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Pearl Millet and Sorghum Improvement in India

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Notices

[1] Effective January 2007, the Discussion Paper series within each division and the Director General's Office of IFPRI were merged into one IFPRI–wide Discussion Paper series. The new series begins with number 00689, reflecting the prior publication of 688 discussion papers within the dispersed series. The earlier series are available on IFPRI's website at www.ifpri.org/pubs/otherpubs.htm#dp.

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ABSTRACT

The spread of modern varieties and hybrids of pearl millet and sorghum that began in the mid-1960s has had an important impact on small farmer welfare in India. The success and sustainability of these improved cultivars resulted from three types (or periods) of interventions by the Indian government: (1) increased investments in crop improvement by national and international agricultural systems during the 1970s; (2) development of efficient seed systems, with the gradual inclusion of the private sector in the 1980s; and (3) the liberalization of the Indian seed industry in the late 1990s. In addition to increased overall production levels of sorghum and millet, there have been substantial yield gains in semi-arid regions as well as improved cultivars adopted in some of the poorest areas of India. The innovations of new, hybrid technology have not been limited to the Green Revolution crops; they have also had significant impact on the productivity of small-farmer households growing dryland crops, such as millet and sorghum in India.

Keywords: Millions Fed, Food Security, Pearl Millet, Sorghum, India

1. INTRODUCTION

World cereal area and production has steadily expanded over the past five decades. The productivity (specifically yields) of cereals has also doubled during the same period. Sorghum and other millet crops currently constitute an estimated 11.4 percent of the cereal area harvested and 4.1 percent of the total output of world cereals produced (FAOSTAT 2007). Sorghum and millets are often a recommended option for farmers operating in harsh environments where other crops do poorly, as they are grown with limited rainfall and often without application of any fertilizers or other inputs. Moreover, these crops constitute the principal source of energy, protein, vitamins, and minerals for millions of the poorest people in these regions.

Millets and sorghum comprise a group of annual grasses, found mainly in arid and semi-arid regions of the world.[1] These grasses produce small seeded grains and are often cultivated as cereals. They are widely grown in Africa, Asia, China, and the Russian Federation (FAO 1995), and can be used as either grain or forage. They are resistant to drought, have a short duration (typically three to four months from planting to harvest), and can be grown in a wide range of soil types.

Sorghum or jowar (Sorghum bicolor) is predominantly grown in the arid and semi-arid regions of India (Maharashtra, Andhra Pradesh, Karnataka, and Tamilnadu), areas with as little as 400 to 500 mm rainfall per year. As many as 100 distinct cultivars of sorghum have been identified in the sorghum-growing regions of India, and India is the unique center of origin for the post-rainy (rabi) season varieties of sorghum. Pearl millet or bajra (Pennisettum typhoides) is the next most important millet crop in India in terms of area and production, after sorghum. India is also considered to be the secondary center of origin for pearl millet, with many distinct cultivars growing throughout the country. Given sufficient rainfall (typically just 500 to 600 mm per year), pearl millet tends to be preferred over sorghum and is grown extensively in the dry western and northern regions of the country (Gujarat, Rajasthan, and Haryana). In other parts of India it is grown as a winter crop. Pearl millet is primarily a fodder crop in the western part of Rajasthan and Gujarat—especially during the summer when green fodder is scarce. In arid regions of India, pearl millet is a major source of food.

In India, agriculture is the major source of livelihood for nearly 70 percent of the population and accounts for 28 percent of Gross Domestic Product. Agricultural growth averaged 2.7 percent per annum between 1990 and 2002, driven by the introduction of high-yielding varieties of wheat, rice, and maize, and by the expansion of irrigation and other infrastructure facilities and services. Cereal crops occupy nearly 65 percent of the total cropped area; the rest is occupied by sugar crops, spices, horticulture crops, and oil seeds (ICAR 2006).[2] Agricultural output of the major cereals registered a sharp increase immediately following the green revolution, largely due to a growth in yields. However, the yield growth pattern has not been uniform, tending toward deceleration in the 1990s (Reserve Bank of India Bulletin 2006).[3]

Production Trends

India is a major producer of sorghum and other millets. Sorghum and pearl millet account for nearly 5 percent (each) of the total cropped area, but this area is concentrated primarily in the arid and semi-arid regions of India, with nearly 60 percent of the rural population[4] (ICAR 2006). India ranks second

[1] Millets in general refers to a group of small, seeded cereal crops that includes pearl millet, finger millet, little millet, fox tail millet, and other minor crops. In this paper, we discuss only pearl millet and its cultivars. Pearl millet is also known as "bulrush millet" or "spiked millet"; sorghum is referred as "great Indian millet."

[2] Out of the total cereals share of 65 percent, rice and wheat account for nearly 32 percent of the total cropped area, followed by sorghum, millets, maize, minor food crops, and pulses.

[3] The annual growth rate for the yields of major food grains (rice, wheat, and maize) during the period 1970–80 registered 1.1 percent; during the period 1981–90, there was a sharp increase to 2.7 percent. However, the rate of growth in yields has been slowing down since 1991: the period 1991–2000 periods registered a 1.3 percent growth in yield for major cereals.

[4] Arid and semi-arid regions constitute more than 50 percent of the total area of India.

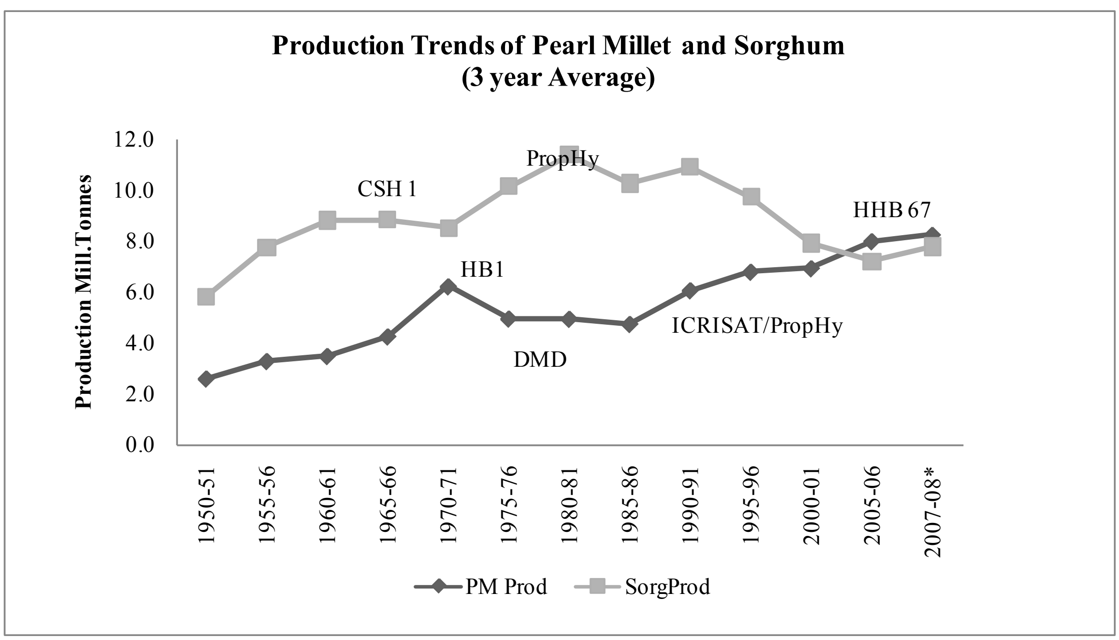
worldwide in both area and production of sorghum and millets (FAOSTAT 2007). Although the area sown to sorghum and millet has steadily declined over the past four decades, an increase in yields is evident, especially since the mid-1970s.

Distinct trends in production, area, and yield levels of sorghum and millet define three general periods: post-independence (1947–65); public-supported growth (1966–85); and private sector driven growth (1986 to present).[5] The post-independence period witnessed major increase in production of sorghum and pearl millet (Figure 1). Official data indicate that area and yields increased substantially for both crops (Figures 2 and 3). Official statistics suggest that yields were a major contributor to increased production of sorghum and millet during the post-independence period; however, this conclusion is based on very low estimated yields in the first few years after independence, which may be unreliable (Evenson and Pray 1991).

During the second period (1966–85), sorghum production increased quite rapidly while pearl millet production was stagnant. Although total area gradually declined for both crops, yields rose for sorghum but not pearl millet. By the mid-60s, new hybrids of sorghum and pearl millet were developed as part of the All India Coordinated Crop Improvement Projects. It appears that the sorghum hybrids—particularly CSH series from the Indian government research system, which are short duration, high-yielding types—were successful at raising yields. One factor that may have held down pearl millet yields during this period was the recurrence of downy mildew (Pray and Ribeiro 1991; McGaw 2001; Breese et al. 2002; Figure 3).

In the last period, from 1986 to the present, the production trends were reversed: sorghum production declined while pearl millet increased. Areas declined substantially for both crops, but much more for sorghum, and pearl millet yields increased more than sorghum yields. By 1986, ICRISAT had made a major contribution to pearl millet research by developing downy-mildew-resistant male sterile lines and releasing two hybrids (ICMH 451 and 501). These lines became the basis for numerous hybrids developed through private research, which would steadily drive up pearl millet yield and production.

Figure 1. Production trends of pearl millet and sorghum (1950-2008)

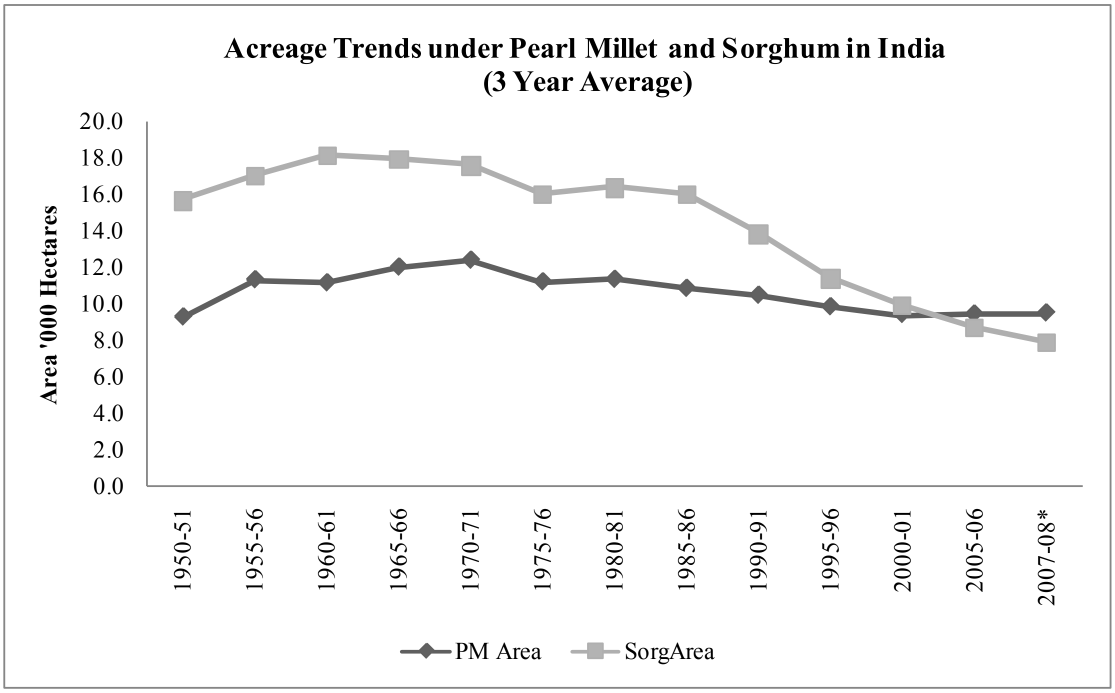


Note: For the year 2007–2008, we used actual data to denote current trend.

Source: Data from Ministry of Agriculture, Government of India (2008).

[5] We use three-year averages in analyzing the data, to compensate for weather variability.

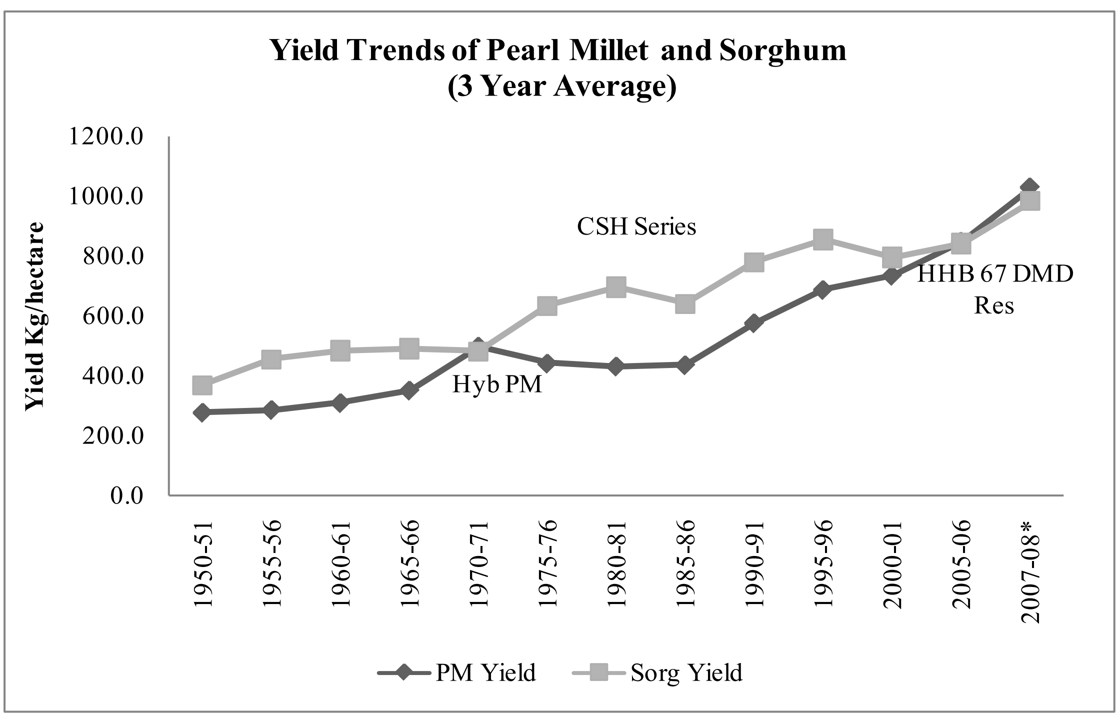
Figure 2. Acreage trends under pearl millet and sorghum in India (1950-2008)



Note: For the year 2007–2008, we used actual data to denote current trend.

Source: Data from Ministry of Agriculture, Government of India (2008).

Figure 3. Yield trends of pearl millet and sorghum (1950-2008)

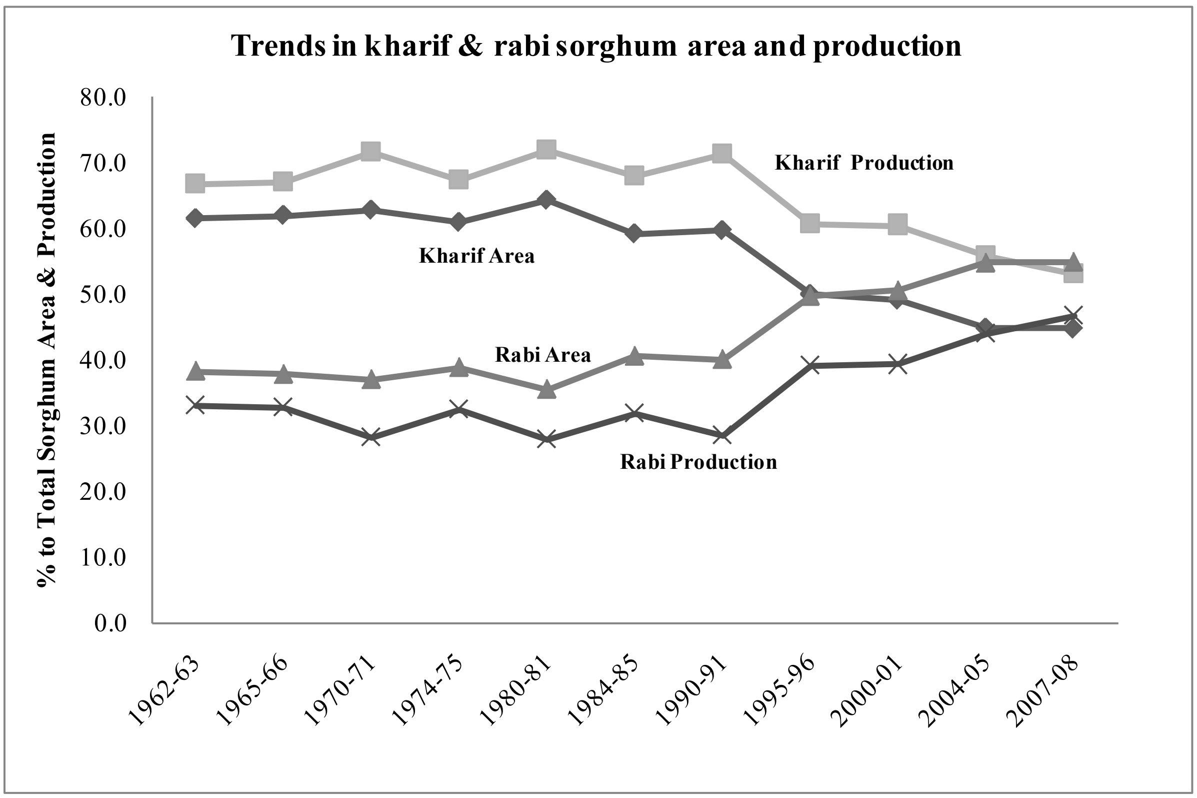


Note: For the year 2007–2008, we used actual data to denote current trend.

Source: Data from Ministry of Agriculture, Government of India (2008).

The sorghum story is complicated by a major shift in production, from the rainy season (*kharif)* to the post-rainy season (*rabi)*.[6] Changing consumption preferences among consumers toward wheat and rice rather than coarse grains reduced the demand for both *rabi* and *kharif* sorghum, creating competition (especially for rainy season sorghum) from modern varieties of food as well as cash crops. *Kharif* sorghum production accordingly declined, despite successful crop improvement efforts by public and private sector breeders. *Kharif* sorghum yields, however, are steadily increasing, currently at 900 kg/hectare, despite losses to pests and diseases (ergot and mold). Production declines in both seasons are evidently mainly driven by reductions in area (See Figure 4).

Figure 4. Trends in kharif and rabi sorghum area and production in India (1962–1963 to 2007–2008)



Source: Data from Ministry of Agriculture, Government of India (2008).

As Figure 2 shows, much like the better known Green Revolution crops (rice and wheat), dry land crops such as millet and sorghum have also shown increased and stable yields during the past five decades. Millet and sorghum occupy less than 9 percent of the total irrigated area in India (MoA 2006)—far less than other cereals.[7] The technology advancement in millets and sorghum has nevertheless kept their production levels stable, despite the decline in area planted.

Consumption Patterns

Annual per capita consumption of pearl millet in India has declined by 57 percent, from an average of 14 kg in 1998 to only 6 kg in 2003. Per capita consumption of sorghum declined by around 42 percent during the same period (CWC 2003); the current level is about 5 kg (Parthasarathy et al. 2006). In the

[6] This research mainly focused on *kharif* (rainy season) sorghum.

[7] Wheat has 90 percent of its total planted area under irrigation; rice has 56 percent and maize 21 percent).

major sorghum-producing regions, however, per capita consumption is still high. In rural Maharashtra, per capita annual consumption of sorghum is around 75 kg, accounting for almost half (48 percent) of per capita consumption of all cereals in those districts. Similarly, among the major pearl millet producing regions, per capita consumption was highest (92 kg/year) in rural Rajasthan and the dry areas of Gujarat. In those two regions, pearl millet accounts for more than 50 percent of cereal consumption, contributing about 20 to 40 percent of the total energy and protein intake (Parthasarathy et al. 2006).

The decline in consumption of millets and sorghum reflects rising per capita income levels, along with changing food habits and tastes and the increasing availability of fine cereals at subsidized prices, offered through government-sponsored public distribution systems (PDS). The PDS system in India is based on the wheat and rice model, which is less relevant in many areas and especially in the dryland farming areas, where millets, sorghum, and pulses were traditionally the staple grains for household consumption (Dayakar Rao, Reddy, and Seetharama 2007).

The demand for sorghum and millet has been enhanced, however, by increasing use in the poultry (especially layer feed) and animal feed sector. In the past four decades, the share of sorghum used as feed has increased from 38 to 50 percent. Dayakar Rao, Reddy, and Seetharama (2007) projected that by the year 2010, the likely demand for sorghum for poultry and cattle feed would be around 3 million metric tons. There is also huge demand for sweet-stalked and high energy sorghum, as a major bio-energy crop for the production of industrial alcohol, gasohol, and electricity.

Interventions

The spread of modern varieties and hybrids of pearl millet and sorghum, beginning in the mid-1960s, has had an important impact on small farmer welfare in India. Table 1 summarizes the impacts on production, yield, private sector participation, and household participation.

Table 1. Pearl millet and sorghum improvement in India: Impacts at-a-glance

Impact Indicators	Pearl millet	Sorghum	
		Kharif (rainy season)	*Rabi* (post rainy season)
Households directly affected (2006–2007)	6 million	3 million	-
Total acreage under high-yielding varieties (2006–2007)	6 million hectares	4 million hectares	-
Changes in yields (1980–81 to 2005–2006)	64% increase	85 % increase	4% increase
Changes in production (1980–2005)	28 % increase	32 % *decrease*	38% increase
Private sector participation (# of seed companies involved in distribution)	61	44	-
Private sector share in the supply of HYVs	82 %	75%	-

Source: Data provided by Ministry of Agriculture, Government of India 2007; NRCS (Hyderabad) 2007; and NSAI 2009.

The success and sustainability of these improved cultivars was the result of three types of interventions (corresponding to the three historical periods defined above) that were implemented by the Indian national and state governments working in collaboration with the international agricultural research center ICRISAT. These interventions included:

- Public sector research regarding sorghum and millet plant breeding (especially increased resistance to diseases and pests) and crop management
- Government support for seed production by both the public and private sector
- Government policies that allowed the private seed industry to grow

Indian public sector agricultural research agencies have been breeding improved millet varieties since the early part of the twentieth century. The development of hybrid sorghum in India started in the early 1960s, with the establishment of hybrid breeding programs at a number of agriculture research centers: IARI (Indian Agricultural Research Institute); the State Agricultural Universities in Haryana, Karnataka, and Andhra Pradesh; the Directorate of Sorghum and Millet research in Hyderabad; and the All-India coordinated sorghum improvement program (AICSIP) of the Indian Council of Agricultural Research (ICAR). In 1972 the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) was established, further spurring sorghum and millet improvement research.[8] It drew on the work of a number of publicly funded Indian agricultural research agencies[9] as well as research conducted around the world. ICRISAT undertook a major effort to collect and conserve representative millet germplasm from the areas of origin as well as areas of cultivation.

Improved crop varieties and breeding lines developed by ICRISAT and the Indian public research institutes constitute a major source of the open-pollinated varieties and hybrids that were distributed by public and private seed companies, as well as of breeding materials for private seed companies.[10] As a result, the adoption of improved pearl millet and sorghum varieties by farmers (both hybrids and open-pollinated varieties) has increased dramatically, beginning in the mid-1960s.[11] Initially, from the mid-1960s to early 1990s, the rate of uptake of improved wheat and rice varieties exceeded that for sorghum and pearl millet; since then, however, the relative growth rates reversed, and the crop area shares in improved sorghum and pearl millet varieties are now comparable to the numbers for rice and wheat.

To summarize:

- National average yields of sorghum and pearl millet have more than doubled over the last four decades, though with significant spatial variation in different parts of the country.
- Almost 80 percent of the sorghum and pearl millet areas are sown to high-yielding varieties (HYVs), with privately bred hybrid cultivars substantially more widely adopted for pearl millet than for sorghum.

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[8] ICRISAT was established at Hyderabad, India, to focus research on the arid and semi-arid regions of the world. Its mandate crops are sorghum, pearl millet, finger millet, groundnut, chickpea, and pigeonpea.

[9] Some of the prominent public research agencies engaged in millet research are: National Dry land Research Center (Hyderabad), All India Millet Improvement Research project of ICAR (Indian Council of Agricultural Research), and Small millets Research Program at the University of Agricultural Sciences (UAS, Bangalore).

[10] A 1998 survey jointly carried out by ICRISAT and Rutgers University on private seed companies in India found that pearl millet breeding materials from ICRISAT provided the base material for 80 percent of the research products from private seed firms (Ramaswami, Pray, and Kelley 2001).

[11] The trends in HYV adoption of millets should be interpreted with care. Although the growth of millet crops is comparable to other major cereals, this trend is more pronounced in irrigated and favorable regions of the country, with a gap in the adoption of improved cultivars in arid and semi-arid systems.

2. INTERVENTIONS: GOVERNMENT-SUPPORTED MILLET AND SORGHUM RESEARCH

There was little research on sorghum and pearl millet in the pre-independence period. Even after independence these crops received very little research attention, until the creation and expansion of the All India Coordinated Crop Improvement Projects. In the early 1960s, the Indian Council of Agricultural Research, with Rockefeller Foundation assistance, initiated research on hybrid sorghum and pearl millet. ICAR then initiated the All India Coordinated Pearl Millet Improvement Project (AICPMIP) and the All India Coordinated Sorghum Improvement Project (AICSIP), in 1967 and 1969. These programs organized government research and conducted multi-location testing for improved characteristics of hybrids and varieties, working with state agricultural universities, research institutes, ICRISAT, and experiment stations. The first sorghum hybrid, CSH 1 (Coordinated Sorghum Hybrid), was bred in India and officially released for commercial cultivation in 1964, followed by the first pearl millet hybrid (HB 1) in 1965.

The creation in 1972 of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) further stimulated substantial research on sorghum and pearl millet. Interviews with private firms found that by 1970, four companies had their own sorghum and pearl millet breeding programs; by 1985 the number had grown to ten companies (Pray et al. 1991). In 1981, MBH-110 (pearl millet) was the first private hybrid of any crop to be officially released by the government of India.

Table 2. Pearl millet and sorghum crop varieties released in India, 1961–2005

Release period	ICAR		ICRISAT [a]		Other notified varieties [b]	
	Sorghum	P. Millet	Sorghum	P. Millet	Sorghum	P. Millet
			(Number of varieties) [c]			
1961–70	nr	nr	nr	nr	9	5
1971–80	1	3	2	nr	39	10
1981–90	nr	3	8	14	53	23
1991–2000	32	79	13	28	58	7
2001–2005	4	7	2	3	22	54
Total	37	92	25	45	262	207

Notes: nr = no release.
[a] Refers to the period 1991–1998 and 2004–2005 for ICRISAT.
[b] Notified varieties include releases from State Agricultural Universities.
[c] Includes both varieties and hybrids.
Source: Data provided by the Ministry of Agriculture, Government of India (2002) and ICRISAT Annual Reports.

A major driver for the spurt in private sector growth was the strong public sector research support program on sorghum and millet. International agricultural research centers such as ICRISAT exchanged breeding material with both public and private research institutions. National agricultural research centers such as ICAR and the agricultural universities provided breeder seed to the national and state seed corporations as well as the private seed companies, to be multiplied as foundation seed and distributed through company outlets, farmer cooperatives, and private dealers. Table 2 shows that public sector research in millet and sorghum has resulted in many improved varieties.

In general, the private companies with research programs acclaimed the contribution of public research (Pray et al. 1988). The development of in-bred lines or restorers takes a long period of time—usually up to nine seasons. For private firms, their association with ICRISAT or ICAR and State Universities is thus invaluable, as the public institutions provide developed in-bred lines free of cost. Former ICRISAT-based scientists and other university-based scientists also assisted small seed companies to develop proprietary hybrids. All the pearl millet hybrids developed by private firms in the late 1980s (with the exception of a few developed by MNCs) used at least one ICRISAT line.

Pray et al. (1991) estimated that in the late 1980s, private investments into pearl millet improvement were at the same level as public investments, and the share has increased considerably since then. This might appear surprising, as pearl millet is grown largely by subsistence farmers in India. However, the large size of the market together with the fact that farmers were already used to regular seed replacements provided a sufficient business incentive. Moreover, as all pearl millet hybrids periodically develop diseases, there is ongoing demand for new and better products.

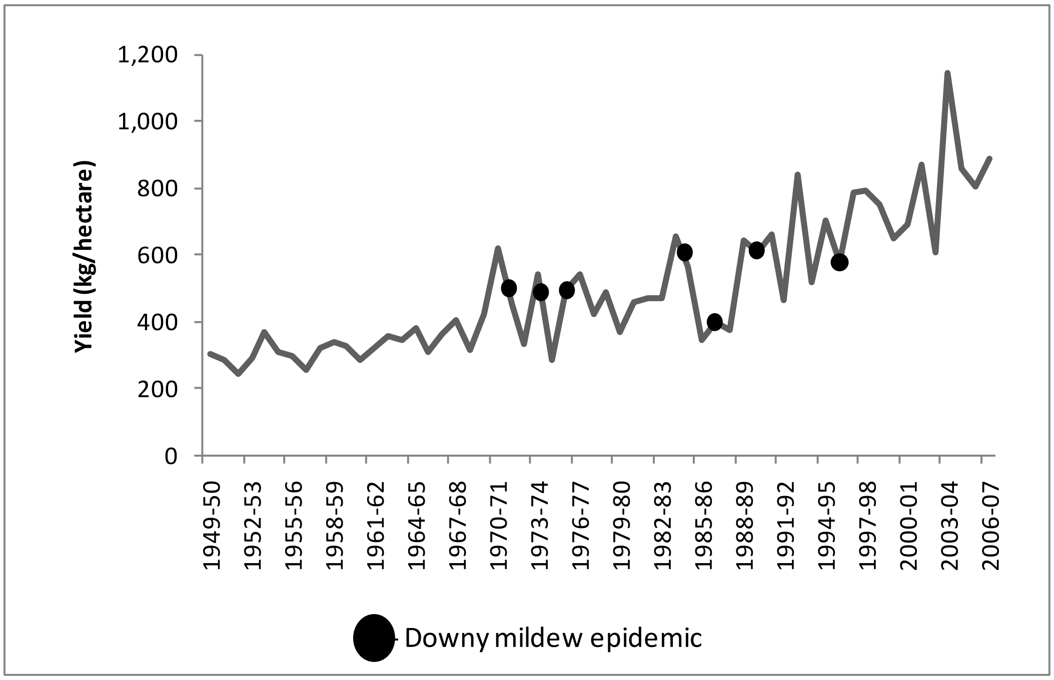
Until late 1980s, public agencies played the major role in varietal development, multiplication of seeds, and distribution through seed outlets (by state departments of agriculture, national and state seed corporations, and farmer cooperatives). Beginning in the early 1990s, small-sized private seed firms began to "bulk up" publicly bred varieties and began distributing the seed through their own networks of private dealers. Private companies began to breed their own millet varieties in the 1970s, but it took a decade to produce the first commercially successful improved cultivars. A recent Government of India report (Reserve Bank of India 2005) on the status of Indian agriculture claimed that nearly 80 percent of the commercial seed sales of pearl millet and sorghum are by private seed companies.

Pearl Millet Research

India, which produces more than half the world's pearl millet (FAOSTAT 2006), has been the center of research efforts since the 1960s, when the availability of cytoplasmic-genetic male-sterile lines brought a succession of hybrids. Before ICRISAT was founded in 1972, most of the research was done by the Indian Council of Agricultural Research (ICAR) and other Indian organizations, raising yields to new highs. Since the mid-1960s, when hybrid pearl millets were first introduced in India, average grain yields have nearly doubled, despite the shift to more marginal production environments. The All India Coordinated Pearl Millet Improvement Project (AICPMIP) was started in 1967 in Poona, Maharashtra, and later moved to Mandor (Jodhpur), Rajasthan. The first pearl millet hybrid HB 1 (developed by Punjab Agriculture University, Ludhiana) was released in 1965, making pearl millet one of the earliest public-bred hybrid crops marketed in India.

In 1974–75, a heavy attack of DMD reduced pearl millet production dramatically, to 3.3 million tons—a decrease of 57 percent from previous years. The second series of millet hybrids was released during 1974–75 (PBH 10 and 14) and proved more tolerant than previous cultivars, but they also broke down quickly. The two other hybrids brought during the mid 1980s, BJ 104 and BK 560, were known for their short duration and drought resistance; they had improved adoption levels and slowly brought back production levels up to 6 million tons. However, these cultivars also suffered from DMD, and the government of India withdrew both of them from commercial use in 1986 (Pray and Ribeiro 1990).

Figure 5. Pearl millet and downy mildew in India



Source: McGaw 2001.

Downy mildew (*Sclerospora graminicola)* epidemics constitute the major risk to cultivation of pearl millet hybrids, a risk that can be reduced by effective crop improvement research. Losses can approach 100 percent in individual fields, and are estimated to average 14 percent across India. When one hybrid is overcome by rapidly evolving pathogen populations, other hybrids having a genetically identical parental line soon follow—and pearl millet hybrids in India are in fact based on a narrow range of closely-related parental lines. This results in rapid cultivar turnover, mostly driven by disease pressure rather than yield or quality improvements, to the detriment of pearl millet consumers, producers, and all those involved in the seed trade (Breese et al. 2002).

Proper agronomic recommendations made it possible to harness the potential of high-yielding hybrids and varieties. Popular public hybrids such as HHB 67 (released by Haryana Agricultural University in 1989) delivered increased production levels from the early 1990s until now—with current production at 9 million tons. Today, hybrids cover more than 50 percent of the total national pearl millet area of 24.7 million acres (Thakur et al. 2003).

Box 1. Marker assisted selection (mas) and pearl millet hybrids: The case of HHB 67 improved (HHB 67-2)

HHB 67, a public-bred hybrid, was developed and released by Haryana Agricultural University in 1995–96 and was widely adapted by farmers in Haryana and Rajasthan, covering nearly 400,000 hectares. The hybrid is grown under rainfed farming systems, and its short duration allows farmers to prepare for a following crop, such as chickpea, wheat, barley, or oilseed mustard. This means two crops per season—one for food and fodder, and one for cash. After more than 10 years of widespread and repeated cultivation, the hybrid was constantly attacked by downy mildew (DMD). A new hybrid, "HHB 67 improved," was accordingly released by the Haryana State Varietal Release Committee in 2005–2006.

To create the new version of the hybrid, the male parent line (bred at ICRISAT-Patancheru) was adapted by marker-assisted backcrossing to add the gene(s) for downy mildew resistance, transferred from elite parent ICM 451 to H 77/833-2 (the male parent of the original HHB 67). The female parent of HHB 67-2 was bred at ICRISAT-Patancheru by conventional backcrossing to add several genes for downy mildew resistance from ICML 22 to 843A/B (the A/B-pair used as female parent of the original HHB 67); this conventional process took three times as long as breeding the improved male parent. ICRISAT then multiplied breeder seed for these improved seed parents, sufficient to cover 200,000 hectares in the 2007 season.

A downy mildew epidemic can destroy 30 percent of the grain harvest. For HHB 67, this would amount to a loss of at least $7.7 million in just the first year of an epidemic.[12] The introduction of the downy-mildew-resistant hybrid (HH B 67 Improved) moreover promises an additional estimated return of $2.6 million, reflecting an improved yield advantage of 10 percent over the existing cultivar. According to Hash, the success of this program can be attributed mainly to "reasonably strong linkage of the 'upstream' biotechnology end of the series of projects to the more 'applied' plant breeding product development, testing and delivery end."

Source: Hash et al. 2007.

Over the past two decades, research and development (R&D) in pearl millet has become increasingly privatized, reflecting a general shift in India's agricultural research system from publicly dominated to privately driven seed development and distribution (Pal and Byerlee 2003). Productivity of pearl millet increased more than twofold over the last five decades, owing to the widespread use of high-yielding and disease-resistant cultivars, along with improved production technology. The accomplishments of pearl millet breeding are considered a success story in India, with a large number of high-yielding and disease-resistant single-cross hybrids and open-pollinated varieties very widely used by Indian farmers. The public and private sectors also developed strong and effective seed production and distribution programs.

Rainy Season (Kharif) Sorghum Research

The first set of sorghum hybrids was released in the mid-1960s. These were followed by the release of more popular hybrids, like CSH5 and CSH 6 in the mid-1970s and CSH 9 in the early 1980s, augmenting the spread of sorghum HYVs and open-pollinated varieties and boosting productivity. The gains in productivity, however, were countered by the decline of planted area. Sorghum production levels increased slowly from 6 million tons during the 1950s to a maximum of 11 million tons in the early 1980s. It started declining thereafter, and currently stands around 9.2 million tons (Figure1).

[12] This figure represents 30 percent of the harvest of 550,000 hectares yielding 0.7 t/ ha, valued at Rs. 3000.

Box 2. Coordinated sorghum hybrids (CSH-series): The role of Indian national agricultural research

Historically, sorghum improvement has been an important success, supported by Indian national agricultural research institutions such as ICRA and SAUs. The national program released 19 *kharif* (rainy) and 11 *rabi* (post-rainy) cultivars, and state programs released an even greater number. The worth of these improved cultivars is demonstrated in their successful adoption by farmers. With the 1964 release of CSH-1, the first commercial hybrid, sorghum became the second crop after maize in developing high-yielding hybrids. Since CSH-1, nineteen more hybrids were released through the ICAR system, and several more hybrids adapted to specific regions were released at state levels.

Hybrids CSH 1 to CSH 23 are a testimony to the success of Indian sorghum breeding, not only in terms of yield enhancement, but also in the diversification of parental lines and progressive advances in breeding resistance to major pests and diseases. The hybrids played a major role in pushing up productivity and production, particularly in the case of *kharif* sorghum. CSH 1, CSH 5, CSH 6, CSH 9, CSH 14 and CSH 16 show dramatic increases in productivity. From CSH 5 and CSH 6, with a yield potential of 3.4 t/ha, yield potential was raised to 4.0 t/ha in CSH 9 and to more than 4.1 t/ha in CSH 16 and CSH 23.

Source: NRCS 2007.

Next to China, India has the highest level of adoption of improved cultivars in Asia (65 percent of total sorghum area). The partnership between ICRISAT and NARS for sorghum improvement spans more than three decades. This has resulted in the development and release of several improved varieties and hybrids of sorghum exclusively for semi-arid regions of India. Adoption of these improved cultivars benefits more than 9 million farmers and enhances food security for the poor in the Indian semi-arid tropics (SAT).[13]

In India, more than 4 million hectares are planted in more than 54 hybrids developed by private sector seed companies, based on ICRISAT-bred parental lines or their derivatives. In particular, the ICRISAT-private sector partnership hybrids, JKSH 22 and VJH 540 (known for high-yield potential, large grain, and earliness), showed rapid adoption, covering 210,000 ha in 2002 and 142,000 ha in 2003 in the rainy season areas in the major sorghum growing states. Several other private sector hybrids with ICRISAT content (such as MLSH 296, GK 4009, and GK 4013) are also widely adopted in India. Two other hybrids are highly popular among farmers because of their higher grain and fodder yield potential, coupled with good grain and stover quality: PVK 801 (a dual-purpose, rainy-season adapted sorghum variety currently cultivated in more than 100,000 hectares in Maharashtra), developed by ICRISAT in partnership with Marathwada Agricultural University (MAU), Parbhani; and SPV 1411 (Parbhani Moti), a post-rainy season variety with pearly-white large grains (cultivated in more than 200,000 hectares in Maharashtra and Karnataka). Another hybrid is also popular, as its grain and fodder yield potential is better than the highly popular hybrid CSH 16. This is hybrid SPH 840, developed by ICRISAT in partnership with Panjabrao Deshmukh Krishi Vidyapeeth, Akola. These examples of ICRISAT-bred hybrid parents illustrate the power of partnership to exploit the complementary expertise of ICRISAT, Indian NARS, and the private sector in developing and delivering desired products. Adoption of these improved cultivars, coupled with improved crop production technologies, resulted in an increase in sorghum grain productivity of 280 kg/ha during the period from 1971 to 2003.

The use of improved varieties of sorghum across different states decreased the unit cost of production during the 1980s and 1990s as compared to the early 1970s, despite the increased costs of production entailed in additional inputs (Bantilan and Deb 2002). The productivity gains from improved cultivars have more than compensated for the cost of the additional inputs used for their cultivation (Reddy et al. 2007). The reduction in per ton cost of production in the 1990s was 40 percent and 37

[13] Based on the acreage under HYVs (sorghum and pearl millet) and average farm size in different regions of India, we estimate that approximately 9 million farmers benefit directly by adopting new, improved cultivars.

percent in Maharashtra and Rajasthan, respectively, as compared to the early 1970s. The cost-benefit ratio of production of improved cultivars in India is 1: 1.4 (Bantilan and Deb 2002).

Box 3. ICRISAT-Private Sector partnerships in sorghum improvement

The ICRISAT-Private Sector (PS) partnership has greatly contributed to the development and marketing of improved hybrids and varieties in Asia. In India, more than four million ha of rainy season sorghum (80 percent of the total rainy season sorghum area) and one million ha of the summer season sorghum are planted with about 70 PS-based hybrids, of which 54 are based on ICRISAT-derived parental lines or their derivatives. Another high-yield potential hybrid resulting from the ICRISAT-PS partnership, VJH 540, has been extremely popular, increasing in area planted from 650 ha in 1997 to 14,020,000 ha in 2003 (in rainy season in major sorghum growing areas)—based on the increase in seed sales from 6.5 tons in 1997 to 1420 tons in 2003. These examples illustrate the power of partnership between ICRISAT and the PS to develop and deliver desired products to the farming community. Several other private sector hybrids, such as MLSH 296, GK 4009 and GK 4013, are also widely adopted in India. The high rate of adoption of ICRISAT-based hybrids is due to their large grain and high grain and fodder productivity. These hybrids have made substantial contributions to enhance cultivar diversity, productivity, and yield stability, and have improved the livelihoods of poor farmers in the dry areas.

Source: Reddy et al. 2007.

The popularity of hybrids triggered hybrid seed production in India. Several seed villages in Andhra Pradesh and Karnataka became prosperous through large-scale hybrid seed production. Seed production of one ICRISAT-private sector partnership hybrid, JKSH 22, earned farmers on average more than Rs 137 million per year in AP and Karnataka, and Rs 1200 million in Maharashtra and other sorghum-growing areas in India (Reddy, Ramesh, and Gowda 2005).

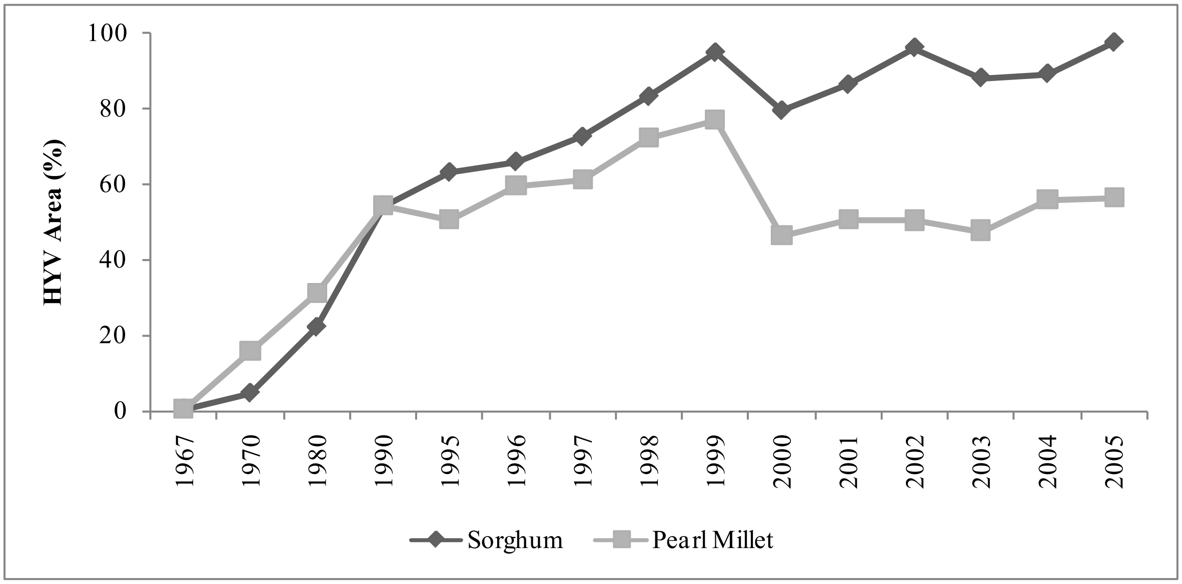
Post-rainy (Rabi) Sorghum Research

Most of the research and marketing activities are focused on millet and rainy season (*kharif*) sorghum only. In India, sorghum is produced in two seasons: the rainy or *kharif* (monsoon) season; and the *rabi* season (when crops are grown, if possible, on residual ground moisture). Currently sorghum is cultivated on 9.2 million hectares in India. The total area under sorghum has declined since 1961, entirely in the rainy season, from 62 percent in 1962–63 to 45 percent in 2007–2008. Its share in post-rainy season planting in fact increased from 38 percent in 1962–63 to 58 percent in 2007–2008) (Figure 6). In the last 15 years, a total area of 6.9 million ha—especially from *kharif* sorghum acreage—has been diverted to other crops. This trend is most evident in the states of Northern Karnataka and Maharashtra; but even there, the post-rainy season share of total sorghum area increased from 9 percent in the 1960s to 21 percent during 2004–2005.

Hybrid breeding in sorghum has been targeted toward the rainy season; improvement of *rabi* sorghum did not receive as much emphasis and effort as *kharif* sorghum until the nineties. Conventional breeding has so far been unsuccessful in developing higher-yielding (and drought-tolerant) sorghum hybrids for the post-rainy season. Consequently, with more than 90 percent of the sorghum acreage in the rainy season now planted to hybrid varieties, rainy season sorghums average twice the grain yield of post-rainy sorghum.

More than 80 percent of the post-rainy sorghum area is still dominated by two important cultivars: *Maldandi*, a local landrace; and M-35-1, a selection from *Maldandi* first released in 1930 (NRCS 2007). The average replacement rate for sorghum during the post-rainy season is 16 years. Unlike *kharif* sorghum, biological and environmental factors limit further yield and crop improvement in *rabi* sorghum. Participatory varietal selection trials were conducted jointly by ICRISAT and the National Research Centers for Sorghum (NRCS) in 1999–2001, in order to identify post-rainy season sorghum types suitable for further crop improvement, but the effort was not very productive. They found no restorer or cytoplasmic male sterile lines that would make it possible to exploit any heterotic vigor (to develop "hybrids"); and the purified selections made out of the existing varieties (*Maldandi* and its derivative M-35-1) failed to outperform what farmers were already growing. For *rabi* sorghum, the fodder yield is given even more importance than for *kharif* sorghum. Grain quality is moreover as important as the grain yield.

Figure 6. Percent of HYVs under sorghum and pearl millet (1967-2005)



Source: Data from Ministry of Agriculture, Government of India.

Recent statistics reveal a considerable decline in sorghum area, production, and consumption in the primary growing regions of India. During the rainy season in particular, sorghum acreage has declined due to competition from other high-value crops, such as maize, cotton, and soybean. Public and private seed suppliers recognize, however, that the states of Karnataka and Maharastra, where the area under post-rainy sorghum is increasing, continue to offer scope for investment. Pioneer Hi-Bred Seeds in India developed two sorghum hybrids (Pi-8703 and Pi-8704) exclusively for post-rainy season growers. These two hybrids yield 30 percent more than the existing traditional cultivar *Maldandi;* with one or two supplemental irrigations, the yield increase would be over 50 percent. Other seed companies (JK agri genetics and Proagro seeds) have also engaged in post-rainy season sorghum research.

Public research institutions such as the University of Agricultural Sciences (Dharwad, Karnataka) and NRCS (Hyderabad) are also involved in developing specific cultivars for *rabi* season. Five *rabi* hybrids and five varieties have been released so far by public sector research institutions. However, the yield potential of the newly bred cultivars is only marginally higher than M 35-1, the widely grown local cultivar. The first *rabi* hybrid released was CSH 7R and the latest one is CSH 19R. The four *rabi* varieties released, CSV 8R, CSV 14R, CSV 18, and Swathi, were better received than the early *rabi* hybrids such as CSH 7R and CSH 8R. The more recent hybrids (CSH 15R and CSH 19R) are more productive, but their acceptability is limited, as farmers are reluctant to invest in hybrid seeds during *rabi* without irrigation (NRCS 2007).

The area under *rabi* sorghum, especially in Maharashtra and Northern Karnataka, may not decline substantially and is expected to stabilize at between 4.5 and 5 million ha. *Rabi* sorghum is highly valued as food, because of its excellent grain quality and because it is produced during the post-rainy season. It commands higher prices in the market than *kharif* sorghum, often on a par with or higher than (the local durum) wheat. *Rabi* sorghum is also highly valued as fodder during lean months and is grown without irrigation. The *rabi* sorghum stover is also highly valued for its quality; it is much more important than *kharif* sorghum stover, as its harvest precedes the lean summer months. The economic contribution of fodder to the total income from *rabi* sorghum is estimated at 45 to 57 percent in varieties and 39 to 47 percent in hybrids, in Maharashtra and Andhra Pradesh (NRCS 2007). Thus, even at the low productivity level, *rabi* sorghum is far more profitable to the producer than *kharif* sorghum. Both the grain and the stover enjoy strong demand which may further expand.

3. INTERVENTIONS: GOVERNMENT SUPPORT FOR SEED INDUSTRY GROWTH

At the beginning of the Green Revolution, it became clear to the Indian government and to key state governments that a major constraint on the spread of modern varieties would be the seed distribution system, either by state extension services or the nascent private sector. The first state seed corporation, evolving out of the Pantnagar Agricultural University in Uttar Pradesh, became a model for the National Seed Corporation (NSC) and other state seed corporations. The Indian government, with the financial support of the World Bank and technical assistance from the Rockefeller Foundation, financed the development of State Seed Corporations (SSCs) in most major states of India in the 1960s.

Government seed production increased throughout the 1970s, but moved away from direct involvement by the state departments of agriculture (except in Tamil Nadu). Between 1968 and 1971, state governments reduced seed production; only a few have revived it, some using contract growers on large departmental farms. The State Seed Corporations (SSCs) replaced departments of agriculture in seed production. Universities and ICAR institutes expanded distribution of certified seed through farmer fairs and mini-kits.

The institutional framework for the seed industry was developed at the same time, also with technical assistance from the Rockefeller foundation. The Indian Seed Act was established in 1966 as the basis for the regulatory framework. The Indian seed industry was heavily regulated, limiting the entry and formation of large firms (domestic or foreign) and restricting or banning the private importation of seeds for both commercial and research purposes.

Support for Private R&D and Seed Distribution

The seed sector was deregulated in 1971, with relaxed restrictions on seed imports and entry of private firms. In 1988, a new seed policy spurred enormous growth in private sector seed supplies in India. Today, the Indian market for agricultural seed is considered one of the biggest in the world, with annual sales at around $1080 million. The domestic market accounts for $975 million in sales, and international trade (mainly with developing countries) accounts for the remaining $20 million. The Indian seed industry has now evolved from public-sector domination into a multi-faceted industry, with a large involvement of private firms and increasing emphasis on research and development.

In the absence of public sector research, a private seed industry would have started much later and developed much more slowly (Pray and Ribeiro 1990). Public plant breeding developed hybrid maize, sorghum, millet, and cotton in the 1960s, creating demand that the private commercial seed industry would build on. In the late 1960s and 1970s, government programs provided subsidies and technical advice to small and medium-sized firms to produce and multiply seeds. The 1970s were a period of experimentation for all companies: private firms invested in research and breeding activities to produce various public hybrids, using various seed-growing locations and production strategies. The only companies that produced and sold their own hybrids were Mahyco, Pioneer, and Nimbkar.

Another key seed policy instrument enhanced the participation of private firms: varieties could be multiplied and sold to farmers without going through the regular certification process, by selling their hybrids or varieties as “truthfully labeled” (TFL) seed. Seed certification procedures for most crops also favored private firms’ participation in seed markets. Farmers could have some assurance of minimum quality of seed even if they did not know the company that produced it. But as certification was (and is) voluntary, it did not slow down the development of private hybrids of millet and sorghum. Companies always had an option of selling their seed as “truthfully labeled” rather than certified.[14]

Government research programs produced a steady supply of new hybrids of sorghum, pearl millet, and cotton which increased the demand for hybrids. This was due in part to the expansion of

[14] Well-established enterprises with reputations to protect may sell seed that has no official seed certification. Such seed is often described as “truthfully labeled” and bears a label describing minimum seed quality standards, self-certified and not certified by any official agency (Tripp 2001).

government research during the 1970s, particularly in the state universities. Public research on pearl millet and sorghum grew more rapidly than for other hybrids after the establishment of ICRISAT in 1972. Public research also provided the basis for successful private research and development. The first private pearl millet hybrids were based on local lines developed in the public sector and exotic lines brought in by ICRISAT.

The expansion of the seed industry in the late 1980s and early 1990s brought about a significant rise in investment research, along with growth in the supply and demand for improved seeds in Maharashtra and other pearl millet growing states. The cultivars that had dominated during the 1980s were mostly replaced by new varieties and hybrids. The benefit-cost ratio of shifting from public hybrids (of sorghum and millet) to private hybrids was much higher for small farmers than for large farmers. In the 1990s the seed market was dominated by ICRISAT-based hybrids. While the adoption of privately released hybrids of pearl millet and sorghum increased (developed by private firms such as Mahindra Hybrid Seed Company and ProAgro and Pioneer), most of these hybrids contain parent materials from ICRISAT and other public research agencies (Bantilan and Deb 2002). Other public research hybrids, such as the Coordinated Sorghum Hybrids (CSH) series, also remain popular with farmers.

The use of improved cultivars of pearl millets was most pronounced in the states of Maharashtra and Gujarat (up to 90 percent), Haryana (85 percent), and Tamil Nadu (80 percent). For sorghum, the adoption of improved varieties was higher for rainy season than post-rainy season; 71 percent of the total sorghum area in India was under improved cultivars by 1998–89 (Bantilan and Deb 2002).

Pray et al. (1991) and Pray and Ramaswami (2001) summarized the factors in making hybrid seed of pearl millet and sorghum widely available in India:

1. Government/ICRISAT research programs produced the high-yielding varieties and hybrid parental lines.
2. Seed industry development programs of the National Seed Corporation (assisted by the Rockefeller foundation and USAID) trained companies in producing quality, foundation, and certified seeds during the early 1970s.
3. Private companies multiplied seed and sold it to farmers using wider market networks.

Pray and Ramaswami (2001) sought to measure the impact of these efforts to liberalize India's seed sector by comparing 1987 with 1995. They provided evidence that liberalization increased the competitiveness of the seed sector as well as the amount of seed research conducted by Indian and foreign seed firms, and suggested that Indian farmers would be the ultimate beneficiaries of these policy changes.

Matuschke and Qaim (2008) estimated the determinants of pearl millet adoption and the impact of increasing privatization on technology diffusion. Their analysis is based on a comprehensive survey of 266 pearl millet farmers in the state of Maharashtra in the semi-arid tropics of India. Maharashtra, the state with the second largest area under pearl millet in India, accounts for 18 percent of the national pearl millet area and 15 percent of total production (Fertiliser Association of India 2004). The Government of Maharashtra reports that seed distribution of hybrid pearl millet by public and private sources tripled between 1990 and 2000. (Statistics provided by the Department of Agriculture, State Government of Maharashtra, Mumbai, 2005.)

The econometric estimation by Matuschke and Qaim (2008) identified three factors that contributed to the adoption of pearl millet hybrids over recent decades: education level, distance to the main source of information, and good market infrastructure. In addition, the increasing role of private companies in seed development and distribution had a positive effect on innovation rates. The study refutes the notion that privatization of seed markets would hamper technological progress in the small farm sector, and suggests that even in typical subsistence crops, such as pearl millet, the private sector can play an important role. As noted above, however, the Indian private sector breeding programs often depend on germplasm that has been developed in the public sector. In pearl millet, for instance, many of the proprietary hybrids build on freely accessible breeding lines from ICRISAT and other public organizations.

The Consortium Model

In 2000, ICRISAT developed a new kind of public-private partnership called a "consortium" model: private companies jointly fund research with ICRISAT to develop parental lines that are made publicly available. Initially, 14 private seed companies pledged a total of $109,000 annually to the consortium to support applied plant breeding research at ICRISAT. All materials developed through this research will remain as international public goods, freely available to all (ICRISAT 2002). Companies engaged in this consortium include international corporations (Pioneer, Bayer Crop Sciences, Monsanto, and Syngenta) and a large number of domestic seed companies (Advanta India, Nuziveedu, Ganga Kaveri, Nav Bharat, J K Agri-Genetics, Mahendra Hybrids, Mahyco, New Nandi, Plantgene, Proagro, Zuari, Prabhat Agri Biotech, and Shriram Bioseed Genetics).

Box 4. Impact of public-private partnerships: The case of pearl millet hybrids in India

A case study of two hybrids was carried out by ICRISAT in the year 2006 to document the impact of ICRISAT-derived breeding materials on the consortium partners. Two of the leading private seed companies (JK and Pro Agro (Bayer crop science)) had developed successful hybrids of pearl millet on ICRISAT-bred A-lines (or their sub-selections), by exploiting their residual variability. Since almost all the ICRISAT-bred A/B lines were developed by pedigree-bulk breeding, a small degree of within-line variability does exist, as demonstrated in a few selection experiments for flowering time and downy mildew resistance.

– The hybrid JKBH 26, developed by JK Agri Genetics, is based on an A-line that has no other hybrid, public or private, on the market. This hybrid has been under cultivation since 1996, retaining its initial high level of downy mildew resistance. The hybrid was adopted by increasing number of farmers for its high grain and stover yield as well as its high level of downy mildew resistance, reaching a peak adoption level of more than 400,000 ha in 2005.

– The hybrid 9444 was developed by Proagro Seed Company (now Bayer BioScience). It is also highly valued for its high grain and stover yield, good stover quality (farmers' perception), and downy mildew resistance. This hybrid is also highly tolerant to temperatures as high as 45°C during flowering time. The adoption of this hybrid rapidly increased from 60,000 ha in 2001 to more than 400,000 ha in 2006.

Source: R.P. Mula et al. 2007

As of 2006, 18 seed companies in the consortium supported variety improvement research on rainy season and post-rainy sorghum, and 34 supported pearl millet research. The research focuses on diversifying the genetic base of these three crops to reduce vulnerability to diseases and pests, improve seed quality, and field-test promising hybrids. ICRISAT's Hybrid Parents Research Consortia (HPRC) brings together small- and medium-sized domestic firms for the purpose of commercializing sorghum, millet, and pigeonpea hybrids, thus contributing to the commercial viability of both domestic seed firms and the wider seed market in India (Spielman, Hartwich, and Grebmer 2007).

4. ECONOMIC IMPACTS

Corn, sorghum, and pearl millet are the three most widely planted cereals in India after rice and wheat. Pearl millet (with 10 percent of the total cropped area and 35 percent of total seed sales by value) and sorghum (with 15 percent of the total cropped area and 30 percent of the seed sales) together constitute about 12 percent of the total value of seeds sold commercially in 1999–2000 (Statistics provided by the Department of Agriculture, Ministry of Agriculture, Government of India).

For all the crops listed except sorghum, saved seed was formerly the dominant source of seed but has dramatically declined. Similarly for sorghum, the proportion of source seed to saved seed increased during the 1990s (Mahyco 2001). There was a substantial increase in the sale of proprietary hybrids for pearl millet (nearly an eight-fold increase in the 1990s) and maize (a threefold increase), and a less dramatic increase for sorghum, at around 20 percent. In contrast to proprietary hybrids marketed by private companies, sales of publicly bred sorghum and pearl millet hybrids have declined considerably. There was also a significant reduction in the sale of open-pollinated varieties (OPVs) of pearl millet from 1990 to 1999, but an increase in OPVs of sorghum during the same period (Nagarajan, Smale, and Glewwe 2007).[15]

About 55 percent of the area under sorghum and pearl millet cultivation in India were planted with high-yielding varieties (HYVs) during 1992–94. This nearly doubled the productivity of both crops compared with the pre-HYV era. The area under HYV cultivation continues to rise and so does productivity, with no yield plateau in sight. In addition, cultivar diversity has increased substantially, leading to more appropriate choices of cultivars being available to farmers, and hence improved yield stability. But these positive changes in adoption scales and cultivar diversity have occurred primarily in relatively favorable environments and in states with well-developed seed production infrastructure (Rai et al. 1999).

Six million hectares of pearl millet (more than 60 percent of the total pearl millet area) is planted with more than 70 hybrids, of which at least 80 percent are hybrids from the private sector (Dar et al. 2006). More than 60 of these hybrids are based on ICRISAT-bred hybrid parents (mostly seed parents), or on the proprietary hybrid parents developed from ICRISAT-bred improved germplasm. It has been conservatively estimated that the annual return to India's farmers from pearl millet varieties developed by ICRISAT total $50 million—more than 12 times the cost of its investment in pearl millet research.[16] Unlike pearl millet, sorghum research in India is mostly implemented by public sector institutions such as ICAR and SAUs, rather than by the private sector, and estimated returns on the research investment are also higher. The annual return to India's farmers from government investment in sorghum crop improvement and development of HYVs (by NRCS and AICSIP) for the period from 1981 to 1999 is estimated at Rs. 11,450 million (or about $275 million)—nearly 30 times as much as the cost of investment (NRCS 2007).

The hybrid technology has also contributed to employment generation and to farmers' income at the seed production stage. Pearl millet hybrid seed production in India is primarily accomplished each year during the summer season in one district of Andhra Pradesh, and it generates an additional annual income of $1 million to the seed-producing farmers' community in that district. According to the Seedsmen association of Andhra Pradesh (2004–2005), nearly 90 percent of the total requirement of sorghum hybrid seeds and 65 percent of pearl millet seeds are produced by the contract seed growers from the state. Seed production activity employs more than 0.2 million farmers directly or indirectly in the state.

[15] The adoption of pearl millet hybrids increased both due to its yield advantage (compared with open-pollinated varieties) and also due to active promotion by the private companies. A survey by Nagarajan (2004) found that private companies foresee further area expansion under pearl millet in new areas, especially in Gujarat and in some parts of Maharashtra.

[16] http://www.worldbank.org/html/cgiar/newsletter/Oct96/6millet.html

Maharashtra state, with a large number of private seed companies and an aggressive state seed corporation, had about 18 improved pearl millet cultivars in various scales of cultivation during the mid-1990s, compared with no more than three during the mid-1980s. Similar changes in pearl millet cultivar diversity occurred in Gujarat. These two leading states now have 85–90 percent of total pearl millet area under HYV cultivation. In Gujarat this consists mostly of hybrids; in Maharashtra, a substantial proportion is still an OPV (variety ICTP 8203).

Pearl millet constitutes an important staple crop, especially for marginalized households, for whom coarse cereals account for a larger share in daily diets than wheat and rice (Ramaswami 2002). Pearl millet hybrids are widespread and have been increasingly adopted over the past decades (Bantilan, Deb, and Singh 2000; Thakur et al. 2003). Pray et al. (2001), in a study in Andhra Pradesh, Karnataka and Maharashtra, found that the share of coarse cereals (millets, maize and sorghum) in total cereal expenditure was the highest for the poorest 30 percent of the population. As a result, any yield improvement in coarse cereals would have a direct impact on the poorest households. Especially in the states of Karnataka and Maharashtra, where coarse cereals are more important in the diet of poor households than rice and wheat, productivity increases in coarse grains are more important in increasing the welfare of the poor than productivity increases in rice and wheat.

In sum, the contribution of private hybrids to agricultural productivity is significant, both in production and distribution of seed. These results are especially striking because they pertain to semi-arid tropical regions, where the green revolution based on HYVs of wheat and rice has had limited impact. Given that the semi-arid tropics tend to be poorer than the more favorably endowed growing regions (the Punjab and the Indo-Gangetic plains), and given that private hybrids have had most impact in subsistence crops, it is likely that poor farmers in semi-arid areas have gained from the spread of private hybrids.

Western Rajasthan is an arid, dryland zone, with little rainfall and sandy soils. It is one of the major pearl millet growing regions in India. In the early 1990s, ICRISAT, in collaboration with the Rajasthan Agricultural University, a local NGO, and farmers in selected villages in western Rajasthan, started a program of farmer participatory breeding of improved pearl millet cultivars that continued for about ten years. Major benefits perceived by households in villages of western Rajasthan included an improved choice of varieties to suit the weather, helping them to manage the risk of rainfall failure. This further stabilized their long-term yields. Improved technology allowed greater land augmentation, increasing yields of pearl millet; more stable yields further enabled farmers to shift a portion of farmed area from millets to cash (and other) crops (Bantilan et al. 2003). Researchers documented that increased adoption of technology also resulted in increased asset generation by individual households in western Rajasthan, such as building “pucca or concrete houses” with the surplus cropping income. The participatory rural appraisals conducted by ICRISAT researchers in these villages also found increased rates of schooling (increases in enrollment of up to 20–22 percent within four years of adoption)—especially for girl children (Parthasarathy and Chopde 2000).

Studies conducted by Pray et al. (1991) and Pray and Ramaswami (2001) on the economic impacts of seed industry reforms found that farmers gained most from the resulting increase in private research. They found that in 1986–87, yields of private pearl millet and sorghum hybrids were higher than public hybrids and open pollinated varieties, in all-India coordinated yield trials conducted by the Indian Council of Agricultural Research (ICAR) in farmers’ fields. For instance, Mahindra’s pearl millet hybrid, MBH 110, out-yielded the publicly bred check hybrid BJ 104 by an average of 23 percent. Researchers examined returns on several crops, using the increase in net income of seed firms and farmers from the sale and use of private rather than public hybrids as an estimate of the total benefits from private varietal improvement research. They found that the seed companies captured no more than 18.5 percent of the benefits from using improved sorghum varieties. Similarly, for hybrid pearl millet, seed firms captured only about 6 percent of benefits, with more than 90 percent of benefits accruing to farmers. A study by Singh, Morris, and Pal (1997) on the maize seed industry in India found similar results regarding the benefit shares to farmers versus seed supply companies.

According to Pray and Ribeiro (1990), the social internal rates of returns to private pearl millet and sorghum research were at least 50 percent. The annual returns to Indian pearl millet farmers from cultivating varieties from ICRISAT and private firms are estimated at $54 million (ICRISAT 1998). The impact of private sector research became much more evident during the late 1990s, with increased area under private hybrids of cotton, pearl millet, sorghum, maize, and fodder.

Evenson and Gollin (2003) show that, while crop improvements have been less pronounced for millets and sorghum than for rice and wheat in India, the progress in these crops has nevertheless been significant. A study of the impacts of ICRISAT's research showed that privately released millet varieties relied heavily on ICRISAT-developed male-sterile lines and restorers in developing their hybrid pearl millet and sorghum (Bantilan and Deb 2002).

Nagarajan, Pardey, and Smale (2007) examined the relationship between biological (varietal) diversity of pearl millet in the farm communities of semi-arid regions of Andhra Pradesh and Karnataka. They found that communities with high income levels (combined farm and off-farm) maintained greater richness of millet varieties across their farms, perhaps because of greater access to improved materials and greater capacity to grow them. The educational level was also higher in these communities and had a positive effect on crop diversity at the community level. Higher seed-to-grain price ratios also enhanced millet profits among village communities, reflecting the use of modern varieties. Formal seed transactions through dealers also correlated with improved millet diversity among the village communities surveyed.

A key finding is that the presence of active local (formal and informal) seed markets enhances millet profits of farming communities. These findings suggest that, through judicious introduction of improved varieties that complement their local varieties by providing a needed trait, it may be feasible to enhance farmer income while supporting millet crop diversity to promote the resilience of farming communities in these marginal environments (Nagarajan, Pardey, and Smale 2007). The long-term influence of proprietary hybrids and varieties is not only apparent in favorable environments but has also proven important in drylands.

5. SUSTAINABILITY OF THE INTERVENTIONS

In the more favored growing environments of India (such as the states of Punjab, Maharastra, and Haryana), where farmers have access to irrigation and rising incomes are changing food consumption patterns, the area sown to sorghum and other millet crops is gradually giving way to rice, wheat, maize, and other specialty crops (Seetharam, Riley, and Harinarayana 1989). However, farmer demand for a range of millet crops and millet varieties in the arid and semi-arid regions (including the states of Karnataka, Andhra Pradesh, Rajasthan, and Gujarat) is unlikely to diminish in the near future, as there are currently few substitute crops for these harsh growing environments.

An estimate by FAO (2004) found that 55 percent of the world's semi-arid lands with rainfed farming potential are located in Sub-Saharan Africa and South Asia (including India), and these areas are characterized by the lowest per capita nutrition levels and the highest population growth rates. These semi-arid regions are likely to be home to an additional 400 million people by 2025.[17] Soil salinity and drought still remain major abiotic stresses that pose a threat to agricultural production in this part of the world. Water is becoming an even more scarce resource, and significant expansion of irrigation does not seem feasible in many of these semi-arid countries. Furthermore, public irrigation systems need substantial investments for rehabilitation, modernization, operation, and maintenance. Desertification may be aggravated over time, either by over-exploitation by native populations or by regional climatic changes. These factors underscore the need for concerted efforts toward developing crops that are more tolerant of stressful environments.

Millet and sorghum are reasonably tolerant to extreme soil and weather conditions. They also have other desirable attributes: higher nutritive value (including micronutrients such as iron, calcium, and zinc) compared with most major cereals; higher fodder value; and higher tolerance to pests and diseases. For these reasons, a case can be made for conserving as well as promoting cultivar diversity for these two major dryland cereals to help meet future food and feed needs, especially those of subsistence producers in these less-favored economic and physical environments.

The emerging trends in the use of sorghum for alternative purposes (such as biofuels and animal and poultry feeds) provide some evidence of increased demand for these crops in India. While sorghum is largely used as a feed grain throughout the world, in India the cost of production and quality limitations make it less attractive compared to maize. The current feed production in the country is estimated at 2.7 million tons and is expected to grow by 3.9 million tons by the year 2010. India's huge livestock population and the increasing demand for milk and products also creates pressure for production of green and dry fodder and forages. Under semi-arid conditions, sorghum and millet are the major suppliers of green and dry fodder and forages, especially critical during the lean season; 20 to 60 percent of dry fodder supply in the semi-arid regions of India is provided by sorghum crops alone. Moreover, the diversification of rainy season sorghum as a bio-energy crop has vast potential for helping to meet the growing demand for fossil fuels.

Part of the reason for the stagnating production of sorghum and pearl millet is the growing competition in dry regions from other major cereals, including maize, plus cash crops, which benefit from government price support programs. The per capita consumption of sorghum in rural India declined from 1.59 kg per month in 1973 to 0.45 kg per month in 2003–2004 (NRCS 2007). Some of this decline is due to governmental policies that excluded sorghum from public procurement at minimum support price (MSP) and from supply through public distribution systems (NRCS 2006). Government policies encouraged increased consumption of wheat or rice in the regions where sorghum was traditionally valued as the preferred cereal. The calculation of MSP shifted against sorghum and coarse cereals over years. The MSP of rice and sorghum were equal during 1980–81; but by 1995–96, MSP was 9 percent lower for sorghum than for rice. Moreover, government policies on pricing sorghum and millet vis-à-vis

[17] The semi-arid lands are characterized by unpredictable weather, long dry seasons, inconsistent rainfall, and soils that are poor in nutrients. They include parts of 48 countries in the developing world, including most of India, locations in South East Asia, Sub-Saharan Africa, much of southern and eastern Africa, and a few locations in Latin America.

pulses, oil seeds, and other dryland crops were similarly unfavorable and further accelerated the diversion of kharif sorghum or millet toward other commercial alternatives. The implication for sustainable sorghum and pearl millet production is clear: if the government decides that it cannot afford to continue subsidizing wheat, rice, and maize production, demand for sorghum and pearl millet is likely to increase.

The public sector research system continues to provide new technological opportunities for the public and private seed industry to develop profitable products. More than 50 private companies marketing approximately 75 hybrids of pearl millet, as well as nearly 11 companies marketing 20 hybrids of sorghum, based their production on seed and pollen parents from ICRISAT. ICRISAT's public-private pearl millet and sorghum consortia have helped increase cultivar adoption while enhancing resource mobilization towards research by the public sector. ICRISAT has generated more than $2 million (as of December, 2005) since the consortium program was initiated in 2000. The funds generated augment ICRISAT's core funds to support crop improvement research for developing elite sorghum, pearl millet, and pigeonpea hybrid parents to serve both the public and private sectors. This resource mobilization is particularly significant in light of diminishing core funding for crop improvement research at ICRISAT.

ICAR and State Agricultural University breeding programs are the major source of germplasm as well as of finished in-bred lines to private breeding programs. Abandoning public breeding programs could therefore lead to less technological diversity and higher seed prices, with negative implications for agricultural development in general and smallholder farmers in particular. Decisions on appropriate public and private sector roles must be country- and crop-specific, to achieve desirable welfare and distribution effects (Matuschke and Qaim 2008). Strong public-private partnerships such as the ICRISAT consortium model, as well as government-sponsored science parks, represent a strategic approach to providing the necessary infrastructure for research as well as the skilled human resources needed for technology exchanges.

6. CONCLUSION

Despite the fact that India's combined sorghum and millet production has been stagnant since 1965, new technology has nevertheless had an important impact on improving small farmer productivity in some of the poorest areas of India. Yields doubled since 1966, largely due to improved genetics and crop management, initially spearheaded by public research (1966–85) and then by the private sector (1986 to present). Unlike the major Green Revolution crops, very little of the increase in yields can be attributed to irrigation, since at least 90 percent of these crops are grown under unirrigated/rainfed conditions. The doubling of yields allowed farmers to grow the same amount of food on half the land, often switching the rest to valuable cash crops and increasing their incomes. The improved crops contributed to food security additionally because they are considerably more resistant to drought than the other major food grains. Furthermore, it is clear that these new technologies primarily benefit poor consumers, because the wealthy tend to eat rice or wheat.

The data on the spread and benefits from the improved hybrid cultivars in these crops show that hybrids can be very valuable to small farmers who grow crops in dryland conditions. Pray et al. (1991) showed that 80 to 90 percent of the benefits from the adoption of hybrids of these crops went to farmers rather than to the seed companies. The takeover of pearl millet and sorghum seed markets by proprietary hybrids nevertheless shows that private firms capture sufficient benefits to induce them to invest in research to develop cultivars for small farmers in unirrigated regions.

The lessons from the Indian interventions to improve sorghum and pearl millet hybrids highlight three important interventions.

1. *Investments in public sector plant breeding and crop management research by national government, state governments, and international agricultural research centers*. In the early days of the development of hybrids of sorghum and millets, all three contributed OPVs, hybrid cultivars, and the inbred lines which benefited farmers directly while providing the basis for private researchers to develop new cultivars.
2. *Government investments in seed production via government and private institutions*. The Indian national and state governments, with the help of donors, made major investments in government seed corporations for production of the Green Revolution cultivars of wheat, rice, maize, pearl millet, and sorghum. At the same time, small private sector seed companies were permitted to enter into the seed business and make profits. Training for seedsmen in both public and private institutions was provided by the government.
3. *Sector liberalization beginning in the mid-1980s*. Instead of allowing SSCs to become regional monopolies, the governments opened the doors to investment by large Indian firms which had been excluded from this sector until 1986; they also allowed foreign direct investment in the sector at about the same time.

Liberalization has been coupled with ongoing indirect government support for private operations: continuing public investment in hybrid breeding; public-private partnerships; provision of inbred lines and germplasm for developing proprietary hybrids; and a seed law that allowed truthfully labeled seed instead of mandatory registration and government testing of new cultivars. This approach has led to a vibrant and sustainable supply of new cultivars and seed that are resistant to important diseases and pests and tolerant of drought.

REFERENCES

Bantilan, C., D. Parthasarathy, and R. Padmaja. 2003. Enhancing research-poverty alleviation linkages: experience in the semi-arid tropics. In *Agricultural research and poverty reduction: Some issues and evidence*, eds. Shantanu Mathur and Douglas Pachico. CIAT Publication No. 335, Economics and Impact Series no. 2. Cali, Colombia: International Center for Tropical Agriculture (CIAT).

Bantilan, M. C. S., and U. K. Deb. 2002. Grey to green revolution in India: Role of public-private-international partnership in research and development. Paper presented at the BAEA-IAAE conference on "Public-Private Sector Partnership for Promoting Rural Development," Dhaka, October 2–4.

Bantilan, M. C. S., U. K. Deb, and S. D. Singh. 2000. Farm level genetic diversity in pearl millet in India. Poster Paper presented at the 3rd International Crop Science Congress, Hamburg, August 18–22.

Breese, W. A., C. T. Hash, A. Sharma, and J. R. Witcombe. 2002. Defeating downy mildew: Improving pearl millet, the staple cereal crop of some of the world's poorest people, whilst keeping one step ahead of downy mildew. Poster presented at the conference on Plant Pathology and Global Food Security, at Imperial College, London, July 8–10.

CWC (Central Water Commission). 2003. Statistical report. New Delhi: Department of Statistics, Ministry of Agriculture, Government of India.

Dar, W. D., B. V. S. Reddy, C. L. L. Gowda, and S. Ramesh. 2006. Genetic resources enhancement of ICRISAT mandate crops. *Current Science* 91 (7): 880–884.

Dayakar Rao, B., S. Reddy, and N. Seetharama. 2007. Reorientation of investment in R&D of millets for food security: The case of sorghum in India. *Journal of Agricultural Situation in India* 64 (7): 303–305.

Evenson, R. E., and D. Gollin. 2003. Review: Assessing the impact of the green revolution, 1960 to 2000. *Science* 300: 758–762.

Evenson, R. E., and C. E. Pray, eds. 1991. *Research and productivity in Asian agriculture*. Ithaca, N.Y.: Cornell University Press.

FAO (Food and Agriculture Organization of the United Nations). 1995. Sorghum and millets in human nutrition. FAO Food and Nutrition Series No. 27. Rome: FAO.

________. 2004. FAOSTAT- agriculture. Rome: FAO.

________. 2007. FAOSTAT- agriculture. Rome: FAO.

Fertiliser Association of India (FSA). 2004. *Annual Report*. New Delhi: FSA.

Hash, C. T., R. S. Yadav, A. Sharma, R. Bidinger, K. M. Devos, M. D. Gale, C. J. Howarth, S. Chandra, G. P. Cavan, R. Serraj, P. S. Kumar, W. A. Breese, J. R. Witcombe. 2007. Release of pearl millet hybrid HHB 67-2: An improved downy mildew resistant version of HHB 667 produced by marker assisted selection. ICRISAT Highlights. Patancheru, Andhra Pradesh: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

ICAR (Indian Council of Agricultural Research). 2006. *Annual report*. New Delhi, India: Krishi Bhavan.

ICRISAT (International Crops Research Institute for Semi Arid Tropics). 1998. *Annual report*. Patancheru, Andhra Pradesh, India: ICRISAT.

________. 2002. Research for impact: Annual report. Patancheru, Andhra Pradesh, India: ICRISAT.

Mahyco. 1999. Marketing database: Benchmarking the seed market. Jalna, Mumbai, India: Mahyco.

Matuschke, I., and M. Qaim. 2008. Seed market privatisation and farmers' access to crop technologies: The case of hybrid pearl millet adoption in India. *Journal of Agricultural Economics* 59 (3): 498–515.

MoA (Ministry of Agriculture). 2006, Agriculture statistics at a glance. New Delhi: Directorate of Economics and Statistics, Government of India.

Mula, R. P., K. N. Rai, V. N. Kulkarni, and A. K. Singh. 2007. Public-private partnership and impact of ICRISAT's pearl millet hybrid parents research. SAT e-Journal 5 (1). ICRISAT, Patancheru, Andhra Pradesh, India.

Nagarajan, L., M. Smale, and P. Glewwe. 2007. Determinants of millet diversity at the household-farm and village-community levels in the drylands of India: The role of local seed systems. *Agricultural Economics* 36(2): 157–167.

Nagarajan, L., P. Pardey, and M. Smale. 2007. Seed systems and millet crops in marginal environments of India: Industry and policy perspectives. *Quarterly Journal of International Agriculture* 46 (3): 263–288.

NRCS (National Research Centre for Sorghum). 2006. *Annual report*. Rajendra Nagar, Hyderabad, India: NRCS.

________. 2007. *Perspective plan: Vision 2025*. Rajendra Nagar, Hyderabad, India: NRCS.

NSAI (National Seed Association of India). 2009. *Annual report*. New Delhi: NSAI.

Pal, S., and D. Byerlee. 2003. The funding and organization of agricultural research in India: Evolution and emerging policy issues. ICAR Policy Paper 16. New Delhi, India: National Centre for Agricultural Economics and Policy Research.

Pal, S., and R. Tripp. 2002. India's seed industry reforms: Prospects and issues. *Indian Journal of Agricultural Economics* 57 (3): 443–457.

Parthasarathy Rao, P., P. S. Birthal, B. V. S. Reddy, K. N. Rai, and S. Ramesh. 2006. Diagnostics of sorghum and pearl millet grain-based nutrition. *International Sorghum and Pearl Millet Newsletter* 47: 93–96.

Parthasarathy, D., and V. K. Chopde. 2000. Building social capital: Collective action, adoption of agricultural innovations, and poverty reduction in the Indian semi-arid tropics. Paper Prepared for Global Development Network (GDN). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India.

Pray, C. E., S. Ribeiro, R. A. E. Mueller, and P. Parthasarathy Rao. 1991. Private research and public benefit: The private seed industry for sorghum and pearl millet in India. *Research Policy* 20: 315–324.

Pray, C. E., and B. Ramaswami. 2001. Liberalization's impact on the Indian seed industry: Competition, research, and impact on farmers. *International Food and Agribusiness Management Review* 2 (3): 407–420.

Pray, C. E., B. Ramaswami, and Timothy Kelley, 2001. The impact of economic reforms on R&D by the Indian seed industry. *Food Policy* 26 (6): 587–598.

Pray, C. E, S. Ribeiro, R. Mueller, and P. Parthasarathy Rao. 1988. Private research and public benefits: The private seed industry and sorghum and pearl millet in India. Research Paper-P-398-0282-1-89. New Brunswick, N.J.: Department of Agricultural Economics, Rutgers University.

Pray, C. E., and S. Ribeiro. 1990. Government seed policy, the development of private seed industry, and the impact of private R&D in India: The final report of the Indian seed industry project. New Brunswick, N.J.: Department of Agricultural Economics, Rutgers University.

Rai, K. N., D. S. Murty, D. J. Andrews, and P. J. Bramel-Cox. 1999. Genetic enhancement of pearl millet and sorghum for the semi-arid tropics of Asia and Africa. *Genome* 42: 617–628.

Ramaswami, B. 2002. Understanding the seed industry: Contemporary trends and analytical issues. *Indian Journal of Agricultural Economics* 57 (3): 417–429.

Ramaswami, B., C. E. Pray, and T. Kelley. 2001. The impact of economic reforms on R&D by the Indian seed industry. *Food Policy* 26 (6): 587–598.

Reddy, B. V. S., S. Ramesh, and C. L. L. Gowda. 2005. Forging research and development partnerships with private sector at ICRISAT: Sorghum as case study. *International Sorghum Millets Newsletter* 46: 6–10.

Reddy, B. V. S., S. Ramesh, S. T. Borikar, and K. Hussain Sahib. 2007. ICRISAT–Indian NARS partnership sorghum improvement research: Strategies and impacts. *Current Science* 92 (7): 909–915.

Reserve Bank of India (RBI). 2005. *Economic survey of India*. Mumbai, India: RBI.

________. 2006. *Annual report 2005–06*. Mumbai, India: RBI.

Seetharam, A., K. W. Riley, and G. Harinarayana. 1989. *Small millets in global agriculture*. New Delhi: Oxford and IBH Publishing.

Singh, R. P., M. L. Morris, and S. Pal. 1997. Efficiency and equity considerations in the maize seed marketing system: Role of public and private sectors in India. *Indian Journal of Agricultural Marketing* 52 (4): 28–34.

Spielman, D. J., F. Hartwich, and K. von Grebmer. 2007. Sharing science, building bridges, and enhancing impact: Public-private partnerships in the CGIAR. IFPRI Discussion Paper 708. Washington, D.C.: International Food Policy Research Institute.

Thakur, R. P, V. P. Rao, K. N. Amruthesh, H. S. Shetty, and V. V. Datar. 2003. Field surveys of pearl millet downy mildew: Effects of hybrids, fungicide, and cropping sequence. *Journal of Mycology and Plant Pathology* 33: 387–394.

Tripp, R. 2001. *Seed provision and agricultural development*. London: Overseas Development Institute.

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