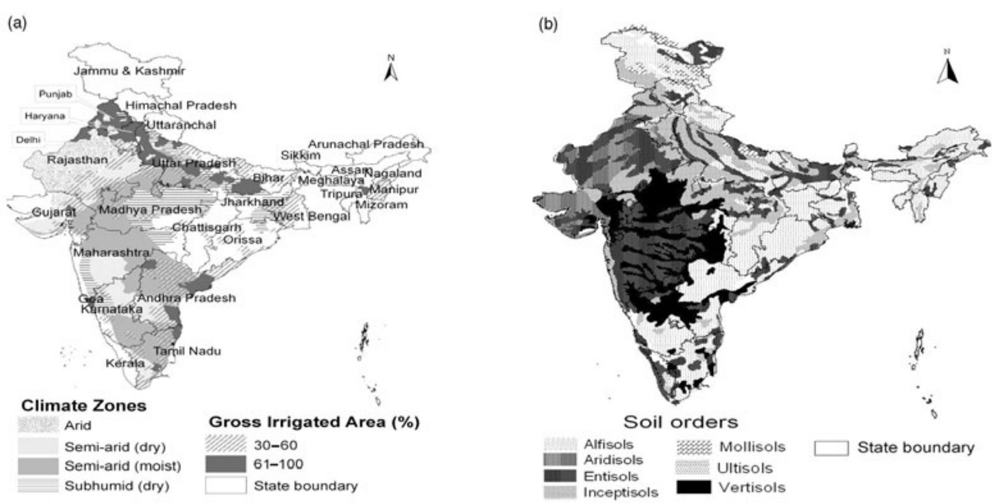

Fig. 6.1. (a) Climate zones and states and (b) soils of India.

Table 6.2. Biophysical characteristics and dominant production systems of various rainfed agroecologies of India[a].

	Agroecology			
Attributes	Arid	Semi-arid dry	Semi-arid wet	Subhumid dry
% of geographical area	19.6	12	25.9	21.1
Rainfall (mm)	<500	501–700	701–1100	1101–1600
Soils	Aridisols, vertic-vertisols	Vertisols, vertic inceptisols, alfisols	Vertic inceptisols, alfisols, entisols	Vertisols, vertic soils, alfisols, mollisols, entisols
Length of growing period (days)	60–90	90–120	120–150	150–210
Production systems	Pearl millet, short-duration pulses, perennials and livestock farming	Pearl millet, groundnut, *kharif* and *rabi* sorghum and cotton-based systems	Soybean-based, maize-based and sorghum-based systems	Rainfed rice followed by pulses and oilseeds

[a] Source: Singh *et al.* (2000).

Methods of yield gap analysis

The potential yields were estimated using a crop simulation approach and review of research station experimental data. The yields estimated coupled with the state-level yields were used to estimate the yield gaps for a particular crop as described below.

SIMULATED RAINFED POTENTIAL YIELDS This is the potential yield of an improved variety simulated by the crop growth model under optimal management conditions, except that water availability is the main limiting factor for crop growth. We used Decision Support System for Agrotechnology Transfer (DSSAT) v3.5 software (Hoogenboom *et al*., 1999) to simulate potential yields of sorghum, pearl millet, maize, soybean, groundnut and chickpea; InfoCrop software (Aggarwal *et al*., 2006) for rice and cotton, and APSIM software (McCowen *et al*., 1995) for pigeonpea. All the crop models in these software need similar kind of weather (daily solar radiation, maximum and minimum temperatures and rainfall) data, soil profile data and cultivar-specific parameters (genetic-coefficients) to simulate crop growth, yield and resource use by the crops. Multi-year simulation of the rainfed potential yield of a crop was carried out for several locations in a state and averaged over time and space to estimate the rainfed potential yields. These have been described in detail for legumes by Bhatia *et al*. (2006) using DSSAT. A similar method was followed for other crops using APSIM or InfoCrop software.

EXPERIMENTAL STATION YIELDS This is the maximum possible rainfed yield of an improved cultivar usually obtained at the experimental stations in research plots under good care and supervision when factors other than water availability have minimal effect on limiting crop growth. To obtain these yields, the annual reports of the All India Coordinated Research Projects (AICRPs) of various crops since the late 1990s were reviewed. The yields obtained for the top five entries of legumes (soybean, groundnut, chickpea and pigeonpea) and of all the entries of cereals (sorghum, pearl millet and maize) were averaged for each year and location to calculate the rainfed yield potential. These were further averaged over the years and compared with the state/district level average yields for estimating yield gap.

STATE MEAN YIELDS State mean yields were determined from the area and production data of a crop for each district in a state. Total production was divided by the total area under the crop in a state to calculate state mean yield. Mean yields were then further averaged over the years (number of years depending upon the data availability) and compared with the potential yields to estimate yield gaps.

YIELD GAPS Yield gaps were quantified using simulated potential yields, experimental potential yields and the state mean yields, all obtained under rainfed conditions. Simulated yield gap was the difference between the simulated mean potential yield and the mean state yield. The experiment station yield gap was calculated as the difference between the experiment station mean yield and the mean state yield.

Potential yield and yield gap of cereals

RICE Rice in India is grown almost throughout the country except for the arid eastern parts of Rajasthan. Of the 43 million ha of harvested rice area, almost 51% is now irrigated. Most of the rice-producing areas of Punjab, Haryana, Andhra Pradesh and Tamil Nadu are irrigated. Rainfed rice is grown in several states, such as West Bengal, Uttar Pradesh, Orissa, Bihar, Assam, Karnataka, Maharashtra, Madhya Pradesh and Jharkhand. The production of rice in India has increased from 42.7 million t during 1972–1976 to 85.3 million t during 2002–2006 (Table 6.3). This has been due to an increase in the area under rice in the initial years and later due to an increase in yield per ha and irrigation coverage.

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 area of India. The mean yield of rice is more than 3000 kg/ha in several districts of Punjab, Haryana, Andhra Pradesh and Tamil Nadu. Farmers in these states have much higher per capita income than do the traditional rice-growing states of eastern India. The yields are generally less than 2000 kg/ha in central Indian rainfed states such as Madhya Pradesh and in eastern Indian states such as Orissa and Bihar (Fig. 6.2), where the production is strongly associated with the distribution of rainfall. 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 relate to the land and soil, such as soil acidity in southern and eastern India, salinity and alkalinity in northern India.

Table 6.3. Area, production and yield of cereals from 1972–1976 to 2002–2006 in India[a].

Attribute	1972–1976	1982–1986	1992–1996	2002–2006
Rainfed rice				
Area (million ha)	38.2	40.6	42.7	43
Production (million t)	42.7	58.0	78.7	85.3
Yield (kg/ha)	1120	1430	1840	2000
% irrigated area	39	43	49	50
Maize				
Area (million ha)	6.0	5.8	6.1	7.4
Production (million t)	6.3	7.4	9.8	13.8
Yield (kg/ha)	1050	1280	1630	1870
% irrigated area	17.7	19.2	21.5	19.3
Kharif sorghum				
Area (million ha)	10.3	10.1	6.4	4.1
Production (million t)	6.6	7.7	7.2	4.1
Yield (kg/ha)	640	760	1130	1000
Rabi sorghum				
Area (million ha)	5.8	6.1	5.6	4.9
Production (million t)	2.7	3.0	3.5	3.3
Yield (kg/ha)	460	490	640	640
Pearl millet				
Area (million ha)	11.9	11.1	9.9	9.3
Production (million t)	5.3	5.4	6.9	8.1
Yield (kg/ha)	440	490	680	870

[a] Source: GOI (2006).

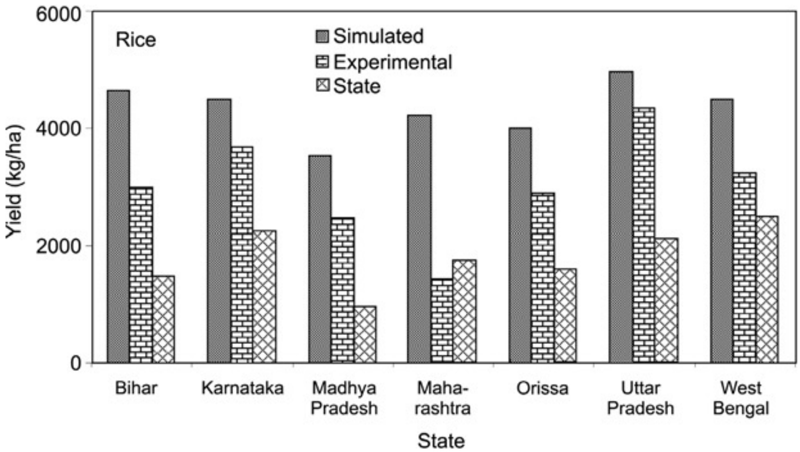

Fig. 6.2. Mean simulated potential, experimental and measured state-level yields of rice in India. Note that measured yields are average values of irrigated and rainfed areas.

The simulated rice yields varied considerably across major rainfed states, depending upon rainfall, soil and other location-specific factors. The mean rainfed simulated potential yield varied from 3540 kg/ha in Madhya Pradesh to 4970 kg/ha in Uttar Pradesh (Fig. 6.2). The experimental potential yields showed a large variation from 1420 kg/ha in states such as Maharashtra to 4350 kg/ha in Uttar Pradesh. The farmers' mean yields at the state level showed considerable variation (Fig. 6.2). These were lowest in Madhya Pradesh followed by Bihar and Orissa. By comparison, the mean yields in Karnataka, Uttar Pradesh and West Bengal were more than 2000 kg/ha. It is difficult to draw any meaningful conclusion from such state mean yields because a considerable fraction of these were from irrigated areas. Nevertheless, rainfed yields in these states will be lower still than the values presented here.

The results showed that, irrespective of the definition of potential yield, there is a considerable yield gap across all states, indicating a large scope for increasing rainfed rice yields in future. On average, the gap relative to simulated potential was close to 2500 kg/ha. It was more than 3000 kg/ha for Bihar and less than 2000 kg/ha for West Bengal. At the experimental station level, the gap varied from 740 kg/ha (in West Bengal) to 2230 kg/ha (in Uttar Pradesh). This value was around 1500 kg/ha in all other states.

MAIZE Maize is the third most important crop in terms of total production among cereals in India. The five major states producing maize in the country are Madhya Pradesh, Bihar, Karnataka, Uttar Pradesh, Rajasthan and Andhra Pradesh. Most of the maize (about 90%) in India is grown during the summer monsoon season (*kharif*) under rainfed condition. It currently occupies 7.4 million ha with production of 13.8 million t with an average productivity of about 1870 kg/ha (Table 6.3). The increase in production of maize over the years in India has been because of increase in both area and yield of the crop. Maize cultivation in most of the states is under moderate input supply conditions due to various biophysical and socio-economic drivers which have held back the maize yield. Thus, there is greater scope to increase its productivity from the current levels.

The maize yields were simulated for Madhya Pradesh (Guna and Indore), Bihar (Patna), Uttaranchal (Pantnagar), Uttar Pradesh (Varanasi), Rajasthan (Kota) and Andhra Pradesh (Hyderabad). The simulated yields for most of the states were higher than the experimental yields and ranged from 4320 to 6630 kg/ha across states (Fig. 6.3). The experimental yields ranged from 3160 to 4640 kg/ha across states. These yields were almost double the actual state-level yields, which ranged from 1090 to 2460 kg/ha across states. The yield gap

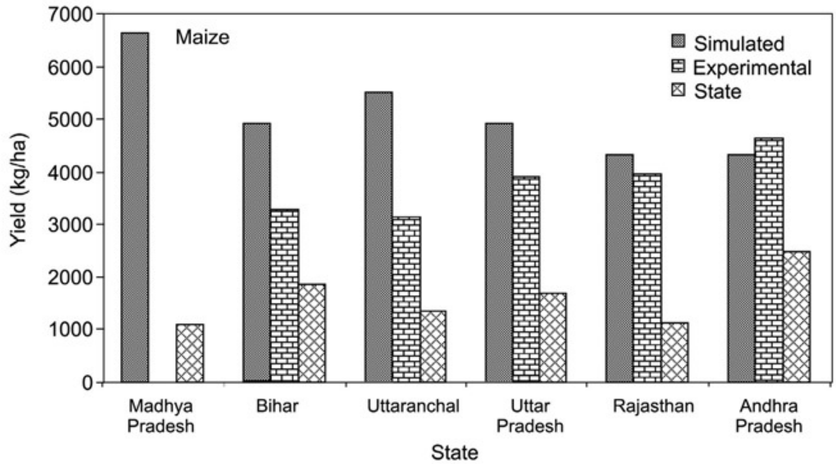

Fig. 6.3. Mean simulated, experimental and measured state-level yields of maize in India.

based on the mean simulated yields ranged from 1860 to 5540 kg/ha across states; the highest yield gap was for Madhya Pradesh and the lowest for Andhra Pradesh. Based upon the experimental yield, the yield gap across locations ranged from 1430 to 2840 kg/ha across states. These results show that the farmers' yields under rainfed situations can be more than doubled in the states through proper agronomic management involving improved varieties and soil fertility management.

SORGHUM Sorghum is grown in India during both the rainy (*kharif*) and post-rainy (*rabi*) seasons. It is an important source of food for people and fodder for livestock in the rainfed regions of India. The total area under *kharif* sorghum has declined from 10.3 million ha during 1972–1976 to 4.1 million ha during 2002–2006 (Table 6.3). Similarly, total production declined from 6.6 million t to 4.1 million t after some increase during the early 1980s and 1990s. However, the yield per ha increased from 640 to 1000 kg/ha. Maharashtra is the largest *kharif* sorghum growing state with about 1.8 million ha out of the total 4.1 million ha grown in India. Madhya Pradesh and Rajasthan come next with 0.61 million ha each, followed by Karnataka with 0.34 million ha. Maharashtra produces 2.3 million t out of a total production of 4.10 million t of sorghum produced in the country. Uttar Pradesh, Andhra Pradesh, Tamil Nadu and Gujarat are the other states having a large area under sorghum.

Kharif sorghum. The mean simulated rainfed potential yield in Karnataka was the highest (3640 kg/ha), followed by Madhya Pradesh (3610 kg/ha) and Maharashtra (3220 kg/ha). The experimental station yields ranged from 2280 to 4580 kg/ha, the highest being for Karnataka and the lowest for Uttar Pradesh. Based on the simulated yields, the yield gap ranged from 1940 to 2750 kg/ha. However, based on the experiment station yields, the yield gaps were low and ranged from 1340 to 3280 kg/ha across states (Fig. 6.4). These results on yield gap indicate the potential to enhance productivity of *kharif* sorghum in different states by adopting improved agronomic management practices of sorghum production.

Rabi sorghum. Mean experimental potential yields for the three major states ranged from 1940 to 2960 kg/ha, the highest being for Andhra Pradesh and the lowest for Maharashtra (Fig. 6.5). The simulated potential yields were lower than the experimental station yields, which were 1110 kg/ha for Maharashtra and 1640 kg/ha for Karnataka. This is because rainfed simulations were carried out for a longer period, often for 15–26 years for each location, than the number of years for which the experimental data were available. Thus, the simulations captured

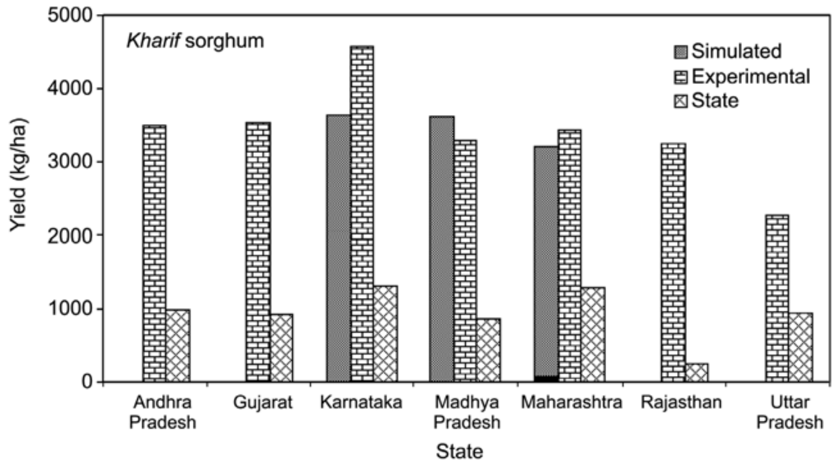

Fig. 6.4. Mean simulated, experimental and measured state-level yields of *kharif* sorghum in India.

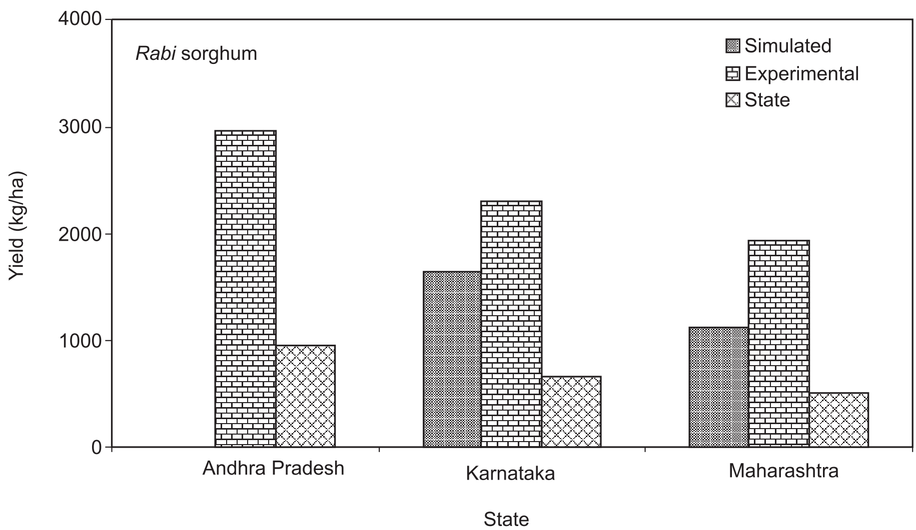

Fig. 6.5. Mean simulated, experimental and measured state-level yields of *rabi* sorghum in India.

more effects of temporal and spatial variations in rainfall on crop yields than the experimental yields. Based upon the experimental yields, the yield gap ranged from 1430 to 2020 kg/ha for the three states. However, the yield gap between the simulated potential yield and the state yield was 600 kg/ha for Maharashtra and 990 kg/ha for Karnataka. These results indicate that *rabi* sorghum yields in the three states can at least be doubled with improved crop management practices comprising improved variety, nutrient management and timely sowing of the crop immediately after the cessation of monsoon rains. Supplemental irrigation to the crop would further enhance the crop yields.

Total area of *rabi* sorghum in the country has decreased from 5.8 million ha in 1972–1976 to 4.9 million ha in 2002–2006; however, total production has increased from 2.7 million t to 3.3 million t during the same period (Table 6.3). This was possible due to an increase in yield from 460 kg/ha to 640 kg/ha during the span of 30 years. Maharashtra has the largest area (3.21 million ha) under *rabi* sorghum followed by Karnataka (1.45

million ha) and Andhra Pradesh (0.35 million ha).

Unfavourable 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 preventing the significant increase in productivity of *rabi* sorghum in a sustainable manner. Therefore, the input components, including supplemental irrigation, rather than the high-yielding varieties of *rabi* sorghum, were responsible for the increase in productivity.

PEARL MILLET The total area under pearl millet decreased from about 11.9 million ha during 1972–1976 to about 9.3 million ha during 2002–2006 (Table 6.3). Total production increased from 5.3 million t during 1972–1976 to 8.1 million t during 2002–2006. This increase in production was because of an increase in yield from 440 kg/ha to 870 kg/ha during the same period. Rajasthan has the highest area (4.74 million ha) under pearl millet production. Other states cover about 0.61 million ha under pearl millet. The average yields across states range from 670 to 1280 kg/ha.

Mean simulated rainfed yield of Rajasthan was the lowest at 1460 kg/ha, whereas Madhya Pradesh had the highest mean yields of 2530 kg/ha. Karnataka and Maharashtra had a simulated mean yield of 2170 kg/ha and 2000 kg/ha, respectively (Fig. 6.6). The potential yields for Andhra Pradesh, Gujarat, Haryana and Tamil Nadu could not be simulated because of the lack of input data for executing the pearl millet model. The experimental potential yields were the lowest at 1440 kg/ha for Rajasthan and the highest at 3550 kg/ha for Tamil Nadu. The yield gap between simulated mean yield and state-level mean yield ranged from 670 to 1660 kg/ha, the lowest being for Rajasthan. Yield gaps based on experimental data were low for Rajasthan, Haryana and Gujarat and ranged from 610 to 920 kg/ha, whereas for other states, the yield gaps ranged from 1260 to 2480 kg/ha and the highest was for Tamil Nadu. These results show that, except for Gujarat, Haryana and Rajasthan, the farmers' yield can be more than doubled with improved crop production technology including improved varieties and nutrient management.

Potential yield and yield gap of pulses

India is the largest producer of pulses in the world. They are important for protein production, nitrogen-fixing ability and adaptability to cropping systems. Among these, pigeonpea and chickpea are the most important ones. Often these form part of the intercropping, sequence cropping or traditional mixed seeding systems,

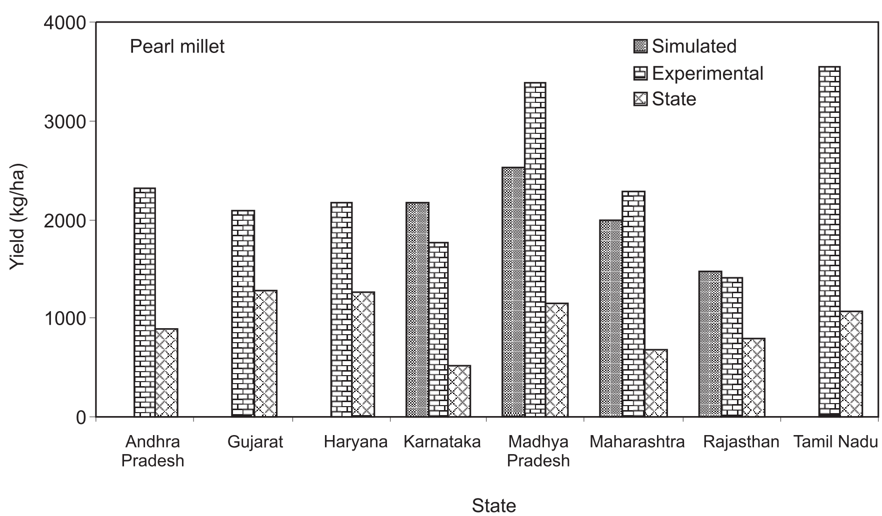

Fig. 6.6. Mean simulated, experimental and measured state-level yields of pearl millet in India.

providing the much-needed stability to the production system. Pigeonpea, particularly owing to its long duration, is often intercropped with short-duration cereals, so that the land equivalent ratio is optimized. Over 90% of pigeonpea, mainly long-duration and medium-duration cultivars, is grown in dryland areas as a mixed crop or intercropped with cereals (sorghum, maize, pearl millet), legumes (groundnut, soybean, black gram, green gram, cowpea) and commercial crops (cotton, castor, cassava) (Singh *et al.*, 2000). However, more recently short-duration pigeonpea is being grown as a sole crop during the rainy season in some areas in north India as part of the crop rotation in the rice–wheat production system.

PIGEONPEA Over the years, the area under pigeonpea in India has increased from about 2.6 million ha during 1972–1976 to 3.5 million ha during 2002–2006 (Table 6.4). However, during the corresponding years, the total production has been fluctuating and ranged from 1.8 million t in 1972–1976 to 2.4 million t during 2002–2006. This increase in production was primarily because of an increase in the area under pigeonpea rather than an increase in productivity. Among the states, Maharashtra has the largest area (1.03 million ha), which accounts for 31% of the total pigeonpea area in the country. The other five states, namely Uttar Pradesh, Karnataka, Gujarat, Madhya Pradesh and Andhra Pradesh, each having an area of about 10–12%, together contribute 60% of the total pigeonpea area in the country.

Average simulated potential yields across the states ranged from 830 to 1960 kg/ha, the lowest being for Gujarat and the highest for Uttar Pradesh (Fig. 6.7). The experimental station mean yields across states ranged from 1370 to 1840 kg/ha, which were somewhat higher than the mean simulated yields for most of the states. Among the states, the average state-level productivity was the highest for Uttar Pradesh (1090 kg/ha), followed by Gujarat (880 kg/ha) and Madhya Pradesh (810 kg/ha). The average productivity was less than the national average (690 kg/ha) in Maharashtra (610 kg/ha), Karnataka (410 kg/ha) and Andhra Pradesh (330 kg/ha). Both the simulated and the experimental station yields indicated that in major pigeonpea-growing regions in India, the average rainfed

Table 6.4. Area, production and yield of legumes (pulses and oilseeds) and cotton from 1972–1976 to 2002–2006 in India[a].

Attribute	1972–1976	1982–1986	1992–1996	2002–2006
Pigeonpea				
Area (million ha)	2.6	3.1	3.5	3.5
Production (million t)	1.8	2.4	2.4	2.4
Yield (kg/ha)	700	760	700	690
Chickpea				
Area (million ha)	7.6	7.3	6.9	6.8
Production (million t)	4.8	5.0	5.3	5.4
Yield (kg/ha)	630	690	770	790
Soybean				
Area (million ha)	0.1	1.1	4.6	7.2
Production (million t)	0.1	0.8	4.5	7.3
Yield (kg/ha)	880	700	980	1000
Groundnut				
Area (million ha)	7.1	7.2	7.9	6.2
Production (million t)	5.4	6.0	8.1	6.4
Yield (kg/ha)	770	830	1030	1020
Cotton				
Area (million ha)	7.4	7.5	8.2	8.4
Production (million t)	6.2	7.6	12.2	15.7
Yield (kg/ha)	140	170	250	310

[a] Source: GOI (2006).

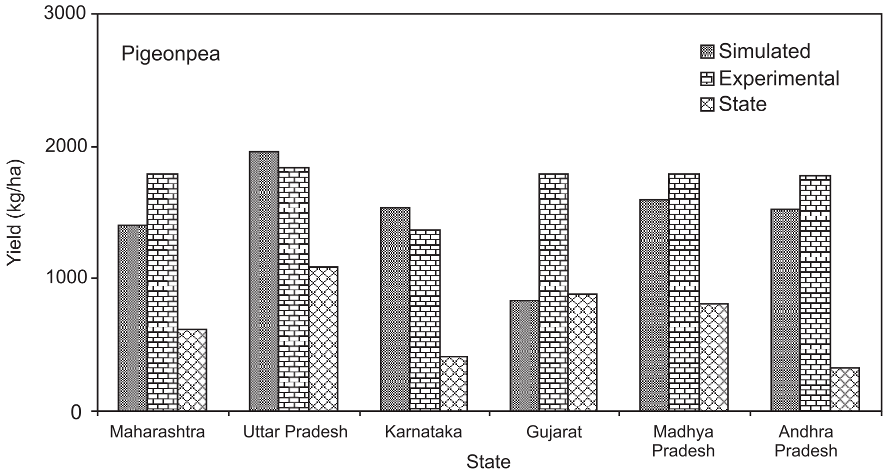

Fig. 6.7. Mean simulated, experimental and measured state-level yields of pigeonpea in India.

potential is almost double as compared with the national average (690 kg/ha) and indicates that there are ample opportunities for improving the production and productivity of the pigeonpea crop in India.

CHICKPEA India is the largest producer of chickpea in the world. It accounts for 61% of the total area and 66% of total production in the world. In India chickpea represents 32% (6.8 million ha) of the total pulses area and 49% (5.4 million t) of the total pulses production. During 1972–1976, chickpea was cultivated in 7.6 million ha with a production of 4.8 million t. After 1972–1976, the area under chickpea gradually decreased, whereas the average production showed a slight increase (Table 6.4). During 2002–2006, the area and production of chickpea was 6.8 million ha and 5.4 million t, respectively. The productivity of the crop has been fluctuating greatly and has shown an increase from 630 kg/ha in 1970 to 790 kg/ha during the same period. Being a *rabi* crop, chickpea fits very well in the sequence cropping systems in north and central India (Singh *et al*., 2000).

With an area of about 2.6 million ha and production of 2.4 million t, Madhya Pradesh alone contributes 37% of the total area and 42% of the total production of chickpea in the country. The soybean–chickpea cropping system has become a well-established and profitable cropping system in the rainfed area of this state. Other major chickpea-producing states are Rajasthan (1.08 million ha), Maharashtra (1.02 million ha), Uttar Pradesh (0.74 million ha), Karnataka (0.42 million ha) and Andhra Pradesh (0.39 million ha). Average yield in these states ranges from 550 to 1590 kg/ha, with Andhra Pradesh having the highest yield (GOI, 2006).

Across the chickpea-growing states, the average potential yield of chickpea ranged from 1250 to 2120 kg/ha. The major rainfed area under chickpea in India is spread across Madhya Pradesh, Maharashtra and Karnataka. The average simulated yields in these states were 1620, 1860 and 2120 kg/ha, respectively. The average experimental station yields for these states were 2060, 1460 and 1350 kg/ha, respectively (Fig. 6.8). Average state-level productivity of Madhya Pradesh, Maharashtra and Karnataka is 880, 560 and 460 kg/ha, respectively. Rajasthan and Uttar Pradesh, where the crop is grown with supplemental irrigation, have productivity levels of 830 and 870 kg/ha, respectively. In general, it is evident from the simulated as well as the experimental station yields that the potential of rainfed chickpea in the major geographical regions is between 1250 and 2200 kg/ha, which is substantially higher than the present national average of about 800 kg/ha. Chickpea yield

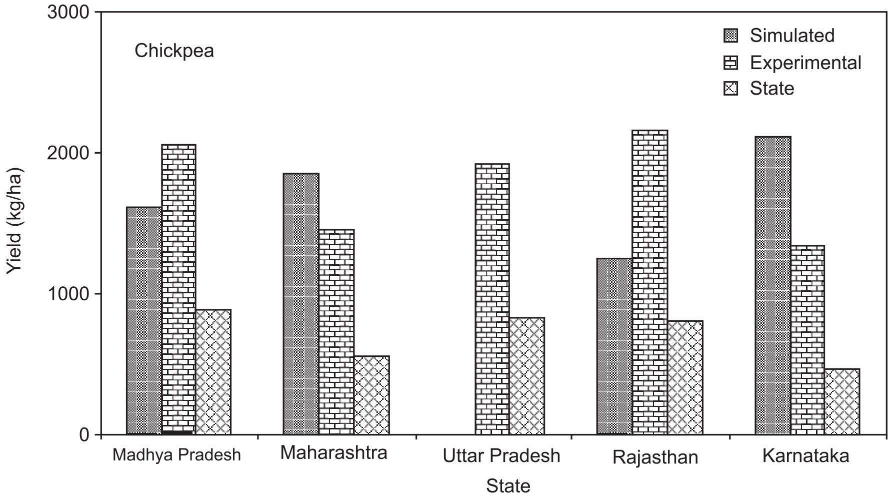

Fig. 6.8. Mean simulated, experimental and measured state-level yields of chickpea in India.

gaps can be bridged by adoption of high-yielding varieties and improved agronomic management. Supplemental irrigation will be an essential component of technologies to increase productivity of chickpea in India.

Potential yield and yield gap of oilseeds

India occupies a premier position with regard to oilseed production, covering 19% of the area and 10% of the production in the world (Singh *et al.*, 2000). All the oilseed crops together are grown on an area of 25.3 million ha, which is next only to food grains. The multiplicity of crops and growing environments makes India's oilseed production scenario a complex one. By and large, the production always lags behind the requirement. Groundnut, rapeseed, mustard, sunflower, safflower, soybean, sesame and castor are the important oilseed crops. Most of these crops are grown under rainfed conditions and on poor soils constrained with water and nutrient stresses. The production and productivity of these oilseeds have remained more or less stagnant but for a modest gain in selected crops following the launching of the technology mission on oilseeds (Singh *et al.*, 2000). Considering their importance in terms of area and production, only soybean and groundnut are dealt with in these yield gap studies.

SOYBEAN In India, soybean has shown a spectacular growth in production, which increased from 0.1 million t in 1972–1976 to 7.3 million t in 2002–2006. This was primarily due to an increase in the area under soybean with moderate yield enhancement from 880 kg/ha to 1000 kg/ha during the same period (Table 6.4). The soybean crop is primarily cultivated in three states, namely Madhya Pradesh, Maharashtra and Rajasthan, which contribute 98 and 99% of the total soybean area and production of the country, respectively. However, among these three states Madhya Pradesh, with 4.23 million ha area and 4.29 million t of production, is the dominant state with a net 71 and 74% contribution to total soybean area and production in the country.

Two major soybean-growing states in the country (Madhya Pradesh and Maharashtra) have a rainfed yield potential of more than 2000 kg/ha, which is more than double as compared with the existing national productivity of less than 1000 kg/ha. The potential yield was found to be marginally low in Karnataka (1750 kg/ha), while Rajasthan, for which the weather data were available for only one predominant location (Kota), showed a very low simulated potential rainfed yield of 1340 kg/ha. The experimental station yields were also above 2000 kg/ha and ranged from 2080 to 2600 kg/ha. Significantly, low simulated soybean yields as compared with the experimental yields in Rajasthan and Karnataka are because of long-term effects of climatic variability considered during simulation, which was not possible with the experimental data. The state-level mean yields ranged from 640 to 1210 kg/ha (Fig. 6.9). The comparison of potential yields with actual state yields show that, except for Rajasthan, the soybean yields can be almost doubled by adoption of improved agronomic practices.

GROUNDNUT In India, groundnut is the major oilseed crop. The total area under groundnut production during the period 1972–1976 was 7.1 million ha, which increased to 7.9 million ha during 1992–1996 and thereafter declined to 6.2 million ha during 2002–2006 (Table 6.4). A similar trend as for area was observed in total production of groundnut during the period from 1972–1976 to 2002–2006. The total increase in production until 1992–1996 was due to increase in both area and yield, which increased from 770 kg/ha during 1972–1976 to 1030 kg/ha during 1992–1996. After 1992–1996, the yield levels of groundnut stagnated at about 1020–1030 kg/ha. The sharp rise in area and production of groundnut in the post-1987 period was mainly due to the major efforts of the government under the technology mission for groundnut production, which could not be sustained. Groundnut production declined after achieving a peak production of 9.68 million t in 1988–1989.

Among the states, Andhra Pradesh and Gujarat together contribute 52% to the total groundnut area and production in the country. Another 34% is contributed by Karnataka, Tamil Nadu and Maharashtra. The rest of the area is scattered in the states of Rajasthan, Orissa, Madhya Pradesh and other parts of India.

Among the major states covering the groundnut area in India, the simulated potential rainfed yield was more than 2000 kg/ha (2330–3490 kg/ha) except for Tamil Nadu (1200 kg/ha) (Fig. 6.10). The experimental yields for the states ranged from 1660 to 2590 kg/ha. Higher experimental yields and state yields, especially for Tamil Nadu, indicate some input of irrigation to the crop in the state. For other states, the state yields ranged from 850 to 1340 kg/ha, which indicate the substantial scope to at least double the yields of groundnut in the major rainfed growing states (Andhra Pradesh, Gujarat and Karnataka) considering simulated or experimental potential yields.

Potential yield and yield gap of cash crop cotton

Cotton in India is grown typically in the rainy season in semi-arid regions. The largest area is in

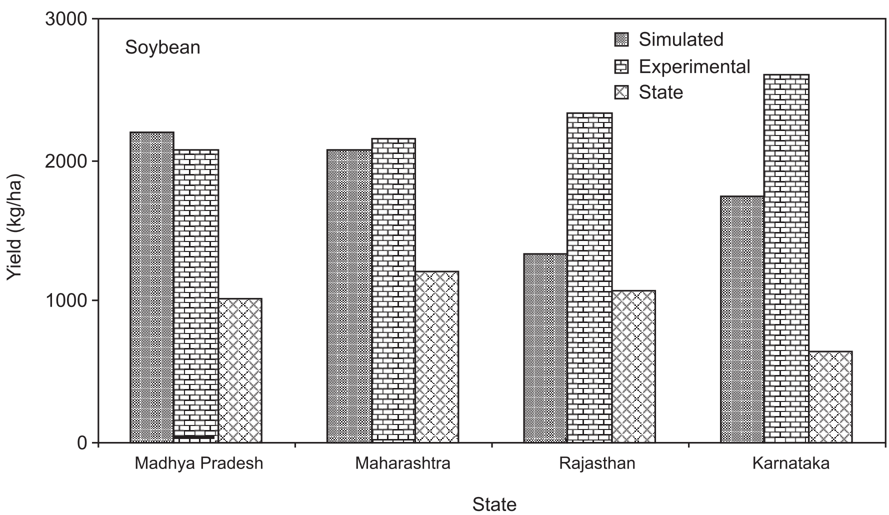

Fig. 6.9. Mean simulated, experimental and measured state-level yields of soybean in India.

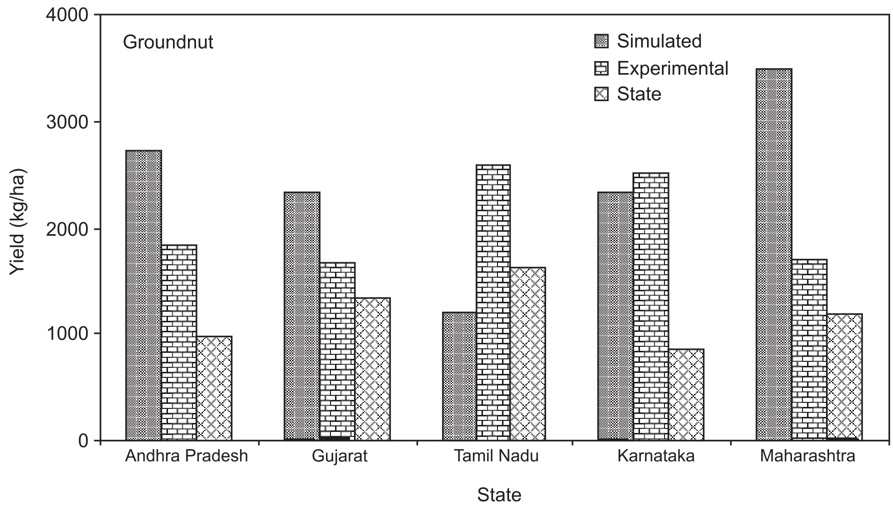

Fig. 6.10. Mean simulated, experimental and measured state-level yields of groundnut in India.

the states of Maharashtra, Andhra Pradesh and Gujarat, followed by Punjab, Haryana, Karnataka and Madhya Pradesh. In the north Indian states of Punjab, Haryana and Rajasthan, the entire crop is irrigated, whereas in other states, it is partially irrigated or rainfed. Almost the entire crop is rainfed in Maharashtra, the largest cotton-cultivating state, accounting 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 9 million ha area. On average the production of cotton since 1972–1976 has increased from 6.2 million t to 15.7 million t during the period 2002–2006 (Table 6.4). The increase in production was more due to yield increase over the years, from an average value of 140 kg/ha during 1972–1976 to 310 kg/ha during 2002–2006 rather than due to an increase in the area under the crop.

Simulation results showed reasonable potential yields of rainfed cotton in different regions. At the state level, the simulated rainfed potential yields varied from 1400 to 1830 kg/ha. The lowest potential was in the states of Karnataka and Madhya Pradesh, whereas the highest yield was in Andhra Pradesh (Fig. 6.11). All India mean potential yield was 1650 kg/ha. The experimental potential yields also showed considerable variation. On average, the yields were between 980 and 1110 kg/ha in all states except in Andhra Pradesh, where these were more than 1650 kg/ha.

The mean seed cotton yield at the state level was lowest in Madhya Pradesh (370 kg/ha). This was followed by Maharashtra and Gujarat, where the yield level reached up to 500 kg/ha. In the state of Karnataka, the mean yield was 600 kg/ha and was highest in Andhra Pradesh. However, the actual rainfed yields in Andhra Pradesh, Gujarat and Madhya Pradesh would be somewhat lower than these figures because the reported yields also included the data from irrigated regions.

Mean yield gap between simulated rainfed potential yield and the state mean yield was on average 1120 kg/ha. The lowest gap of 800 kg/ha was recorded for Karnataka while the maximum gap was in Gujarat (1210 kg/ha). At the experimental station level, the gap was highest in Andhra Pradesh and Gujarat, while Karnataka again had the lowest gap (Fig. 6.11). The mean gap at this scale was only 640 kg/ha. Thus, in the main rainfed cotton-producing states there is a sufficient gap that can possibly be bridged by improved management in future. On average, it can be concluded that the yield gap is high in the states of Gujarat, Andhra Pradesh and Madhya Pradesh and low in Karnataka.

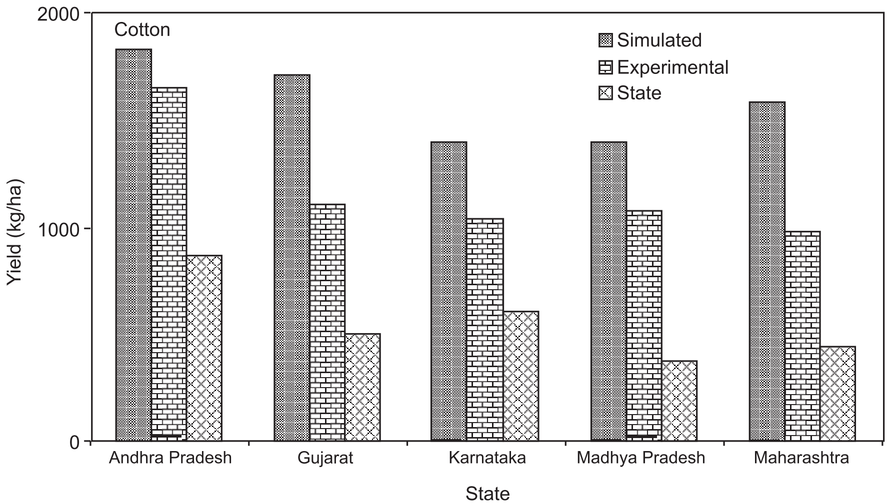

Fig. 6.11. Mean simulated, experimental and measured state-level yields of cotton in India.

Constraints and opportunities for increasing crop yields in India

Extensive land degradation and unfavourable climate are the major abiotic constraints limiting crop production in the rainfed areas of India. Erratic rainfall results in frequent droughts and waterlogging in the rainy-season crops. Both low and high temperatures and drought limit the productivity of post-rainy-season crops, especially legumes. Most of the soils in the rainfed regions of India have low soil fertility caused by soil erosion, continuous mining of nutrients by crops with inadequate nutrient inputs by the farmers. Biotic constraints are also the major yield reducers of rainfed crops. Shoot fly, stem borer and grain mould for *kharif* sorghum, and shoot fly, stalk rot and leaf diseases for *rabi* sorghum are predominant. For pearl millet, downy mildew, smut and rust, and for maize, weeds, rats, termites and stem borers are the major constraints limiting their productivity. For chickpea and pigeonpea, *Helicoverpa*, wilt and sterility mosaic are the major constraints. For groundnut, leaf spot, rust, pod rot and aflatoxin are the major biotic constraints. Boll worm is the major constraint for cotton production. High-yielding improved cultivars resistant to some of these biotic constraints have been developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the national institutes in India and are being promoted for adoption by farmers.

An integrated genetic and natural resource management (IGNRM) approach in the watershed framework is needed to enhance the productivity of rainfed crops in the rainfed areas. Integrated watershed management, comprising improved land and water management, integrated nutrient management including application of micronutrients, improved varieties and integrated pest and disease management, has been evaluated by ICRISAT in several states of India. Substantial productivity gains and economic returns have been obtained by farmers (Wani *et al.*, 2003a,b). Widespread deficiency (80–100% of fields) of micro- and secondary nutrients (zinc, boron and sulfur) have been observed in the farmers' fields in Andhra Pradesh, Gujarat, Rajasthan and Karnataka. Application of micronutrients resulted in a 20–80% increase in yield of several crops, which further increased by 70–120% when micronutrients were applied with adequate amounts of nitrogen and phosphorus (Rego *et al.*, 2007). Thus, improved varieties along with improved management of natural resources have the potential to increase crop production in rainfed areas of India, which need to be promoted and scaled up.

Yield gap of selected crops in north-eastern Thailand

Thailand has a current population of 64 million, which is expected to increase to 69 million by 2025 (United Nations, 2006). Currently, Thailand is a net exporter of rice, cassava, maize and other food items. It imports wheat, soybean and cotton. As Thailand is limited in land area, the future increase in food production must come from an increase in crop yield per unit of land area, from both the irrigated and rainfed regions of the country. North-eastern Thailand (NE Thailand), which has large area under rainfed agriculture, is situated between 14 and 19° N latitude and 101 and 106° E longitude. The area is about 17 million ha or one-third of the whole country. It covers 19 provinces (Fig. 6.12). Despite the same amount of rainfall, NE Thailand is drier than northern and central Thailand because of the short rainy season. Farming is the main occupation and only 20% of the total agricultural area is under irrigation. Cassava, sugarcane, upland rice, maize, soybean and groundnut are the main crops of NE Thailand. However, the cassava area is decreasing because of marketing problems and is being replaced by sugarcane (Land Development Department, 2000; Wangkahart *et al*., 2005).

Production of rice, maize, soybean and groundnut in NE Thailand has followed a similar trend as in Thailand overall (Table 6.5). From 1993– 1994 to 2002–2003, rice production in Thailand and NE Thailand has increased because of both increase in area and yield per hectare. Area cultivated to maize, soybean and groundnut decreased during the same period. Total production of maize increased primarily due to the increase in yield of the crop. The production of soybean and groundnut decreased from 1993–1994 to 2002–2003 in spite of an increase in productivity of these crops. Current levels of yield of rice, maize, soybean and groundnut in NE Thailand are 1960, 3410, 1420 and 1560 kg/ha, respectively.

Biophysical characteristics of north-eastern Thailand

TOPOGRAPHY AND SOILS North-eastern Thailand or the 'Khorat Plateau' is characterized by a shallow basin (saucer-shaped basin) and slopes rather gently south-eastward. The plateau consists of flat-topped mountain and dissected peneplain surface with undulating features. The elevation varies from 200 to 1000 m above mean sea level (msl). Considering differences in the elevation and geology, NE Thailand can be broadly divided into highlands, uplands and lowlands (Fig. 6.12) (Land Development Department, 2000).

The soils in NE Thailand are characterized by sandy or sandy loam to sandy clay loam texture with low to medium fertility (Land Development Department, 2000). Skeleton soils owing to a shallow laterite layer are widespread in the Sakon Nakon Basin and comprise 13% of NE

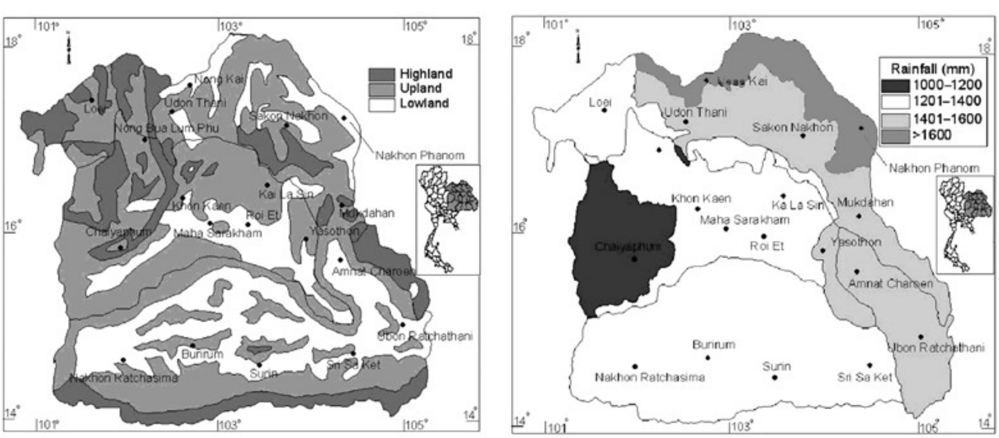

Fig. 6.12. Topography and spatial distribution of rainfall in north-eastern Thailand.

Table 6.5. Area, production and yield of crops in Thailand and north-eastern Thailand[a].

	Area ('000 ha)		Production ('000 t)		Yield (kg/ha)	
Crops	1993–1994	2002–2003	1993–1994	2002–2003	1993–1994	2002–2003
Thailand						
Rice	8389	9905	18304	26295	2180	2660
Maize	1285	1115	3647	4204	2840	3770
Soybean	388	167	520	250	1340	1500
Groundnut	96	69	143	113	1500	1620
North-eastern Thailand						
Rice	4469	4955	7584	9692	1700	1960
Maize	329	279	877	950	2670	3410
Soybean	50	35	69	49	1380	1420
Groundnut	32	26	47	41	1440	1560

[a]Source: FAOSTAT (2006).

Thailand. Saline and sodic soils commonly occur in the plateau and cover about 17% of the region. Fertile soils of the alluvial plain are distributed along the Mekong, Chi and Moon rivers and their tributaries and comprise a rather small area of only 6% of the total NE area. Thus sandy topsoils, salt-affected soils and skeleton soils are the three major problem soils of the north-east. Low soil fertility and erratic rainfall are responsible for the low agricultural productivity of the north-east as a whole (Land Development Department, 2000; Wangkahart *et al.*, 2005).

CLIMATE NE Thailand is influenced by a tropical wet–dry monsoonal or tropical savannah climate. The south-west monsoon from May to September brings warm and moist weather from the Indian Ocean to the region. During November to February, the area is influenced by the north-east monsoon from the Eurasian continent, resulting in cooler and dry weather over the whole region. The mean annual rainfall in NE Thailand is 1375 mm. The mean annual temperature in NE Thailand is about 26.7 °C. In the west and the middle of the region, such as Chaiyaphum, Nakhon Ratchasima, Loei, Khon Kaen and Roi Et province, the rainfall is lower than in the east and the north and is about 1000–1400 mm (Fig. 6.12). In the east and the north, such as Nakhon Phanom, Sakon Nakhon, Nong Kai, Ubon Ratchathani, Udon Thani and Mukdahan provinces, the annual rainfall is about 1500–2300 mm. The highest rainfall (2324 mm) is in Nakhon Phanom province.

The year can be divided into three seasons: rainy, winter and summer. The rainy season starts from the end of May or the beginning of June and extends up to the beginning of October (Fig. 6.13). August and September are the high rainfall months. Maximum and minimum temperatures are the highest in April and start dropping thereafter. Winter lasts from mid-October to mid-February. The summer season extends from February to the end of May. Because the north-east region is located far away from the Gulf of Thailand, the summer season is hot and very dry in the region.

Method of yield gap analysis

Yield gap analysis for the four crops was based on the experiment station yield and actual crop yields obtained during 1998 under lowland, upland and highland topographic conditions of NE Thailand. The experiment station yields obtained under a rainfed situation without any nutrient deficiency were considered as the potential yields of rainfed crops. Actual yields were obtained by recording crop yields of farmers in the region under lowland, upland and highland situations. Actual yields were compared with the potential yields to estimate yield gaps of crops for different topographic situations of NE Thailand (Piara Singh *et al.*, 2001).

Potential yield and yield gap of crops

Agriculture in NE Thailand is based mainly on rainfed crops (upland crops) such as cassava,

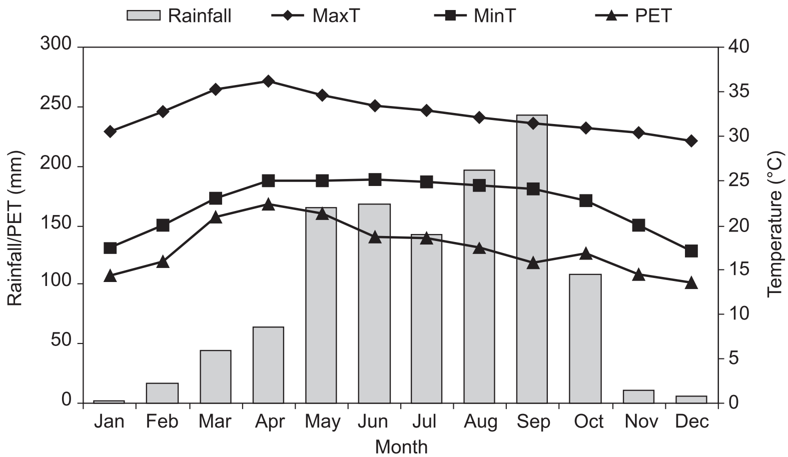

Fig. 6.13. Mean monthly maximum and minimum temperatures and monthly total rainfall and potential evapotranspiration (PET) for Khon Kaen, Thailand.

sugarcane, maize, upland rice, groundnut and soybean, which are important crops of this region. Four crops (rice, maize, soybean and groundnut) were selected to study the yield gap.

RICE Of the total rice area of 10 million ha in Thailand, about 5 million ha area is in NE Thailand (Table 6.5). The yield of rice in NE Thailand is 36% lower than the average rice yield of Thailand. Upland rice in NE Thailand is grown mainly for household consumption. The average experimental yield of rainfed upland rice in NE Thailand is 1490 kg/ha (Fig. 6.14). Farmers' rice yield in the uplands can be increased by about 22% from the current level of their yields with improved practices.

MAIZE Maize is the second most important food crop for human and animal feed after rice. In Thailand, maize has been grown for more than 40 years. Selection and breeding of maize in the country has resulted in higher yields. Of the total production area of 1.1 million ha, about 0.28 million ha is in NE Thailand (Table 6.5). The yields are lower compared with other regions. Experimental yield of maize in NE Thailand is 4710 kg/ha. The farmers' yields from highlands to lowlands increase from 1530 to 3490 kg/ha (Fig. 6.14). Thus the productivity of maize can be increased by 35–200% with improved management from the current levels of farmers' productivity, depending upon the topography.

SOYBEAN In Thailand, soybean cultivation started in 1936. With the expansion of animal husbandry, the requirement for soybean reached about 2 million t/year. From 1993–1994 to 2002–2003, both area and production of soybean decreased; however, the average productivity of soybean in both Thailand and NE Thailand increased (Table 6.5). The experimental yield of soybean in NE Thailand is 1910 kg/ha and the farmers' average yields range from 980 to 1290 kg/ha, depending upon the topography (Fig. 6.14). Thus, the productivity of soybean can be increased by 50–95% with improved management.

GROUNDNUT Both the area and production of groundnut in Thailand have declined since 1993–1994. Currently NE Thailand has only 0.026 million ha under the crop, with a production of 0.041 million t. However, the average productivity of the crop has increased and it is 96% of the average groundnut yield in the country (Table 6.5). The experimental yield of groundnut in NE Thailand is 1740 kg/ha. The farmers' yields in the region ranged from 1160 to 1540 kg/ha (Fig. 6.14). Thus, the farmers' yields can be improved by 13–50% with improved management from the current level of productivity.

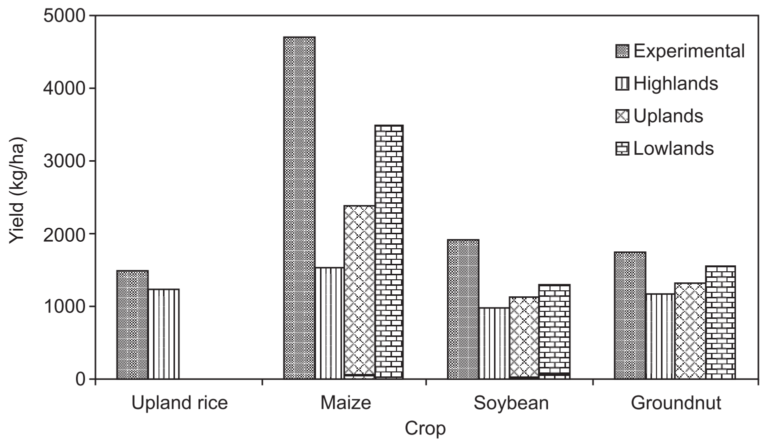

Fig. 6.14. Experimental and actual yields of rainfed crops in north-eastern Thailand.

Constraints and opportunities for bridging the yield gaps in north-east Thailand

Major constraints that limit the yields of crops in NE Thailand are frequent droughts and floods, low soil fertility, soil erosion and land degradation, poor soil water conservation practices, low-yielding crop varieties, shortage of labour, poor agricultural extension for technology transfer, uncertainty of prices and marketing problems, uncertainty of tenure as a disincentive to invest in land development and poor credit facilities and high interest rates by private moneylenders. Bridging the yield gap of upland cropping systems would require adoption of improved soil and water conservation practices, integrated soil fertility management including the greater use of legumes, improved cultivars, a stable land tenure system, affordable credit facilities and assured prices and marketing of agricultural produce. The integrated watershed management approach adopted at Tad Fa watershed site in NE Thailand in collaboration with ICRISAT demonstrated that soil, water and nutrient management (SWNM) and crop management practices not only reduced land degradation but also substantially enhanced crop yields of the farmers (Wangkahart *et al.*, 2005).

Yield gap analysis of crops in northern Vietnam

Northern Vietnam comprises approximately three-quarters uplands (mountains and hills) and one-quarter lowland. The total population of Vietnam is 87 million, which ranks 7th in Asia and 12th in the world and is expected to increase to 106 million by 2025 (United Nations, 2006). The massive population growth which has already taken place in Vietnam has resulted in greater urbanization with more agricultural land being transferred to non-agricultural use. Under such circumstances, pressure on uplands and midlands is increasing for food production to fulfil the local demands and to achieve food security for millions of poor residing in Vietnam. The Vietnam government now has a greater challenge on hand to achieve food security by 2025. Therefore, the uplands are expected to produce more food for meeting the local needs and supply to other regions.

The major crops of northern Vietnam are rice, sweet potato, maize, tea, groundnut and soybean. Of these, only rice and groundnut are exported to other countries. In 2005, rice and groundnut were exported to the extent of 5.3 million t and 0.05 million t, respectively. The other crops exported in the same year were coffee (0.9 million t), rubber (0.6 million t), pepper (0.1 million t), cashew nut (0.1 million t) and tea (0.09 million t). Vietnam normally imports wheat and cotton to meet its domestic needs (General Statistics of Vietnam, 2007). In the lowlands of Vietnam mainly annual crops are grown, while in the uplands annual and perennial crops are grown. In the mountains, legume crops such as groundnut, soybean and mung bean are grown after rice. These are important crops as a source of oil and protein for the mino-ethnic people and fodder for cattle and also for improving soil fertility. Tea and cassava are also common crops as these are drought tolerant and have the ability to grow under poor farm management practices, poor soil fertility and low inputs. Cassava is a staple food when rice production is low and it also provides feed for animals in the upland area.

Climate of northern Vietnam

The climate of northern Vietnam is monsoonal in nature. The south-west monsoon occurs from May to October, bringing heavy rainfall and the temperatures remain high. November to April is the dry season, with a period of prolonged cloudiness, high humidity and light rain. The total annual rainfall ranges from 1100 to 3000 mm (Fig. 6.15). The length of the growing season ranges from 180 to 365 days (Fig. 6.16), which provides the opportunity to grow two crops in a year during spring and summer or autumn–winter. Mean annual temperature is 25 °C, with a mean maximum of 35 °C (in August) and minimum of 12 °C (in January). The climate of northern Vietnam is characterized by four seasons, namely spring, summer, autumn and winter. The spring season is from February to May, summer from June to July, autumn from August to October, and winter from November to January. Six benchmark sites selected for yield gap analysis are located in northern Vietnam, where maximum rainfall occurs from July to September. June and July are the hottest months, while December and January are the coldest months of the year (Chuc *et al.*, 2006).

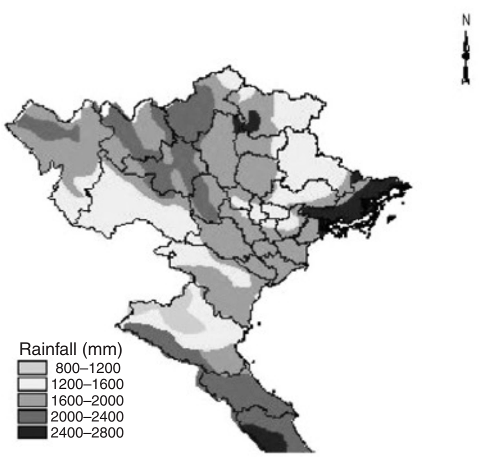

Fig. 6.15. Annual rainfall in northern Vietnam.

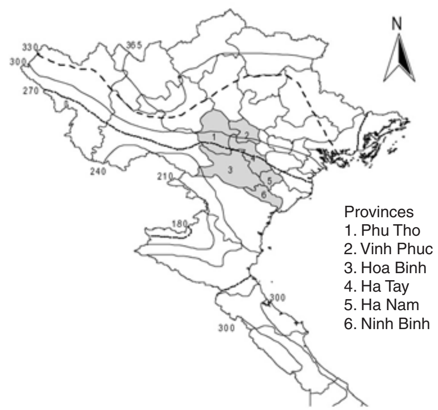

Fig. 6.16. Length of growing season and selected provinces in northern Vietnam.

Area, production and productivity of selected crops in northern Vietnam

Northern Vietnam includes 31 provinces and most of them have an area under soybean, groundnut and maize. There has been a general increase in area, production and productivity of soybean in northern Vietnam since 1995–1996. Between 1995–1996 and 2004–2005, the soybean production increased 2.52 times, which was because of a 72% increase in area and a 47% increase in crop yield (Table 6.6).

The groundnut area also increased in most of the provinces in north Vietnam. Between 1995–1996 and 2004–2005, the groundnut production doubled because of a 26% increase in area under the crop and a 63% increase in yield over the same period (Table 6.6). Since 1999, plastic mulch technology for soil moisture conservation and increasing soil temperature during germination and early plant growth stage and integrated farm management practices were applied in all the provinces of the Red River Delta. It has improved productivity of groundnut by 30–70% as compared with no mulching and traditional practice (Chinh *et al.*, 2000).

Maize is the main crop in the mountainous area of northern Vietnam. Since 1998, these

Table 6.6. Area, production and yield of soybean, groundnut and maize in northern Vietnam during 1995–1996 and 2004–2005[a].

	Soybean		Groundnut		Maize	
Attribute	1995–1996	2004–2005	1995–1996	2004–2005	1995–1996	2004–2005
Area ('000 ha)	72.5	124.5	61.8	78.1	323.6	449.0
Production ('000 t)	65.1	164.3	69.5	143.0	663.6	1377.2
Yield (kg/ha)	900	1320	1120	1830	2050	3070

[a]Source: FAOSTAT (2006).

provinces have been growing hybrid maize cultivars and have applied improved crop management practices promoted by the Vietnam Maize Research Institute. Between 1995–1996 and 2004–2005, maize production has more than doubled, which was because of a 39% increase in area under the crop and a 50% increase in yield during the same period.

Yield gap analysis of crops for the six selected provinces

The six provinces selected for the yield gap study were Phu Tho, Vinh Phuc, Ha Tay, Hoa Binh, Ha Nam and Ninh Binh (Fig. 6.16). Ha Tay, Ha Nam, Ninh Binh and Vinh Phuc provinces are located in the Red River Delta region. These provinces have both upland and lowland areas sown to annual and perennial crops. The rotations of maize–soybean, groundnut–maize, rainfed rice–maize and soybean–mung bean and mono-cultured sugarcane, cassava or tea are the main cropping systems practised in the watershed area of the six provinces, where legumes and maize appear in most of the crop rotations. Thus, maize and legumes play an important role in the existing rainfed farming systems. The farmers normally grow two main crops in a year under rainfed situations. Depending upon the amount of rainfall received, the first crop is sown in February to March and harvested by the end of May or during June. The second crop is sown in July and harvested in November. Yield gap analysis was carried out for soybean, groundnut and maize for the selected provinces.

Methods of yield gap analysis

The estimation of potential rainfed yields and yield gaps was based on simulated yields, experimental station yields and province yields – all obtained under rainfed situation. The potential yields of soybean, groundnut and maize were simulated using DSSAT v3.5 (Hoogenboom *et al.*, 1999) crop models as previously described in the section on yield gap analysis for India. The models were tested and validated using data of three experiments each of maize (2000 spring, 2000 summer and 2001 spring season), soybean (2000, 2001 and 2002 spring season) and groundnut (2000, 2001 and 2002 season) conducted at the Than Ha watershed site in Hoa Binh province (Chuc *et al.*, 2006). Rainfed potential yields of crops were simulated using weather data of 28 years for the five locations (Vinh Phuc, Ha Nam, Ninh Binh, Ha Tay and Phu Tho) and 10 years for the Hoa Binh.

Long-term yield data of yield maximization trials were also available for each crop and benchmark site. These data were averaged over the time period and compared with mean simulated yields and province-level mean yields for the benchmark sites to quantify the yield gaps for each crop (Chuc *et al.*, 2006).

Potential yields and yield gap of crops

SOYBEAN The mean simulated potential yield of soybean across provinces ranged from 1760 to 2240 kg/ha during the spring season, the lowest being at Phu Tho and the highest at Ha Nam (Fig. 6.17). The overall mean potential yield across provinces was 2000 kg/ha. The experimental yields ranged from 1600 to 1900 kg/ha across states, the lowest being at Phu Tho and the highest at Ha Tay. The mean experimental yield across provinces was 1770 kg/ha. Similarly, the province yields were also variable, with overall mean of 1360 kg/ha. On average, the yield gap between the simulated and province yield

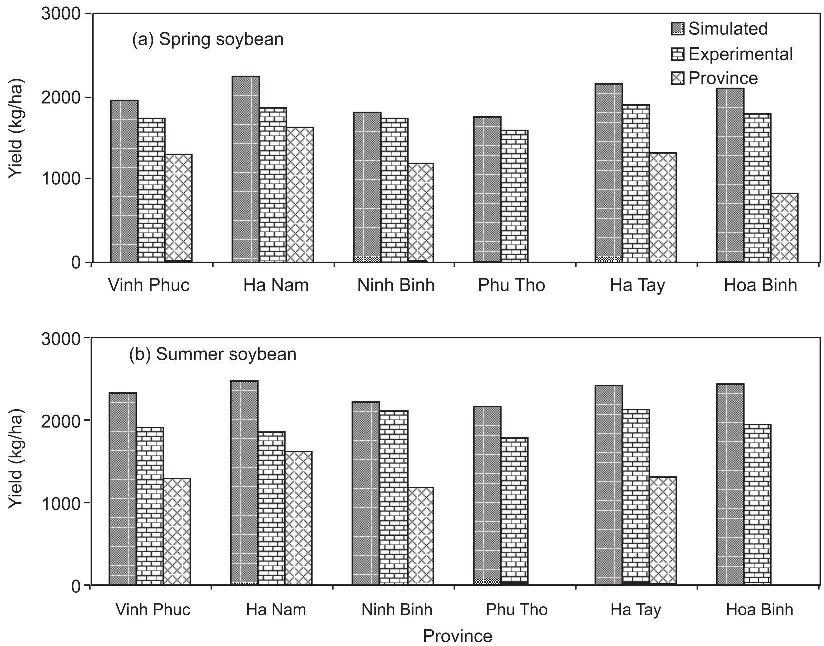

Fig. 6.17. Simulated potential yield, experimental station yields and province mean yield of rainfed soybean in (a) spring and (b) summer seasons at benchmark locations in northern Vietnam.

was 640 kg/ha and between the experimental and province yields it was 410 kg/ha.

In general, the potential yields of soybean were higher during the summer season than during the spring season. The mean simulated potential yield across provinces was 2350 kg/ha with a range of 2160 to 2480 kg/ha. Similarly, the mean experimental yield was 1960 kg/ha, ranging from 1790 to 2140 kg/ha across provinces. The mean yield gap between the simulated potential and the province yield was 1010 kg/ha and between experimental and province yield it was 600 kg/ha.

GROUNDNUT As groundnut is more drought resistant during the initial stages of its growth under rainfed conditions, the spring season for groundnut starts earlier as compared with soybean and maize. During the spring season, simulated potential yields of groundnut across six provinces ranged from 3740 to 4700 kg/ha, with an overall mean of 4170 kg/ha. Whereas, the experimental potential yields ranged from 2550 to 3400 kg/ha with an overall mean of 3010 kg/ha (Fig. 6.18). This indicates that even the experimental yields are below the simulated potential yields by about 1100 kg/ha in the provinces. The province yields of groundnut ranged from 1180 to 2200 kg/ha with an overall mean of 1520 kg/ha. The yield gap between the simulated and province yield was 2650 kg/ha, and between experimental and province yield it was 1490 kg/ha.

During the autumn–winter season, simulated potential and experimental potential yields were lower than those obtained during the spring season (Fig. 6.18). Simulated potential yields ranged from 2910 to 3920 kg/ha with an overall mean of 3530 kg/ha, whereas the experimental yields ranged from 2300 to 2800 kg/ha with an overall mean of 2620 kg/ha. The yield gap between the simulated and province yield was 2010 kg/ha, and between experimental and province yield it was 1100 kg/ha. These results indicate that the groundnut yields in the six provinces during the spring and autumn–winter seasons can be more than doubled with improved management practices.

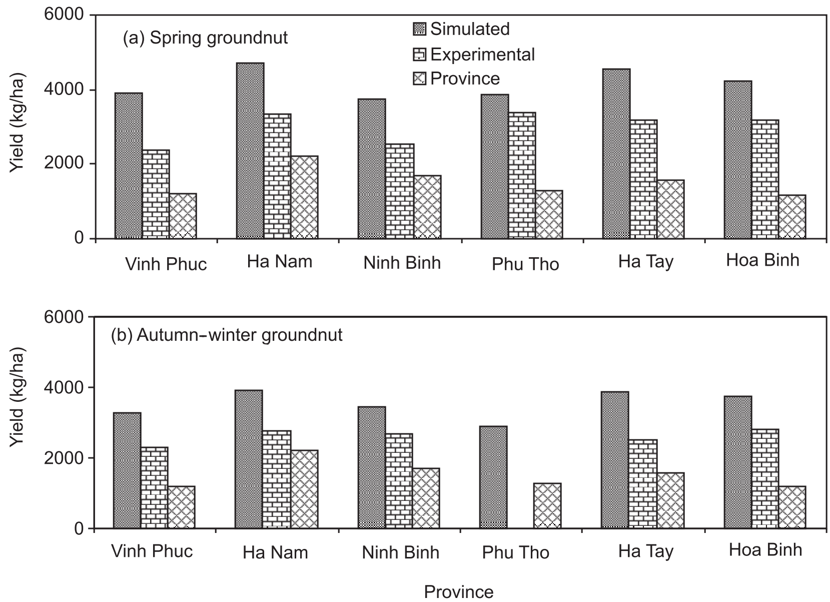

Fig. 6.18. Simulated potential, experimental and province mean pod yields and yield gap of rainfed groundnut in (a) spring and (b) autumn–winter seasons at selected sites in northern Vietnam.

MAIZE Maize is normally sown in spring and summer in the rainfed area of northern Vietnam. During the spring season, simulated potential yields of maize ranged from 4800 to 5430 kg/ha across six provinces, with an overall mean of 5030 kg/ha (Fig. 6.19). The province yields of maize ranged from 2660 to 4180 kg/ha with an overall mean of 3380 kg/ha. The yield gap between the simulated and province yield was 1650 kg/ha. During the summer season, simulated potential yields were higher than those obtained during the spring season (Fig. 6.19). Simulated potential yields during the summer season ranged from 5250 to 5570 kg/ha across six provinces, with an overall mean of 5370 kg/ha. The yield gap between the simulated and province yield was 1990 kg/ha.

Constraints and opportunities for bridging the yield gaps in northern Vietnam

The main constraints for low yields of rainfed crops in northern Vietnam are undulating topography, poor soil fertility, drought and little adoption of improved soil, water, nutrient, crop and pest management practices, leading to inefficient use of natural resources such as rainfall (Wani *et al.*, 2003a). Socio-economic factors (socio-economic status, farmers' traditions and knowledge, family size, household income and expenses) and institutional and policy factors such as government policy, product prices, credit, input supply and market, land tenure and linkage factors consisting of competence and facilities of extension staff; integration among research, development and extension; farmers' resistance to new technology; knowledge and skills; and weak linkages among public, private and non-governmental extension staff also contribute to the problem significantly.

Large yield gaps between current province and potential yields of soybean, groundnut and maize in northern Vietnam could be bridged through large-scale adoption of improved soil, water, crop and pest management options available. Traditionally much emphasis has been put on developing new cultivars; however, the findings from a number of studies have suggested that without appropriate soil, water and nutrient management options the true potential of improved cultivars cannot be realized. Because of increasing competition for land by other sectors of the economy, future increase in crop production can be achieved only by enhancing

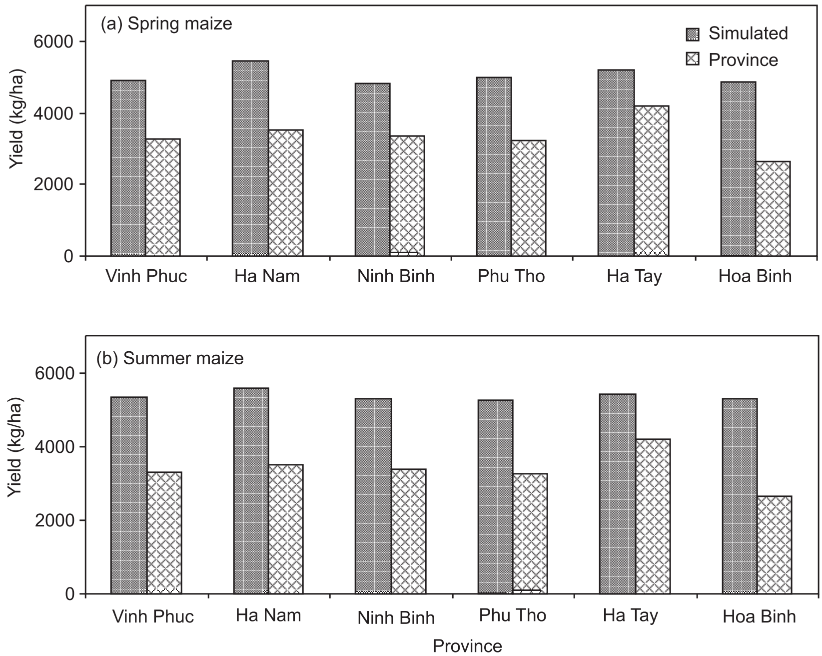

Fig. 6.19. Simulated potential, province mean pod yields and yield gap of rainfed maize in (a) spring and (b) summer seasons at selected sites in northern Vietnam.

productivity per unit of land area rather than area expansion. An integrated watershed management approach, which has been evaluated by the Vietnam Agricultural Science Institute (VASI) and ICRISAT at benchmark watersheds in Hoa Binh and Vinh Phuc provinces, has shown the large potential for reducing land degradation and increasing productivity of crops (Wani *et al.*, 2003a). While no major breakthrough is expected immediately, reducing the yield gap alone in the country could supply 20–60% of the increased annual food demand by the year 2025 (FAO, 2004).

Yield Gap Analysis of Crops in the WANA Region

The WANA region is an enormous and diverse area, with Morocco in the west, Pakistan and Afghanistan in the east, Turkey and Iran in the north and Ethiopia and Sudan in the south. The WANA region covers about 125 million ha of rainfed agricultural land with annual rainfall ranging from 200 to 600 mm with high variability in space and time (Fig. 6.20). The WANA region includes Afghanistan, Algeria, Bahrain, Djibouti, Egypt, Eritrea, Ethiopia, Gaza Strip, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, Turkey, United Arab Emirates and Yemen. Yield gap analysis was carried out for key locations in Morocco, Syria and Turkey.

The soils of the region are diverse, and seven major soil groups account for 86% of the above-mentioned rainfed areas. Agricultural soils of the region are predominantly derived from limestone residuum, thus calcareous with very variable texture, depth, slope and stoniness (Kassam, 1988). In general, soil organic matter levels are low and in some soils, silty and sandy in particular, structural stability is poor, causing surface crusting by rainfall, resulting in serious problems in seedling emergence and surface run-off. Also phosphate and nitrogen deficiencies are common throughout the WANA region. Responses to micronutrients have been observed but are not

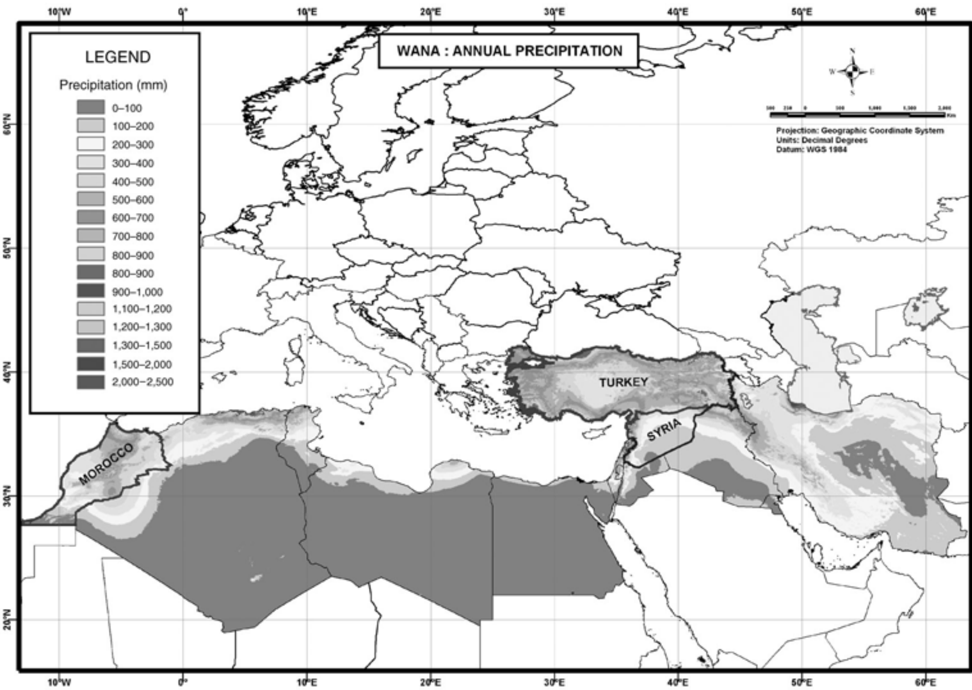

Fig. 6.20. WANA region rainfall isohyets.

widespread in rainfed agriculture. Boron toxicity has been recorded recently as a problem in some parts of the WANA region (e.g. major rainfed wheat-growing areas in central plateau of Turkey) (Harris, 1995).

The climate of the WANA region is characterized by cool (in lowlands) to cold (in highlands) winter and warm to hot arid summer. Locally, conditions are modified considerably by topography and by continental (west Asia) or maritime (North Africa) effects. Precipitation, whether as rain or snow in highland areas of west Asia, is variable in space and unreliable in time and often deficient in amount. In general, coastal areas are wettest and the amount decreases rapidly with distance inland. On average, rain starts in autumn (September–October), reaches a peak in January or February and decreases rapidly until April (in lowlands) or May or June (in highlands). However, year-to-year variability in rainfall distribution is often experienced. The first rains may be delayed by as much as 2 or 3 months and a similar uncertainty attaches to the time the rains end.

Crop production systems in WANA

Rainfall and other sources of water in combination with temperature, soils and socio-economic factors are the major determinants for the multiplicity and complexity of the production systems in the WANA region. These systems are mainly based on cereals (barley in drier areas, wheat in more favourable areas) and legumes (lentil, chickpea and faba bean and a small portion of forages) in rainfed areas and on summer crops in the irrigated areas (FAOSTAT, 2004). In the region, integration with livestock, mainly sheep and goats, is important for nutrient cycling and fertilization of the soils, which eventually improve the soil water use (Cooper *et al.*, 1987). Fallow is still practised mostly in high-elevation cold areas in rotation with cereals. Introduction of forage legume production in rotation with barley has been proved successful but the adoption rate is still low because of socio-economic conditions of the farmers (Osman *et al.*, 1990; Bounejmate *et al.*, 2002). All winter-sown crops are increasingly exposed to drought in the spring or early summer when evaporative demand is high, mostly at flowering and grain-filling stages, and are largely dependent on the stored soil moisture to complete their growth cycles (Cooper *et al*., 1987). Intercropping of cereals or legumes between young olive trees (until fruit production) is becoming a common practice in the wetter areas because of economic considerations of farmers. Almost 30% of the above-mentioned cropped areas in the WANA region are now irrigated and over half the region's crop production is produced under irrigation. The WANA region has about 137 million ha arable land, of which 35 million ha is sown to wheat (FAOSTAT, 2002). About 20–30% of the crop is irrigated and the rest is under rainfed conditions. Productivity of wheat in rainfed areas is still low, around 1.0 t/ha in general, ranging from 0.5 to 1.5 t/ha on average. However, wheat production in the region increased from 47 million t in 1985 to 81 million t in 2004 (FAOSTAT, 2004), which is quite a high increase, bringing certain countries such as Syria and Turkey into self-sufficiency in wheat production on the basis of improved management practices combined with the use of improved varieties and irrigation. But it is unlikely that such expansion in production through irrigation can be sustained without proper water and land management strategies.

Wheat is mostly grown in the 300–600 mm rainfall zone throughout the region. While irrigated areas may produce far higher yields and marketable surpluses, the overall value of rainfed production (about 50% of the total production given above) is much greater than its market value owing to social and other indirect benefits associated with these systems. Rainfed production is dependent on low and extremely variable rainfall and therefore productivity is low and unstable. This is further affected by frequent droughts and continuing land degradation. Research has focused on ways to improve the water availability to crops in rainfed areas. Given the limited ability to utilize new sources of water in the region, a major challenge is sustainable increase in productivity by improving the efficiency of the on-farm use of the limited water resources available. Among the most relevant are those countries with extensive rainfed areas, including Algeria, Morocco and Tunisia in North Africa and Iraq, Jordan, Pakistan, Syria and Turkey in west Asia. Thus, yield gap analysis was carried out in the selected countries of Morocco, Syria and Turkey, representing major agroecologies for the wheat crop, which is the major staple cereal in the region. The general framework for situating wheat crop zones in relation to rainfall is shown in Fig. 6.21.

Analyses of potential yields and yield gaps

To analyse the potential yields and yield gaps of wheat, data were collected from the partner institutions. These included data on experimental yields obtained with improved agronomic

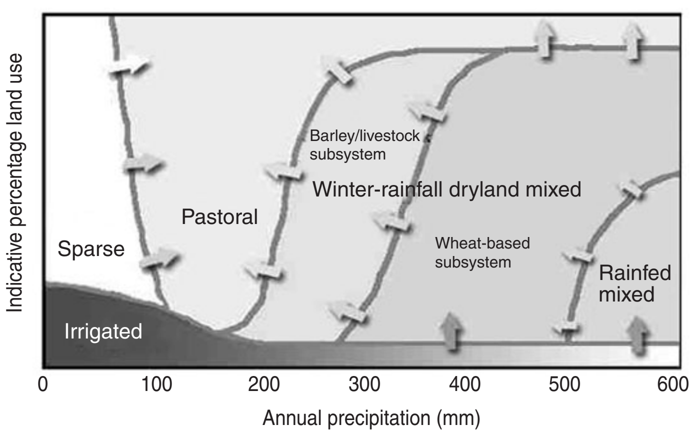

Fig. 6.21. General 'ICARDA' framework for relationship between production systems and precipitation.

management (potential yields) at research stations and simulated potential yields using a cropping systems simulation model on the basis of improved wheat varieties grown in farmers' fields during the period of 10–12 years, depending on the data availability of the three countries (CropSyst) (Stockle *et al.*, 1994; Pala *et al.*, 1996). Farmers' yields were obtained from farmers' fields in the vicinity of on-farm yield trials conducted by researchers; state farm yields were obtained from the large-scale seed production fields of state farms (in Turkey only); and district- or province-level actual yields were obtained from the agricultural statistics of each country (Syria and Turkey only). Morocco in North Africa for mild lowlands and mild highlands, Syria in west Asia for mild lowlands and Turkey in west Asia for cold highlands were selected for the yield gap analysis as major representation of the region (Fig. 6.20).

Wheat area, production and productivity are given in Table 6.7 for the selected major countries representing different agroecologies of the WANA region. Wheat area increased by 16.9% while wheat production increased by 73.6% between 1985 and 2004 because of the yield increase of 48.3% in the WANA region (FAOSTAT, 2004). Since these data are given as an average of irrigated and rainfed regions together, we carried out an analysis of the situation for rainfed regions as follows.

About 75% of the total wheat area is under rainfed conditions; thus the mean wheat area of WANA would be 24,284,000 ha while the irrigated area is 8,094,000 ha. The irrigated wheat yield could be accepted as 3.5–4.0 t/ha on average. Therefore, mean rainfed yield could be calculated as 1.27–1.41 t/ha for the entire WANA region, which is still quite low, although there is a remarkable increase in yield and production of wheat since 1985.

Morocco

Since 1985, the wheat area in Morocco has increased by 61.7%, while production and yield of wheat has increased by 135% and 45.3%, respectively. There is a good potential for further increases in yield with the adoption of improved varieties and agronomic management practices (Table 6.8). In Morocco, two sources of data have been used to calculate the yield gap. In the first case, the data of the WANA Durum Improvement Network Project (WANADIN, 2000) have been used to calculate the yield gaps on the basis of farmers' yields around the research stations compared with the research station yields (Table 6.8).

Potential yield obtained from the research stations under improved management practices is 61–153% more than the farmers' yield. The highest yield increase was obtained in the most

Table 6.7. Area, production and yield of wheat during 1985–2004 in the WANA region[a].

Countries	1985	1990	1995	2000	2004	Mean
Wheat area harvested (million ha)						
Morocco	1.894	2.719	1.968	2.902	3.064	2.509
Syria	1.265	1.341	1.644	1.679	1.831	1.552
Turkey	9.275	9.432	9.400	9.400	9.400	9.381
WANA all	30.105	31.823	32.718	32.034	35.208	32.378
Wheat production (million t)						
Morocco	2.358	3.614	1.091	1.381	5.540	2.797
Syria	1.714	2.070	4.184	3.105	4.537	3.122
Turkey	17.032	20.022	18.015	21.009	21.000	19.416
WANA all	46.691	58.586	62.872	66.484	81.067	63.140
Wheat yield (kg/ha)						
Morocco	1245	1330	555	475	1810	1080
Syria	1355	1545	2545	1850	2475	1955
Turkey	1835	2120	1915	2235	2235	2070
WANA all	1550	1840	1920	2075	2300	1950

[a]Source: FAOSTAT (2004).

Table 6.8. Important wheat-growing regions of Morocco and mean yield gap (during 1990–2000)[a].

Region	Precipitation (mm)	Potential yield (kg/ha)	Farmers' yield (kg/ha)	Yield gap/increase over farmers' yields (kg/ha)	(%)
Loukos	>600	8560	4700	3860	82
Douyet	450–600	5400	3350	2050	61
Marchouch	350–450	5230	3100	2130	69
Settat	250–350	4550	1800	2750	153
Tessaout	<250[b]	6270	3500	2770	79

[a] Source: WANADIN (2000); [b]irrigated.

important semi-arid rainfed areas of Morocco, which is Chaouia-Doukkala provinces (Settat) with variable and limited rainfall.

In the second case, a cropping systems simulation model (CropSyst) (Stockle *et al.*, 1994; Pala *et al.*, 1996) has been used with the agroclimatic data from semi-arid regions (250–350 mm rainfall) given above (Settat region), to identify the wheat yield gap during 1994–2003 cropping seasons on the basis of district/province yield means compared with potential yields coming from research stations and crop simulations on the basis of using improved wheat cultivars grown by farmers with given daily rainfall and soil characteristics with recommended nitrogen fertilizer without pest and disease effects during the 10-year period between 1995 and 2004.

Average yields and the gaps among the farmers, research stations and simulated potential values are presented in Fig. 6.22. In the figure, yield gap I represents the gap between the research station (2190 kg/ha) and farmers' yields (1105 kg/ha in Settat and 1220 kg/ha in Berrechid), measured as 98 and 80% increases over the farmers' yields for Settat and Berrechid sites, respectively. The gap between farmers' and simulated potential yield (3390 kg/ha) is presented as yield gap II, as 207 and 178% yield increases over the farmers' yields for Settat and Berrechid sites, respectively.

Syria

Wheat is grown on about 1.5 million ha or 27% of the total cultivated land in Syria, mainly

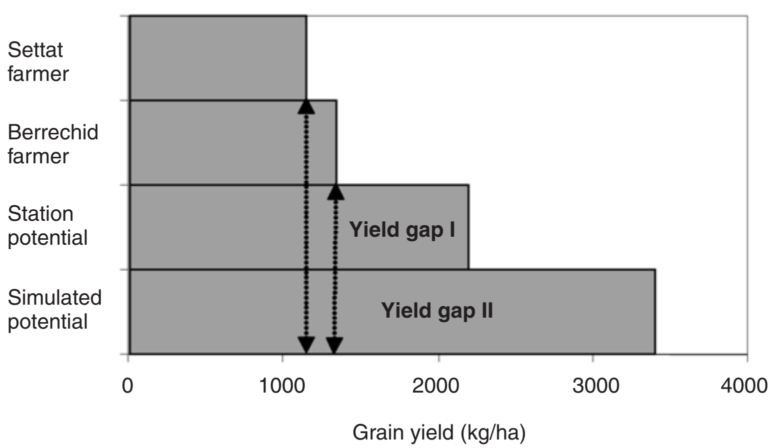

Fig. 6.22. Average wheat yield gap under rainfed conditions in Settat–Berrechid region of Morocco during the 1995–2004 seasons.

under rainfed conditions (300–500 mm annual rainfall), which are increasingly experiencing supplemental irrigation, while drier (<200 mm) areas are fully irrigated (SCBS, 1998). Since 1985, wheat acreage of the country has increased by 45%, while production and yield of wheat increased by 164% and 83%, respectively. Similar to Morocco, there is also a good potential for further increases in yield with the adoption of the improved varieties and agronomic management practices (Table 6.9). In Syria, potential yield obtained from the research stations under improved management practices could on average increase wheat yield over the farmers' yield level by 67–85%. Similar to Morocco, the highest yield increase was obtained in the driest rainfed areas of Syria, which is Zone 2 with variable and limited rainfall, covering about 13% of the country, as similar to Zone 1 (a and b), which covers about 15% of the country. Again improved management practices together with improved varieties have to be adopted by farmers to close the yield gap for sustainable wheat production.

As Zone 1b is the major wheat-producing area of Syria, potential yields were simulated for this zone for 1994–2005 using a simulation model (CropSyst). Farmers' mean yields and research station trials' yields for the Aleppo province and simulated potential grain yields under rainfed conditions for Tel Hadya, Aleppo (long-term average rainfall of 325 mm), representing Zone 1b, are shown in Fig. 6.23. The yield gap between the research station (3675 kg/ha) and farmers' fields (2020 kg/ha), represented as yield gap I, measured a 82% increase over the farmers' yields. The yield gap between farmers' yield (2020 kg/ha) and simulated potential yield (4540 kg/ha), represented as yield gap II, measured a 125% yield increase over the farmers' yields.

Table 6.9. Important wheat-growing regions of Syria and mean yield gap (mean for 1986–2000)[a].

Region	Rainfall (mm)	Research station yield (kg/ha)	Farmers' yield (kg/ha)	Yield gap/increase over farmers' yields (kg/ha)	Yield gap/increase over farmers' yields (%)
Zone 1a[b]	>350	5855	3500	2355	67
Zone 1b[b]	300–350	4935	2930	2006	68
Zone 2[b]	250–300	2165	1170	995	85
Irrigated	200–300	5010	2750	2260	82

[a] Source: WANADIN (2000); [b] rainfed.

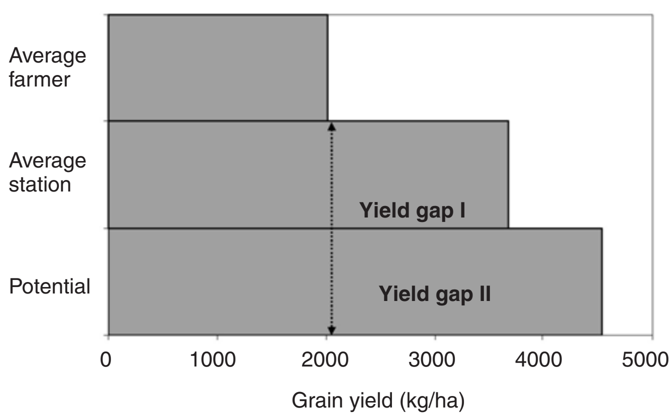

Fig. 6.23. Average wheat yield gap in Aleppo province, Syria during the 1994–2005 cropping seasons.

Turkey

Since 1985, wheat acreage of the country increased by 1.3% only, while production and yield of wheat increased by 23.3% and 21.83%, respectively. However, yield increases have not been as high as for other countries of the region. As most of the wheat is produced in dry, marginal rainfed areas, the yield and production cannot be increased further unless improved agronomic management practices are applied by most of the farmers (Table 6.10). Similar to Morocco and Syria, there is also a good potential for further increases in yield with the adoption of the improved varieties and agronomic management practices, as evident from the yield gaps (Table 6.10).

In central Anatolia (250–500 mm rainfall zone), which is a major wheat-production area of Turkey, the CropSyst simulation model was used to assess potential yields for the 1991–2001 cropping seasons using improved wheat cultivars grown by farmers with recommended nitrogen fertilizer without pest and disease effects. The simulated potential, the research stations' and farmers' mean yields under rainfed conditions are shown for the representative site, Ankara (long-term average rainfall of 360 mm) in central Anatolia, in Fig. 6.24. Yield gap between the research station (2810 kg/ha) and farmers' field (1825 kg/ha), represented as yield gap I, measured a 54% yield increase over the farmers' fields. The gap between farmers' yield (1825 kg/ha) and simulated potential yield (3435 kg/ha), represented as yield gap II, measured a 88% yield increase over the farmers' yields.

Similar to other regions of the WANA, improved management practices together with improved varieties have to be adopted by farmers to close the yield gap for sustainable wheat production.

In summary, the results of the representative areas of three countries of WANA showed the importance of improved soil and crop management practices combined with the use of improved crop varieties, particularly in drier areas, to fill the yield gap for wheat crop for better income and livelihood of the rural communities (Cooper *et al.*, 1987; Harris *et al.*, 1991; Pala *et al.*, 2000; van Duivenbooden *et al.*, 2000).

Major constraints and opportunities for bridging the yield gaps in WANA

The average landholding in the WANA region is 0.5–2 ha. Productivity in such small areas could not be increased easily because of high input costs. Additionally, improved management practices have not been adopted by farmers in the region because of socio-economic factors. Identified constraints include unfavourable growing conditions, unavailability of improved seed and adequate machinery, unawareness of the improved technologies and lack of resources. Therefore, many countries in the WANA region, except Syria and Turkey, have to import wheat for their increasing demand.

Research at the International Center for Agricultural Research in the Dry Areas (ICARDA) and at other regional and national research institutes has led to the development of appropriate technologies and management options for increased water use efficiency, including crop and soil management practices,

Table 6.10. Important wheat-growing regions of Turkey and mean yield gap from the highest yields from state farms and research stations (during 1990–2001)[a].

Region	Rainfall (mm)	Farmers' yield (kg/ha)	State farm highest (kg/ha)	Research station highest (kg/ha)	Yield gap/increase over farmers' yields: State farm (kg/ha)	State farm (%)	Research station (kg/ha)	Research station (%)
Central Anatolia (N)	300–500	2020	2600	3260	580	29	1240	61
Central Anatolia (E)	400–500	1695	2820	3135	1125	66	1440	85
Central Anatolia (S)	250–500	1790	2550	2745	760	42	1180	66
South-eastern Anatolia	200–500	1630	4485	4900	2855	175	3270	201
Eastern Anatolia	450–600	1185	2870	3150	1685	142	1965	166

[a]Source: N Zencirci, Wheat Project Coordinator, Turkey.

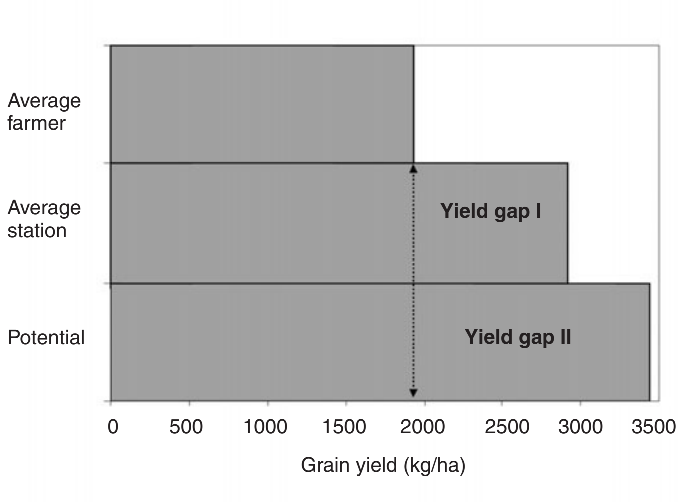

Fig. 6.24. Average wheat yield gap in Turkey (Ankara, Central Anatolia) during 1991–2001 seasons.

improved germplasm and on-farm water management options. One option that has the potential to provide large productivity gains is the use of supplemental irrigation in rainfed crops. Supplemental irrigation of wheat in rainfed areas where water sources are available can boost the crop productivity by three to four times. As a result of research conducted by ICARDA (Oweis *et al.*, 1998, 1999, 2000; Zhang *et al.*, 1998) in collaboration with the National Agricultural Research Systems (NARS), policies are being developed to support the implementation of supplemental irrigation to enhance rainfed agriculture and to better use the limited available water resources. It is also a potential measure for alleviating drought and conserving the natural resource base. There is still a great potential for yield increases in rainfed wheat in the WANA region with the dissemination of improved varieties associated with improved soil and crop management practices such as appropriate crop rotation, timely tillage with conservation practices, timely sowing associated with appropriate sowing method, rate and depth, optimum fertilization, weed and pest control, and appropriate harvest and postharvest handling (Avci *et al.*, 1987; Durutan *et al.*, 1989; Karaca *et al.*, 1989; Harris *et al.*, 1991; van Duivenbooden *et al.*, 2000; Pala *et al.*, 2004; Avci, 2005; Pala, 2005).

Modern bread wheat (*Triticum aestivum)* has been well adapted for survival and production in water-limited environments. Adaptation to various environments has been assisted through selection and cross-breeding for traits that contribute to high and stable yield since that time. Improvements in crop management aimed at improving yield and grain quality probably developed more slowly, but the rate of change has accelerated in recent decades. Many studies have shown that the contribution to increased yield from improved management has been about double that from breeding. Both processes have proceeded in parallel, although possibly at different rates in some periods, and positive interactions between breeding and management have been responsible for greater improvements than by either process alone in southern Australia (Anderson and Impiglia, 2002; Anderson *et al.*, 2005), as well as in similar areas of WANA (Harris *et al.*, 1991).

Several authors have shown the physiological basis for understanding the processes by which agronomic practices can affect the wheat crop in the field through increased water supply and its use efficiency (Passioura, 1977, 1983; Fischer, 1979; French and Schultz, 1984). However, many of these technologies are not widely implemented or are not seen as feasible by farmers. This can be attributed to a number of constraints, including technical, socio-economic and policy factors, but most importantly the lack of community participation in the development and implementation of improved technologies. The participation of farmer, researcher, extension agents in the testing, demonstration and dissemination of improved technology will lead to better awareness of the technology and its adoption by a large number of farmers. Of course, the degree and extent of adoption will remain dependent on the availability of crucial inputs, such as machinery, fertilizer and improved seed.

Yield Gap Analysis of Crops in SSA

The population in SSA is expected to grow at 3% a year and food production at less than 2%. The World Bank estimates that if the current trends in population growth and food production continue then Africa alone will have a food shortage of 250 million t by the year 2020. And poverty and the number of underfed children will grow accordingly (Pinstrup-Anderson, 1994). Currently more than 900 million people live in Africa and almost 200 million people are undernourished. More than 60% of malnourished Africans live in eastern Africa. On the other hand, West Africa as a whole has countered the trend in the rest of the continent, with its malnutrition falling dramatically in recent years (IAC Report, 2004).

In contrast to Asia, the agriculture in Africa is predominantly rainfed. The farming systems are diverse and livestock are an important part of the farming systems. It is envisaged that enhancing the productivity of maize, rice, sorghum, millet, wheat, cassava, yam, legumes, coffee and cocoa, which are the predominant components of the priority farming systems of Africa (IAC Report, 2004), would contribute greatly to reducing poverty and malnutrition in Africa. Here, we have presented the potential yields and yield gap of major crops (pearl millet, sorghum and maize) in the selected countries in West and central Africa and eastern and Southern Africa. The potential yields of the crops are based on simulation analysis or the review of literature on potential yields obtained at research stations or in farmers' fields under best farming practice for the crop or region.

West and central Africa: pearl millet, sorghum and maize

Pearl millet, sorghum and maize are of great importance for food security in the semi-arid tropical environments of West and central Africa. They are generally grown in mixtures with other crops, primarily legumes. Although these cereals do respond dramatically to modern technology, farm yields are generally low and progress has been limited. Most of the increase in production of these crops in the past 30 years has been due to increase in area under the crop and much less due to increase in yield (Table 6.11). In West Africa, since the period 1971–1975, the area under pearl millet, sorghum and maize increased by 57%, 86% and 200%, respectively, and the yields of these crops increased by 28%, 30% and 43%, respectively. In central Africa, although the

Table 6.11. Area, production and yield of pearl millet, sorghum and maize in West and central Africa[a].

	Millet		Sorghum		Maize	
Attribute	1971–1975	2001–2005	1971–1975	2001–2005	1971–1975	2001–2005
West Africa						
Area (million ha)	9.66	15.14	7.08	13.16	2.58	7.92
Production (million t)	5.79	11.62	4.90	11.79	2.20	9.72
Yield (kg/ha)	600	770	690	900	860	1230
Central Africa						
Area (million ha)	0.68	1.18	0.90	1.32	1.84	3.12
Production (million t)	0.42	0.66	0.59	1.15	1.46	2.91
Yield (kg/ha)	610	560	660	880	790	930

[a]Source: FAOSTAT (2006).

production of these crops is less as compared with that in West Africa, the trends in area and yield over time were similar. Future increase in production in Africa would require increase in productivity per unit of land area because of increasing limitations on land availability for annual crop production.

Yield gap of pearl millet in Niger

The pearl-millet-based cropping systems, as they are currently practised in the Sudano-Sahelian zone of West Africa, cannot meet the growing food needs of the region. They must, therefore, be intensified in a sustainable manner. Variable rainfall, coarse-textured soils, acidic pH, low organic matter, low water-holding capacity and nutrient deficiencies, particularly low phosphorus status of soils, are the limiting factors to increasing productivity of millet-based systems. Average yield of pearl millet in Niger is about 450 kg/ha considering all the rainfall environments where millet is grown. Subbarao *et al.* (2000) reported that in a long-term operational-scale study conducted from 1986 to 1996, comprising phosphorus fertilization, tillage and rotation with cowpea, the millet yields on average can be increased from 230 kg/ha with traditional management to 710 kg/ha with improved management, thus giving a yield gap of 480 kg/ha. On average, phosphorus fertilization alone improved the millet yield by 52%, while planting on ridges and phosphorus fertilization improved grain yield by nearly 135%. Combining ridge planting, phosphorus fertilization and rotation with sole cowpea resulted in a 200% increase in grain yield compared with the traditional system of production. These results show the potential to enhance the productivity of pearl millet with improved management in the region.

Potential yield and yield gap of sorghum

The mean potential yields of improved varieties and hybrids obtained in the experimental trials conducted at Samanko in Mali, Bengou in Niger and Bagouda in Nigeria and the corresponding farmers' average yields in these countries were used to quantify the yield gaps of sorghum in West Africa. The farmers' yields ranged from 730 to 1170 kg/ha with their current levels of management and varieties (Table 6.12). The potential yields over the five seasons ranged from 1420 to 2810 kg/ha at Samanko, 1360–4030 kg/ha at Bengou and 4420–5400 kg/ha at Bagouda, which gave a yield gap of 690–2080 kg/ha, 980–3650 kg/ha and 3250–4230 kg/ha for these locations, respectively. These yield gaps indicate the potential to enhance crop yields in these countries if improved agronomic management practices are adopted.

Potential yield and yield gap of maize

Maize is present in many African farming systems. Yield increases have, however, been modest overall, with greatest improvement in irrigated and commercial farming systems. Introduction of improved maize germplasm has had a significant impact on maize production in Africa. In favoured areas under farm conditions, hybrids have shown yield gains of at least 40% over local unimproved material (IAC Report, 2004). In dry areas, hybrids have provided at least 30% yield gain (Rohrbach, 1989; Lopez-Pereira and Morris, 1994). Especially notable is the rapid adoption of improved maize varieties in the savannah areas of western Africa, particularly Nigeria and important maize-growing regions in Ghana, Mali, Senegal and Zaire (Maredia *et al.*, 1998).

Apart from improved varieties, agronomic measures to improve soil fertility have led to

Table 6.12. Mean yield of 25 common entries in the International Sorghum Variety and Hybrid Adaptation Trials (ISVHAT), 1989–1993, at West African locations[a].

Location/country	Farmers' mean yield (kg/ha)	Range in improved yield (kg/ha)	Yield gap (kg/ha)
Samanko/Mali	730	1420–2810	690–2080
Bengou/Niger	380	1360–4030	980–3650
Bagouda/Nigeria	1170	4420–5400	3250–4230

[a]Source: ICRISAT (1989–1993).

dramatic yield improvements. In West Africa, the Sasakawa Global 2000 initiative has introduced a package of improved maize technologies to increase productivity. Farmers were given management training plots of 0.25 ha each and supplied with credit to purchase inputs (i.e. seeds of improved crop varieties, fertilizers and pesticides). While the average yields with improved management were 1.7 to 2.4 times the yields obtained under traditional management in the four countries, the variation in yields was also high (Table 6.13).

Eastern and Southern Africa: maize and sorghum

Maize and sorghum are the major crops grown in East Africa. Total productivity of these crops substantially increased in the region since the late 1970s (Table 6.14). Both increase in area and yield contributed to the increase in production. In Southern Africa, the area under maize and sorghum has decreased over the years. This decrease in area did not significantly influence the production of maize. The total production of maize rather increased because of increase in yield from 1810 to 2840 kg/ha since the late 1970s (Table 6.14). In case of sorghum, total production of sorghum decreased in spite of an increase in yield of sorghum from 1270 to 1930 kg/ha.

Yield gap of maize in Kenya

Trends in maize production were analysed using the production data of Machakos and Makueni districts in Kenya. Machakos and Makueni districts are in the Eastern Province of Kenya and lie between latitudes 37° 00′ E and 38° 30′ E and longitudes 1° S and 3° 15′ S (Fig. 6.25). The two districts cover an area of 1.33 million ha, of which 1.13 million ha is agricultural land including ranches. Actual district crop production statistics for the period 1970–2002 were collected from published (Mbogoh, 1991) and unpublished district annual reports from the Ministry of Agriculture and District Agricultural Officers'

Table 6.13. Yield increase in maize due to the adoption of a technology package comprising improved varieties, fertilizers and pesticides[a].

Country	Period	Traditional yield (kg/ha)	Average improved yield (kg/ha)	Range in improved yield (kg/ha)
Burkina Faso	1996–2000	1120	2700	2200–3500
Ghana	1997–1999	1480	3600	3300–4800
Guinea	1999–2000	1450	2800	2600–3000
Mali	1998–2000	1610	2800	1200–6400

[a]Source: IAC Report (2004).

Table 6.14. Area, production and yield of maize and sorghum in eastern and Southern Africa during the period 1971–1975 to 2001–2005[a].

	Maize		Sorghum	
Attributes	1971–1975	2001–2005	1971–1975	2001–2005
Eastern Africa				
Area (million ha)	7.61	11.00	2.98	4.01
Production (million t)	8.93	15.19	2.40	4.00
Yield (kg/ha)	1170	1380	800	1000
Southern Africa				
Area (million ha)	4.80	3.51	0.42	0.16
Production (million t)	8.67	9.97	0.53	0.30
Yield (kg/ha)	1810	2840	1270	1930

[a]Source: FAOSTAT (2006).

Fig. 6.25. Map of Kenya showing the location of Machakos and Makueni districts.

offices. Long-term climate data for Katumani were obtained from Katumani research station while the experimental station yields were taken from a long-term trial conducted at Katumani research station over 19 crop seasons between 1990 and 1999 (Okwach and Simiyu, 1999).

The area under maize in Machako and Makueni districts of Kenya nearly doubled from 128,000 ha during 1970–1974 to 229,000 ha during 1998–2002. Much of this increase took place during 1985–1995. Since 1995, the area under maize remained constant, mainly due to non-availability of land suitable for maize production. Most of the maize in the districts is grown under rainfed conditions. Productivity of maize during 1970–2002 has varied from 210 to 1390 kg/ha with a coefficient of variation (CV) of 43%, which is primarily attributed to the variability in seasonal rainfall. The CVs for the short (October–December) and long (March–May) season rainfall for the corresponding period are 44% and 46%. However, since 1990 a strong declining trend in maize yields has been observed, which cannot be explained by the variation in rainfall alone. Mean yield recorded during 1998–2002 was only 400 kg/ha, which is nearly 50% of what farmers were harvesting in the early 1970s. A similar declining trend in maize yields during the same period was also observed at the national level, arising primarily from the decline in yields in the districts having a high percentage of area under arid and semi-arid lands (ASAL). Although it is not clear what factors are contributing to this decline, it is assumed that declining soil fertility and extension of agriculture into more marginal areas are the two major contributing factors.

Considering the strong influence of climate on the productivity of maize, the yield trends in above-normal, normal and below-normal rainfall seasons were analysed. Seasons with rainfall up to 250 mm were classified as below normal, with 250–349 mm as normal and those with more than 350 mm as above normal using the criteria derived by Stewart and Faught (1984).

However, we used a rainfall limit of 250 mm to classify the season as below normal instead of 220 mm used by Stewart and Faught (1984). Crop yields based on the district crop production data were found to be higher during the years when both short rainy and long rainy seasons were normal or during the years where the short rainy season is normal and the long rainy season is above normal (Fig. 6.26). Maize yields showed no difference when both seasons were either below normal or above normal, though the rainfall during above-normal years was nearly double that received during below-normal years (Fig. 6.27). This is attributed to the low-input management strategies adopted by the farmers. While analysing the production profile of the district between 1960 and 1990, Tiffen *et al.* (1994) observed that farmers pursue strategies that successfully maintain yields in somewhat below mean years but do not seem to be able to take advantage of very good rainfall. Additionally, during high rainfall seasons, the crop is expected to experience higher nitrogen deficiency as leaching removes small quantities of available nitrogen from the root zone.

PRODUCTIVITY AT FARM LEVEL The results of a survey conducted at two locations, Mwala in Machakos district and Makindu in Makueni district, during the 2003–2004 short rainy season, covering 54 households, indicated that the crop yields varied with season and ranged from complete crop failure to four to five bags per acre in good seasons. Mean yields expected during the three different types of seasons at Mwala and Makindu are summarized in Table 6.15. At Makindu farmers expected lower yields compared with those at Mwala, which can be explained by lower mean annual rainfall at Makindu (about 600 mm) compared with Mwala (about 700 mm). During the 2004 short rainy season, we recorded the yields obtained by farmers at Mwala to verify the farmers' assessment. The 2004 short rainy season was

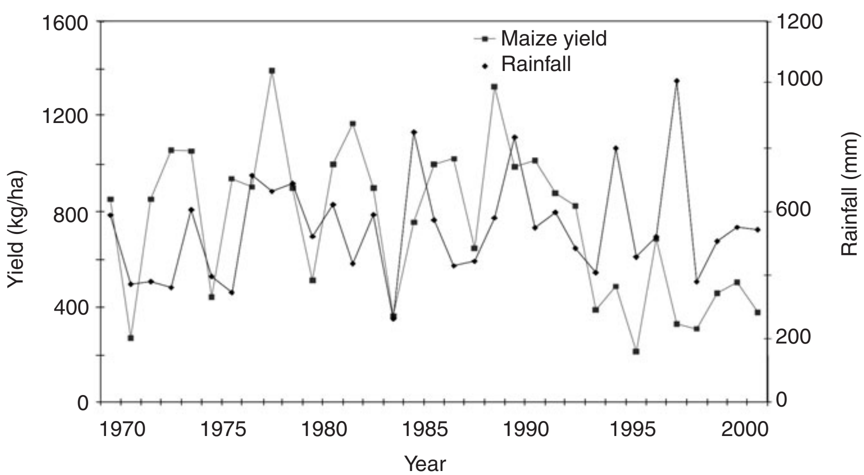

Fig. 6.26. Rainfall and maize yields in Machakos district (data from 1992 onwards are total for Machakos and Makueni districts).

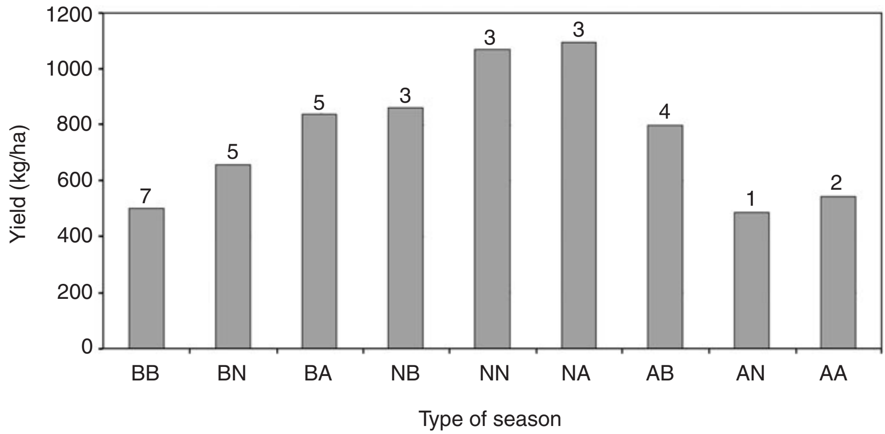

Fig. 6.27. Productivity of maize during below-normal (B <250 mm), normal (N = 250–350 mm) and above-normal (A >350 mm) seasons (figures on the bars indicate the number of years under that category).

Table 6.15. Yields expected by farmers at Makindu and Mwala in different seasons.

		Maize yield (kg/ha)	
Type of season	Rainfall (mm)	Makindu (Makueni)	Mwala (Machakos)
Below normal	<250	115	222
Normal	250–350	335	561
Above normal	>350	748	1297

considered normal with about 250 mm rainfall. Yields recorded varied from 200 to 2200 kg/ha with an average of 1020 kg/ha, which corresponds well with what farmers had indicated to achieve in above-normal season.

RESEARCH STATION POTENTIAL YIELDS AND YIELD GAPS

Data collected from a long-term trial conducted at Katumani research station over 19 seasons were analysed to assess the maize yields achieved on the research station. The low-input system comprised Katumani maize with a plant population of 22,000 plants/ha with no mulch and fertilizer; while the high-input system used the same variety with 53,000 plants/ha and all the stubbles from the previous season as mulch and fertilized with 100 kg nitrogen per ha and 10 kg phosphorus per ha. Of the total 19 seasons, eight seasons were below normal, five were normal and six were above normal.

Under low-input management, highest maize yields were recorded during normal seasons while yields during above-normal years were lower (Fig. 6.28). Maize yields during below-normal years were about 40% of those recorded during normal years. Yields obtained under high-input management clearly indicated the possibility of enhancing the yields by two- to threefold. Although there is possibility of increasing the yields in the below-normal seasons by about 1 t under high-input management, the risk involved in making those investments is very high owing to the possibility of crop failure. The potential to increase yields is much higher during normal and above-normal years with little risk of losing on investments compared with below-normal years. The crop never failed in the seasons that received more than 250 mm rainfall.

SIMULATED RAINFED POTENTIAL YIELDS AND YIELD GAPS

Crop yields were simulated for 93 seasons starting in 1957 up to 2003 using a maize simulation model available in APSIM software and long-term weather data for Katumani (Table 6.16). The model had been earlier calibrated and validated for the Katumani location by Okwach and

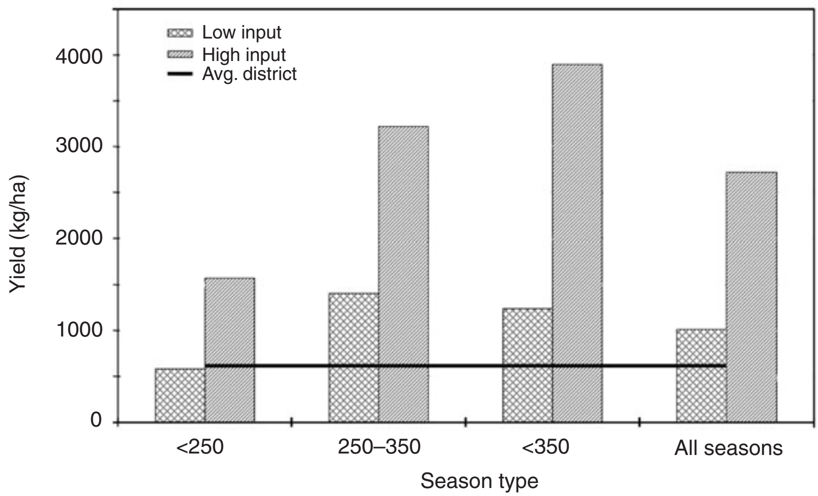

Fig. 6.28. Maize yields under low- and high-input systems in various season types (data from the long-term trial).

Table 6.16. Experimental and simulated yields of maize in different seasons under low- and high-input management.

Management	Below normal (<250 mm)	Normal (250–350 mm)	Above normal (>350 mm)
Experimental yields (kg/ha)			
Low-input management[a]	580	1400	1240
High-input management[b]	1570	3220	3890
Yield gap	990	1820	2580
Simulated rainfed yields (kg/ha)			
Low-input management[a]	310	470	450
High-input management[b]	1560[c]	3310	4220
Yield gap	1250	2840	3770
Simulated potential yields (kg/ha) – water and nitrogen non-limiting			
Short rainy season	7680	7280	7360
Long rainy season	4990	6060	5280

[a] 22,000 plants/ha with no fertilizer; [b] 53,000 plants/ha, stubble mulch, 100 kg N per ha + 10 kg P per ha; [c] 22,000 plants/ha with 50 kg N per ha.

Simiyu (1999) and Okwach (2002). The results showed that complete crop failure occurred during nine seasons, of which five are short rainy seasons and four long rainy seasons. Simulated yields for low-input management were lower than those observed in the trial. This was mainly due to the gradual decline in yields due to fertility depletion. A similar trend would have been observed if the trial had continued for a similar number of seasons. The mean simulated yields under different management options were very similar to the yields obtained in the trial under high-input management.

The maximum possible productivity of maize that can be achieved in Machakos in water and nutrient non-limiting situations was also assessed using the maize model. For this simulation, we used the model option of non-limiting nitrogen and application of irrigation whenever the available moisture fell below 75% of maximum available capacity between sowing and harvest. The maize variety used was Katumani, which is widely adopted in the district. The highest mean yield was obtained with a population of 90,000 plants/ha. Maize yields were found to be higher during short rainy seasons compared with long rainy seasons. The mean yield of all short rainy seasons was 7470 kg/ha, which was 2210 kg/ha higher than the mean yield of all long rainy seasons. While the highest yields during short rains were recorded in the seasons with <250 mm rainfall, mean yields were found to be higher during normal years in the long rainy seasons. This is perhaps one reason why farmers in the region believe that short rainy seasons are more dependable, with higher yields than long rainy seasons.

Yield gap of sorghum in Kenya and Zimbabwe

The mean potential yields of improved varieties and hybrids obtained in the experimental trials conducted at Kiboko in Kenya and Matopos in Zimbabwe and the corresponding farmers' average yields in these countries were used to quantify the yield gaps of sorghum. The farmers' yields ranged from 470 to 860 kg/ha with their current levels of management and varieties (Table 6.17). The potential yields with improved variety and improved management over the five seasons ranged from 1760 to 5240 kg/ha at Kiboko and from 3420 to 5530 kg/ha at Matopos, which gave a yield gap of 900–4380 kg/ha and 2950–5060 kg/ha for these locations, respectively. These yield gaps indicate that the crop yields in these countries can be substantially increased if improved practices are adopted.

Constraints and opportunities for bridging the yield gaps in SSA

In general, there are three major challenges in SSA with respect to soil and water resources for agriculture. First is the climatic variability, which leads to unreliability in the soil moisture available for plant growth, even in high rainfall areas. It is because of this variability that the sub-region has failed to convert its relatively larger gross water resources into meaningful economic assets. Indeed, the level of poverty and frequency of drought-induced food deficits in the region are in sharp contrast to the abundant water endowment in the form of direct rainfall. Second, with inherently low soil fertility of most of the soils in SSA, coupled with very low use of soil fertility-enhancing inputs, many agricultural lands are experiencing a high rate of nutrient depletion, leading to rapidly decreasing productivity of land and water resources. There is a need to develop more integrated management practices. Third, the subsistence nature of smallholder farming in SSA limits investments in the development and sustainable management of land and water resources. These constraints need to be overcome through national and international support to enhance food production in SSA.

Summary and Conclusions

The world population is expected to reach 8.0 billion by 2025. Most of this increase in population is expected to occur in less-developed countries in South and South-east Asia, WANA region and SSA, where most of the poor live. By 2025, while South Asia will have the maximum absolute food demand in the world, SSA will have to more than double its food production from the current levels to meet the food needs of a burgeoning population. About a 55–68% increase in food demand is also expected in South-east Asia and the WANA region. Many countries in the region will have to import food to make up the deficits. With the exception of some countries in SSA, most of the

Table 6.17. Mean yield of 25 common entries in the International Sorghum Variety and Hybrid Adaptation Trials (ISVHAT), 1989–1993, in Kenya and Zimbabwe[a].

Location/country	Farmers' mean yield (kg/ha)	Range in improved yield (kg/ha)	Yield gap (kg/ha)
Kiboko/Kenya	860	1760–5240	900–4380
Matopos/Zimbabwe	470	3420–5530	2950–5060

[a]Source: ICRISAT (1989–1993).

increase in food production must occur as a result of productivity increase per unit of land area rather than area expansion because of increasing land degradation and competition for land for other uses.

Analysis of potential yields and yield gaps of crops at selected locations in South and South-east Asia, WANA region and SSA showed that the actual yields of food and other crops obtained by the farmers are much below the potential yields that can be obtained with improved management. The analysis also showed that, although there are regional differences in the potential of different agroecologies of the developing world, the crop yields can be at least doubled from their current levels by the promotion and adoption of existing 'on-the-shelf' technologies available with the national and international research institutes. It is clear that the full potential of rainfed farming has not been exploited as yet. It is possible to increase food production substantially through crop yield improvements in all the countries in South and South-east Asia, the WANA region and in SSA by proper management and use of natural resource and implementation of improved crop management practices. The IGNRM approach that incorporates soil and water conservation, water harvesting for supplemental irrigation, integrated nutrient management to achieve balanced nutrition of crops, growing of high-yielding improved varieties of crops and integrated pest and disease management needs to be adopted for enhancing crop yields and for efficient management and use of natural resources. The governments need to provide more suitable policy environments and institutional support to promote greater adoption of new and improved technologies to benefit the poor farmers of rainfed areas and to meet the challenge of the greater food needs of the future.

References

Aggarwal, P.K., Banerjee, B., Daryaei, M.G., Bhatia, A., Bala, A., Rani, S., Chander, S., Pathak, H. and Kalra, N. (2006) InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests and environmental impact of agroecosystems in tropical environments. II. Model performance. *Agricultural Systems* 89, 47–67.

Anderson, W.K. and Impiglia, A. (2002) *Management of Dryland Wheat*. In: Curtis, B.C., Rajaram, S. and Gomez Macpherson, H. (eds) Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, pp. 407–432.

Anderson, W.K., Hamza, M.A., Sharma, D.L., Antuono, M.F.D., Hoyle, F.C., Hill, N., Shackley, B.J., Amjad, M. and Zaicou-Kunesch, C. (2005) The role of management in yield improvement of the wheat crop – a review with special emphasis on Western Australia. *Australian Journal of Agricultural Research* 56, 1137–1149.

Avci, M. (2005) New decision support tool: farmer survey for optimizing soil water use in the Anatolian plateau. In: *Management for Improved Water Use Efficiency in the Dry Areas of Africa and West Asia*. Proceedings of a workshop organized by the Optimizing Soil Water Use (OWSU) Consortium, 22–26 April 2002, Ankara, Turkey, pp. 101–109.

Avci, M., Guler, M., Pala, M., Durutan, N., Karaca, M. and Eyuboglu, H. (1987) The effects of the different components of package of cultural practices on wheat yield under central Anatolian conditions of Turkey. In: *Cereal Symposium*. Faculty of Agriculture, 6–9 Oct 1987, Bursa, Turkey (in Turkish), TUBITAK, U.U, pp. 147–157.

Bhalla, G.S., Hazell, P. and Err, J. (1999) Prospects for India's cereal supply and demand for 2020. Food, Agriculture and the Environment. Discussion Paper 29. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Bhatia, V.S., Singh, P., Wani, S.P., Kesava Rao, A.V.R. and Srinivas, K. (2006) Yield gap analysis of soybean, groundnut, pigeonpea and chickpea in India using simulation modelling. *Global Theme on Agroecosystems Report No. 31*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Borlaug, N.E. (2001) Feeding the world in the 21st century: the role of agricultural science and technology. Speech given at Tuskegge University, April 2001, pp. 1–9. Accessible at http://www.agbioworld.org/biotech-info/topics/borlaug/ borlaugspeech.htm

Bounejmate, M., Christiansen, S., Ryan, J., Pala, M. and Shomo, F. (2002) Common vetch to reverse long-term land degradation and alleviate the feed deficits in Syria. In: Ryan, J. (ed.) *Desert and Dryland Development: Challenges and Potential in New Millennium*. Proceedings of the Sixth International Conference on the Development of Drylands, 22–29 Aug 1999, Cairo, Egypt. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, pp. 253–260.

Chinh, N.T., Tam, H.M., Long, T.D. and Thang, N.V. (2000) New technology for groundnut growing in Vietnam. In: *Vietnam Agricultural Science Institute Annual Report 2000*. Agricultural Publisher, VASI, Vietnam, pp. 149–155.

Chuc, N.T., Piara Singh, Srinivas, K., Ramakrishna, A., Chinh, N.T., Thang, N.V., Wani, S.P. and Long, T.D. (2005) Yield gap analysis of major rainfed crops of northern Vietnam using simulation modelling. *Global Theme on Agroecosystems Report No. 26*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Cooper, P.J.M., Gregory, P.J., Tully, D. and Harris, H.C. (1987) Improving water-use efficiency of annual crops in the rainfed farming systems of West Asia – North Africa. *Experimental Agriculture* 23, 113–158.

Durutan, N., Pala, M., Karaca, M. and Yesilsoy, M.S. (1989) Soil management, water conservation and crop production in the dryland regions of Turkey. In: Whitman, C.E., Parr, J.F., Papendick, R.I. and Meyer, R.E. (eds) *Proceedings of Soil, Water and Crop/Livestock Management Systems for Rainfed Agriculture in the Near East Region*, 18–23 January 1986, International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. Amman, Jordan, pp. 60–77.

FAO (2004) International year of rice. Fact Sheet No. 5. (www.rice2004.org).

FAOSTAT (2002, 2004 and 2006) Accessible at http://www.fao.org/

Fischer, R.A. (1979) Growth and water limitation to dryland wheat yield in Australia: a physiological framework. *Journal of the Australian Institute of Agricultural Science* 45, 83–94.

French, R.J. and Schultz, J.E. (1984) Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research* 35, 765–775.

General Statistics of Vietnam (2007) Accessible at http://www.gso.gov.vn (last accessed 31 October 2007).

GOI (Government of India) (2006) *Agricultural Statistics at a Glance*. Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, New Delhi, India. Accessible at http://decnet.nic.in/eands/agstat06–07.htm

Harris, H.C. (1995) Long-term trials on soil and crop management at ICARDA. Soil management: experimental basis for sustainability and environmental quality. *Advances in Soil Science* 19, 447–469.

Harris, H.C., Cooper, P.J.M. and Pala, M. (eds) (1991) *Soil and Crop Management for Improved Water Use Efficiency in Rainfed Areas*. Proceedings of an International Workshop sponsored by MAFRA/ICARDA/CIMMYT, 15–19 May 1989, Ankara, Turkey. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Hoogenboom, G., Wilkens, P.W., Thornton, P.K., Jones, J.W., Hunt, L.A. and Imamura, D.T. (1999) Decision support system for agrotechnology transfer v3.5. In: Hoogenboom, G., Wilkens, P.W. and Tsuji, G.Y. (eds) *DSSAT Version 3. Vol. 4.* University of Hawaii, Honolulu, USA, pp. 1–36.

IAC Report (2004) Realizing the promise and potential of African Agriculture. Accessible at http://www.interacademycouncil.net/CMS/Reports/AfricanAgriculture.aspx

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (1989 to 1993) *ICRISAT Cereals Program Reports. International Sorghum Variety and Hybrid Adaptation Trials, 1989 to 1993*. ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

Kanwar, J.S. (2000) Soil and water resource management for sustainable agriculture imperatives for India. In: International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century, invited papers. 14–18 February 2000, New Delhi. Water Technology Centre and Indian Agricultural Research Institute, New Delhi 110 012, India, pp. 4–6.

Karaca, M., Durutan, N., Guler, M., Pala, M. and Unver, I. (1989) The effect of fallow tillage systems on wheat yields in Central Anatolia of Turkey. In: Unger, P.W., Sneed, T.V., Jordan, W.J. and Jensen, R. (eds) *Challenges in Dryland Agriculture – a Global Perspective*. Proceedings of the International Conference on Dryland Farming, 15–19 August 1988. Amarillo/Bushland, Texas, USA, pp. 131–133.

Kassam, A.H. (1988) Some agroclimatic characteristics of high-elevation areas in North Africa, West Asia, and South-east Asia. In: Srivastava, J.P., Saxena, M.C., Varma, S. and Tahir, M. (eds) *Winter Cereals and Food Legumes in Mountainous Areas*. Proceedings of an International Symposium, 10–16 July 1988, Ankara, Turkey. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, pp. 1–32.

Kumar, P. (1998) Food demand and supply projections for India. Agricultural Economics Policy Paper 98–01. Indian Agricultural Research Institute (IARI), New Delhi, India.

Land Development Department (2000) *Yield Gap Analysis of Three Main Watersheds in the Northeastern Thailand*. Land Development Department, Thailand.

Lopez-Pereira, M.A. and Morris, M.L. (1994) *Impacts of International Maize Breeding Research in the Developing World, 1966–1990*. International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Maredia, M., Byerlee, D. and Pee, P. (1998) Impacts of food crop improvement research in Africa. Special Program for African Agricultural Research (SPAAR) Occasional Papers Series 1. Africa Region. World Bank, Washington, DC.

Mbogoh, S.G. (1991) Crop production. In: Tiffen, M. (ed.) Environmental change and dryland management in Machakos district, Kenya 1930–90: production profile. ODI Working Paper 55. Overseas Development Institute (ODI), London, UK.

McCowen, R.L., Hammer, G.L., Hargreaves, J.N.G., Halzworth, D.P. and Freebairn, D.M.C. (1995) APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50, 255–271.

Okwach, G.E. (2002) Developing an appropriate tool for managing run-off, erosion, and crop production in semi-arid eastern Kenya: a case for APSIM model. CARMASAK Technical Report No. 3. Kenya Agricultural Research Institute, Kenya.

Okwach, G.E. and Simiyu, C.S. (1999) Effects of land management on run-off, erosion, and crop production in a semi-arid area of Kenya. *East African Agricultural and Forestry Journal*, Special Edition 65(2), 125–142.

Osman, A.E., Ibrahim, M.H. and Jones, M.A. (eds) (1990) *The Role of Legumes in the Farming Systems of the Mediterranean Areas*. Proceedings of a workshop on the role of legumes in the farming systems of the Mediterranean areas, 20–24 June 1988, UNDP/ICARDA, Tunis. Development in Plant and Soil Sciences 38. Kluwer Academic Publishers, the Netherlands.

Oweis, T., Pala, M. and Ryan, J. (1998) Stabilizing rainfed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. *Agronomy Journal* 90 (5), 672–681.

Oweis, T., Pala, M. and Ryan, J. (1999) Management alternatives for improved durum wheat production under supplemental irrigation in Syria. *European Journal of Agronomy* 11, 255–266.

Oweis, T., Zhang, H. and Pala, M. (2000) Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agronomy Journal* 92, 231–238.

Pala, M. (2005) Agronomic management for improved water use efficiency in the dry areas of West Asia and North Africa. In: Pala, M., Beukes, D.J., Dimes, J.P. and Myers, R.J.K. (eds) *Proceedings of a Workshop on Management for Improved Water Use Efficiency in the Dry Areas of Africa and West Asia* organized by Optimizing Soil Water Use (OSWU) Consortium, 22–26 April 2002, Ankara, Turkey. International Center for Agriculture Research in the Dry Areas (ICARDA), Aleppo, Syria and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India, pp. 185–200.

Pala, M., Stockle, C.S. and Harris, H.C. (1996) Simulation of durum wheat (*Triticum turgidum* ssp. durum) growth under different water and nitrogen regimes in a Mediterranean environment using CropSyst. *Agricultural Systems* 51(2), 147–163.

Pala, M., Harris, H., Ryan, J., Makboul, R. and Dozom, S. (2000) Tillage systems and stubble management in a Mediterranean-type environment in relation to crop yield and soil moisture. *Experimental Agriculture* 36, 223–242.

Pala, M., Ryan, J., Mazid, A., Abdallah, O. and Nachit, M. (2004) Wheat farming in Syria: an approach to economic transformation and sustainability. *Renewable Agriculture and Food Systems* 19 (1), 30–34.

Passioura, J.B. (1977) Grain yield, harvest index, and water use of wheat. *Journal of the Australian Institute of Agricultural Science* 43, 117–120.

Passioura, J.B. (1983) Roots and drought resistance. *Agricultural Water Management* 7, 265–280.

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

Pinstrup-Andersen, P. (1994) World food trends and future food security: meeting tomorrow's food needs without exploiting the environment. Accessible at www.ifpri.org/pubs/fps/fps18.htm.

Rego, T.J., Sahrawat, K.L., Wani, S.P. and Pardhasaradhi, G. (2007) Widespread deficiencies of sulfur, boron, and zinc in Indian semi-arid tropical soils: on-farm crop responses. *Journal of Plant Nutrition* 30(10), 1569–1583.

Rohrbach, D. (1989) The economics of smallholder maize production in Zimbabwe: implications for food security. MSU International Development Paper No. 11. Department of Agricultural Economics, Michigan State University, USA.

Rosegrant, M.W., Ximing, C. and Cline, S.A. (2002) *World Water and Food to 2025*: *Dealing with Scarcity*. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

SCBS (Syrian Central Bureau of Statistics) (1998) *Statistical Abstract*. SCBS, Damascus, Syria.

Singh, H.P., Venkateswarlu, B., Vittal, K.P.R. and Ramachandran, K. (2000) Management of rainfed agro-ecosystem. *Proceedings of the International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century*. 14–18 February, New Delhi, India. Secretary General, International Conference on Managing Natural Resources for Sustainable Agriculture Production in the 21st Century, pp. 669–774.

Singh, R.P. and Venkateswarlu, J. (1985) Role of All India Coordinated Research Project for dryland agriculture in research and development. *Fertiliser News* 39(4), 43.

Stewart, J.I. and Faught, W.A. (1984) Response farming of maize and beans at Katumani, Machakos district, Kenya: recommendations, yield expectations, and economic benefits. *East African Agricultural and Forestry Journal* 44, 29–51.

Stockle, C.O., Martin, S. and Campbell, G.S. (1994) CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agricultural Systems* 46, 335–359.

Subbarao, G.V., Renard, C.R., Payne, W.A. and Bationo, A.B. (2000) Long-term effects of tillage, P fertilization and crop rotation on pearl millet/cowpea productivity in West Africa. *Experimental Agriculture* 36, 243–264.

Tiffen, M., Mortimore, M. and Gichuki, F. (1994) *More People, Less Erosion. Environmental Recovery in Kenya*. John Wiley and Sons, Chichester, UK.

United Nations (2006) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: the 2006 Revision and World Urbanization Prospects: the 2005 Revision, http://esa.un.org/unpp (accessed 29 October, 2007).

van Duivenbooden, N., Pala, M., Studer, C., Bielders, C.L. and Beukes, D.J. (2000) Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *Netherland Journal of Agricultural Science* 48, 213–236.

Venkateswarlu, J. (1987) Efficient resource management systems for drylands of India. *Advances in Soil Science* 7, 165–221.

WANADIN (2000) West Asia and North Africa Durum Improvement Network Project Final Report. IFAD/ICARDA, Aleppo, Syria.

Wangkahart, T., Toomsan, B., Pathak, P. and Wani, S.P. (2005) Integrated watershed management for land degradation and improving agricultural productivity in north-east Thailand. In: Sharma, BR., Samra, J.S., Scott, C.A. and Wani, S.P. (eds) *Watershed Management Challenges: Improving Productivity, Resources and Livelihoods*. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 314–326.

Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, T.J. (eds) (2003a) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia.* Proceedings of the ADB-ICRISAT-IWMI annual project review and planning meeting, 10–14 December 2001, Hanoi, Vietnam. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003b) Efficient management of rainwater for increased productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture. Limits and Opportunities for Improvement.* CAB International, Wallingford, UK, pp. 199–215.

Zhang, H., Oweis, T.Y., Garabed, S. and Pala, M. (1998) Water use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil* 201, 295–305.