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Estimation of ICRISAT Sorghum Research Spillover Benefits – Strategies for Research Prioritization

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Abstract

ICRISAT is working on sorghum crop improvement primarily in South Asia and sub-Saharan Africa since 1972. Diversified regional focuses and collaborations with different national and international institutes marked the sorghum genetic enhancement research at ICRISAT to a six phase strategy beginning from 1972 to the present. In the initial years, the main focus was on development of improved populations, composites and open pollinated varieties of sorghum. But with rapid development of the hybrid seed industry in Asia and re-orientation of research programs in sub-Saharan Africa, emphasis was laid on developing improved hybrid parents (intermediate products) at ICRISAT, Patancheru for Asia, and finished products (varieties and hybrids) at other ICRISAT locations in Africa, through partnership research from 1995. The Hybrid Parents Research Consortium (HPRC) is a new initiative started in 2000 at ICRISAT, Patancheru with the objective of increasing the scope of accessibility to improved hybrids for poor farmers through effective public-private partnerships. So far, 270 improved sorghum cultivars were released using breeding materials by NARS across 45 countries in Asia, Africa and America between 1975 and 2016. These research products aimed at a given location may spill across regions, nations or even across traditional agro-ecological zones. The potential for such spillovers depends on several factors like bio-physical and socio-economic similarities between locations. Earlier attempts made by ICRISAT have documented the potential of inter- and intra-regional sorghum technology transfers. But, very little has been done in terms of assessing and systematically quantifying the potential and actual inter-regional spillovers from its own research and development efforts. The global sorghum research domains identified during the ICRISAT Mid Term Plan (1994-1998) were more than two decades old and there is a need to upgrade them for better targeting of sorghum crop improvement research at ICRISAT. The Multi-region, single commodity economic surplus model developed by the Australian Centre for International Agricultural Research was adapted and modified for estimation of ICRISAT sorghum spillover benefits. Gross benefits were estimated with an assumption that the global research investments being made at ICRISAT on international public good nature of innovative research. Based on these results, potential research domains, regions and countries were identified for better targeting of ICRISAT research. The findings emanated from this study will not only help in sorghum research prioritization at ICRISAT but also guide the future sorghum research investments portfolio.

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RESEARCH PROGRAM ON
Policies, Institutions and Markets
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ICRISAT
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ACIAR	Australian Centre for International Agricultural Research
AEZ	Agro-Ecological Zone
AICSIP	All India Coordinated Sorghum Improvement Program
ASARECA	Association for Strengthening Agricultural Research in Eastern and Central Africa
ASTI	Agricultural Science and Technology Indicators
CBOs	Community Based Organizations
CWANA	Central and West Asia and North Africa
EECA	Eastern Europe and Central Asia region
ESA	Eastern and Southern Africa
FAO	Food and Agriculture Organization
FTE	Full-Time Equivalents
GIS	Geographic Information System
HPRC	Hybrid Parents Research Consortium
INTSORMIL	International Sorghum and Millet Collaborative Research Support Program
IPG	International Public Good
LAC	Latin America and Caribbean region
LGP	Length of Growing Period
MTP	Medium Term Plan
NARS	National Agricultural Research System
OPVs	Open Pollinated Varieties
PE	Production Environment
ROW	Rest of the World
SA	South Asia
SADC	Southern African Development Community
SPAM	Spatial Production Allocation Model
SRD	Sorghum Research Domain
SSA	sub-Saharan Africa
SSEA	South and South East Asia
WANA	West Asia and North Africa
WCA	West and Central Africa

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1. Introduction

In general, research systems generate technology for a target environment and commodity. Based on the potential, often the outcome of research is spread beyond its initial target. Thus, the research systems generate two types of benefits for their investors: direct benefits[1] and spillover benefits. The traditional research evaluation methods consider only the direct benefits and ignore the spillover benefits. As a result, the output from research is underestimated. When the policy makers decide on the level of investment to be made for research on the basis of the underestimated benefit level, the investment is obviously less than desired. If research spillovers[2] (indirect benefits) are quantified and considered in the research investment decision then the justified level of investment can be made. Furthermore, incorporation of spillover effects in the research policy design strengthens the transparency of the decision making process (see also Norton and Davis 1981). Research spillovers also have an impact on the relative competitiveness of farm producers in different regions and countries. Until now, national research planning usually underestimated returns to research by overlooking spillover effects and thus, tended to under invest in research. International research support, whether bilateral, regional or multilateral, is usually designed to complement national research activities and to generate maximum international rather than just individual national research benefits. It selects research portfolios with explicit considerations of the likely extent of spillover benefits among countries with similar agro-climatic and socio-economic environments (Deb and Bantilan 2001).

The importance of understanding and measuring the spillover effects of agricultural research has been identified in recent times. A better understanding of the spillover effects in research is important for stimulating consistent debate on research policy and also for providing systematic information to support research decision making. In the literature, there have been few detailed attempts (Edwards and Freebairn 1984; Davis 1991; Alston 2002; Bantilan et al. 2004; Maredia 1996) to provide a clear model of research spillovers. The importance of spillover research can be identified in three major aspects which provide a strong basis for understanding them better (Davis 1991). They are:

a. **Input into research policy debate:** Probably the most compelling basis for government involvement in agricultural research is the efficiency argument. It is becoming common to refer to the wide applicability of research as 'spillover' impacts. Given the importance of the spillover effects of research across many locations and environments for government involvement, it is surprising to find that relatively little attention has been given to clearly modelling and measuring these effects.

b. **Input to support research management decision makers:** The applicability of research generated technologies depends significantly on the types of production conditions where agricultural activities take place. While planning strategies research managers are often faced with the issue of whether research programs should focus attention on developing technologies which suit particular production conditions. The more applicable the research is likely to be to all production environments the easier these types of choices will be for managers (see also Davis and Ryan 1987 & 1988). Even if there is applicability for some production environments this is unlikely to be uniform. The levels of these research applicabilities or spillovers can influence many choices.

c. **Enhancement of research evaluation methodology:** During the past fifty years considerable advances have been made in the methodology used to evaluate the welfare gains from publicly funded research. But, there are still several nagging issues which need to be addressed through enhanced research evaluation methodologies. For example, how best to represent the impact of research at an aggregated (usually national) supply level (Lindner and Jarrett 1980)? Whether the entire nation should be treated as a homogenous region or whether we should consider the diversity in production environments in that geographical region?

1. A technological breakthrough in agriculture often leads to increased yields, or improves the quality of output, or enhances the efficiency of input use. If a new technology has benefited both the producers and consumers in the targeted location for which it was generated, such an effect is commonly referred to as a direct benefits. If a new technology has applicability beyond the location or commodity for which it was generated, then it is referred to as a spillover effect (Bantilan and Davis 1991).

2. Three types of spillover effects have been identified: across-location, across-commodity, and price spillover effects. The first two types are direct effects and the last indirect. See more details at Deb and Bantilan (2006).

International Agricultural Research Institutes like ICRISAT have made vital contributions towards achieving inter-regional sorghum research spillover benefits. However very little has been done (see Bantilan et al. 2004) so far in terms of assessing and systematically quantifying the potential and actual inter-regional spillovers from its own research and development efforts. The present research report has made an attempt to quantify the ICRISAT sorghum spillover benefits across the globe using the vast experience and, knowledge that is available, and human capital as well. But, the current study kept major focus on three major regions (SA, ESA and WCA) where ICRISAT has its strong presence and sorghum crop has economic importance.

In general, the most common approach for analyzing the direct welfare effects of agricultural research in a partial-equilibrium framework has used the concept of economic surplus. The sum of both producer and consumer surplus changes measures the net welfare change for a given new technology. When a technology is applicable in multiple regions that differ in their responses to the new technology, it may be necessary to disaggregate some aspects of the study to avoid aggregation biases. It is basically the extension of basic economic surplus model to allow measure these benefits at individual country level. The transfer of technology spillover depends on a variety of factors[3]: the relative costs of direct technology transfer and of adaptive versus comprehensive research programs, the complementarity between screening of existing technologies and carrying out applied research, the environmental sensitivity of the technology, and differences across locales in their factor scarcities are particularly important.

Countries have an incentive to borrow technologies when they can obtain results for less than the full cost. Smaller countries in particular may transfer in a high proportion of their new technologies because they usually cannot afford extensive research programs. There is thus an incentive to underinvest in research in the world as a whole, particularly for basic kinds of research, which suggests a need for international agricultural research centers that can generate technologies applicable to several countries. This is one rationale for the current system of centers supported by the Consultative Group on International Agricultural Research[4]. The existence of technological spillovers has important implications for resource allocations to research within individual countries. First, individual countries may be wise to consider new technologies being produced in international centers and in research systems in countries with similar human, natural, and physical resource bases so that research programs can be structured to complement the research conducted abroad rather than duplicating it excessively. Second, local research capacity may be needed just to enable the country to transfer in and adopt technologies developed elsewhere. Third, the differential effects of research on agricultural productivity across regions in a country may need to be considered. Edwards and Freebairn (1984) and by Davis, Oram and Ryan (1987) developed an extension to basic economic surplus model for measuring these disaggregated benefits at individual homogenous domain level.

2. Performance of sorghum across the globe and in targeted regions

Sorghum [*Sorghum bicolor (L.) Moench*] is one of the main staple foods for the poorest and most food-insecure people across the semi-arid tropics of world. *Sorghum bicolor* ssp. *Verticilliflorum* is believed to be the progenitor of cultivated sorghum (Harlan and Wet 1972). It is cultivated in wide geographic areas in Africa, Asia, America and the Pacific regions. Sorghum is the fifth most important cereal crop in the world, after wheat, maize, rice and barley whereas in India, it is the third largest staple cereal crop after rice and wheat. In Africa, sorghum is the second major crop after maize. It is a staple food, produced and consumed by millions of rural poor in South Asia (SA) and sub-Saharan Africa (SSA). Sorghum is often a recommended option for farmers operating in harsh environments where other crops do poorly, as can be grown with limited rainfall (400 to 500 mm) and often without application of any fertilizers or other inputs. In India, nearly 30-40% of the rainy season sorghum is grown as sole crop while the rest is cultivated as an intercrop with pulses and oilseeds. However, around 90% of the postrainy sorghum is grown as a sole crop which is the most preferred method of cultivation for food consumption. Sorghum is grown for a variety of purposes like food, feed, forage and fuel. However, it is also used for beer, alcohol, starch, sugar, bread

3. See more details at Ruttan and Hayami (1973) and Evenson and Binswanger (1978)

4. See more details at Alston, Norton and Pardey (1998).

and biscuit manufacturing. Sorghum grains constitute the principal source of energy, protein, vitamins and minerals. Above all, sorghum is one of the climate resilient crops that can adapt quickly to climate change conditions.

On the global front, sorghum was grown in 111 countries of the world in the year 2012-14 covering an area of approximately 42.5 m ha with a grain production of 62.5 m tons and an average productivity of 1.469 tons per ha (FAO website: http://www.fao.org) (see Table 1). During the last three decades, cropped area and production reported an annual growth rate of -0.34% and -0.51% respectively. Development and adoption of improved cultivars and, improved management practices have increased the productivity levels significantly despite the tumbling acreage of sorghum across the globe in the recent past.

The details of sorghum production trends in different regions are summarized in Table 2 for the period 1991 to 2014. Overall, the world production was very stable and oscillating around 60 m tons. Among the

Table 1. Geographical distribution of sorghum in the World, 2012-14.

Group/region	No. of countries	Area (m ha)	% share to total	Production (m ton)	%share to total	Productivity (kg/ha)
World	111	42.5	100.0	62.5	100.0	1469
Africa	45	27.1	63.6	25.8	41.2	952
Asia	30	7.7	18.2	9.6	15.4	1243
America	21	6.8	15.9	24.1	38.5	3550
Oceania	1	0.6	1.4	1.9	3.1	3186
Europe	14	0.4	0.9	1.1	1.8	3077

Table 2. Regional production trends in sorghum, 1991-2014 (m tons).

Region	1991-1995	1996-2000	2001-2005	2006-2010	2011-2014
Asia	16.56	13.68	10.99	10.55	9.77
India	10.12	8.62	7.11	7.33	5.91
China	5.35	3.89	2.77	1.95	2.60
Pakistan	0.24	0.22	0.20	0.16	0.12
WCA	10.04	11.36	13.04	14.69	13.17
Nigeria	6.10	7.43	8.08	8.13	5.89
Niger	0.36	0.41	0.72	1.04	1.23
Burkina Faso	1.21	1.12	1.46	1.68	1.75
Mali	0.72	0.59	0.64	1.08	1.12
chad	0.37	0.43	0.52	0.65	0.89
Cameroon	0.40	0.41	0.60	0.97	1.19
ESA	6.15	7.13	7.99	9.01	6.95
Sudan	3.22	3.23	4.02	4.00	4.61
Ethiopia	0.75	1.49	1.76	2.52	3.93
Mozambique	0.16	0.26	0.15	0.31	0.21
United Republic of Tanzania	0.65	0.63	0.58	0.75	0.84
America#	24.33	26.43	22.64	22.24	22.99
United States of America	15.74	15.31	10.83	10.04	8.15
Mexico	4.02	6.11	6.15	6.28	7.03
World	59.59	61.75	58.10	60.28	61.11

America includes Mexico, USA, Argentina, Colombia, Brazil etc.

different regions, the production levels are showing increasing trends in the case of WCA and ESA regions. But, production is declining especially in Asia (India) and America (USA). In the entire list of countries, only Niger, Burkina Faso, Ethiopia and Mexico have exhibited significant improvement in production during the study period. This aptly indicates the huge potential for sorghum expansion in WCA and ESA, especially in Nigeria, Niger, Burkina Faso, Mali, Sudan and Ethiopia. All the other countries have performed marginally between 1991 and 2014.

The details of region-wise sorghum consumption trends from 1970 to 2013 are furnished in Figure 1. The Asia and Southern Asia regions were showing a declining trend in consumption over the study period. This clearly reveals that sorghum as a base staple food is being substituted by subsidized (through the Public Distribution System) cereals like rice and wheat in India. However, certain niche areas like Maharashtra, Karnataka and Andhra Pradesh still depend on sorghum as a staple food. In the case of Africa (ESA and WCA regions), the sorghum consumption trends have consistently been increasing for the last four decades. This pattern indicates the huge demand for sorghum crop in these regions. The America and Europe regions exhibited the more or less stable consumption of sorghum pattern during the study period. The aggregate situation at the world is slightly improving during the recent time.

The details of the country-wise sorghum production scenario are presented in Table 3 for the period 2008-10[5] using FAOSTAT, 2012 data. Among the different regions, the highest production share in the world was observed in America followed by WCA, Asia and ESA. In the countries, the lion's share of global sorghum production is contributed by USA (16.8%) followed by India (12.09%), Nigeria (12.01%) and Mexico (10.86%). In terms of cropped area, WCA was at the top of the list followed by ESA, Asia and America. WCA has huge scope and potential for expanding area as well as production when compared with other regions in the world. Sorghum produced in India (7.69 m ha) constitutes about 18.17% of the global area followed by Sudan 6.29 m ha, Nigeria 5.77 m ha, Niger 2.97 m ha and USA 2.37 m ha. But, India's contribution in the world sorghum production was 12.09%, Sudan (5.91%), Niger (1.81%) and USA (16.86%). The productivity in developed countries is about five times higher than the productivity in developing countries. The world highest productivity levels were observed in USA (4,350 kg per ha) while the productivity in India is hovering around 947 kg per ha. The mean yield levels are roughly 1,000 kg per ha in Africa as well.

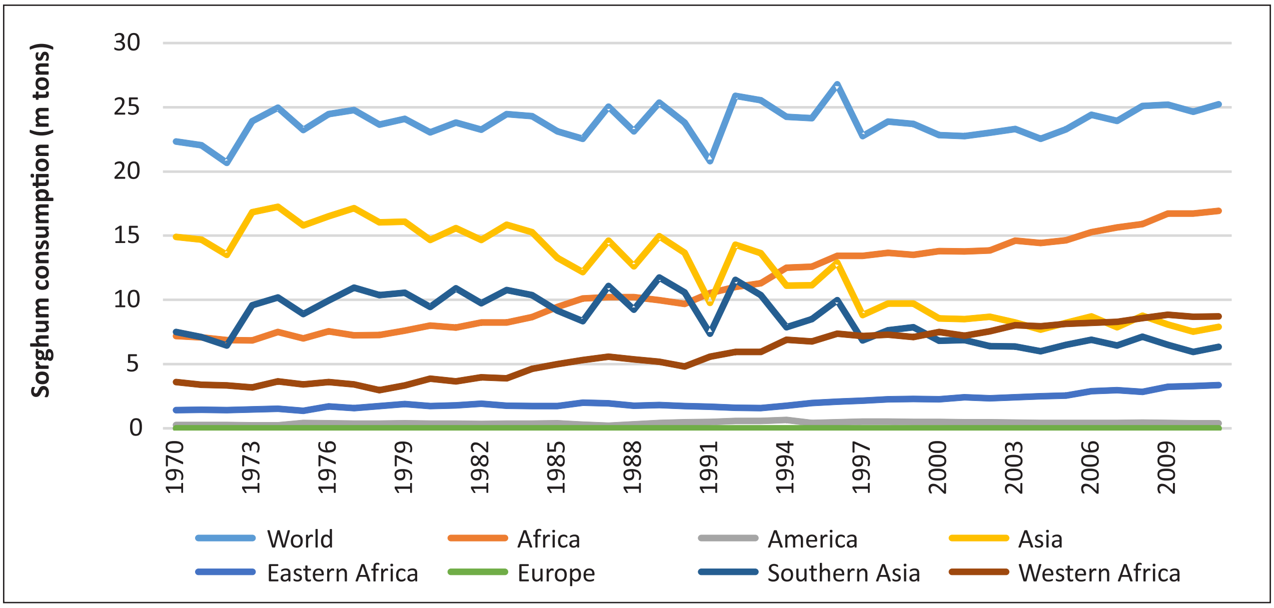

Figure 1. Regional sorghum consumption trends, 1970-2013.

5 2008-10 triennium average referred here because this data was considered as a baseline for the present study and estimation of sorghum research spillovers.

Table 3. Country-wise sorghum production scenario, 2008-10.

Region	Area (m ha)	Production (m tons)	Yield (kg/ha)	% Share to world production
Asia	9.33	10.27	1101.27	17.03
India	7.69	7.29	947.73	12.09
China	0.53	1.75	3303.83	2.90
Pakistan	0.25	0.15	621.23	0.25
Myanmar	0.22	0.21	950.17	0.34
Others	0.63	0.87	-	1.44
WCA	14.52	14.30	2040.13	23.71
Nigeria	5.77	7.25	1259.17	12.01
Niger	2.97	1.09	361.50	1.81
Burkina Faso	1.85	1.80	969.97	2.98
Mali	1.10	1.25	1136.77	2.07
Chad	0.86	0.66	757.83	1.09
Cameroon	0.70	1.03	1463.37	1.71
Others	1.28	1.24	-	2.05
ESA	10.86	8.62	849.45	14.29
Sudan	6.29	3.56	561.07	5.91
Ethiopia	1.59	2.70	1694.00	4.47
Mozambique	0.62	0.39	626.40	0.64
United Republic of Tanzania	0.70	0.69	1008.57	1.14
Somalia	0.35	0.08	234.60	0.14
Uganda	0.34	0.41	1229.23	0.69
Zimbabwe	0.30	0.07	247.23	0.12
Others	0.67	0.72	-	1.19
WANA	0.74	1.53	5177.76	2.54
America#	6.27	22.84	-	37.86
United States of America	2.37	10.17	4313.20	16.86
Mexico	1.77	6.55	3711.40	10.86
Others	2.13	6.12	-	10.15
Other regions	0.60	2.76	3762.00	4.58
World	42.32	60.32	1423.83	100.00

America includes Mexico, USA, Argentina, Colombia, Brazil, etc.

3. Sorghum crop improvement at ICRISAT, 1972-2016

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has been involved in the genetic enhancement of sorghum since its inception in 1972. Sorghum research at ICRISAT started in four regions Asia (1973), West and Central Africa (1975), Southern Africa (1984) and Eastern Africa (1984). There was also a program in Latin America based at the CIMMYT in Mexico from 1978 to 1993, and in Sudan from 1977 to 1985. The breeding goals (involving partners) have under gone significant changes since ICRISAT was established. The identification of geographic functional regions with a set of constraints has resulted in the gradual shift in breeding strategy from initial wide adaptability to specific adaptations, and to trait-based breeding for threshold traits through the 1980s and 1990s (see Figure 2). The ICRISAT, Patancheru-based wide adaptability approach was abandoned by the early 1980s, and three research centers with regional hubs were established in Africa and one in Central America to take up breeding for region/production system-specific adaptations. Later, during the preparation of ICRISAT's medium term plan (MTP 1994-98) for 1994-98, sorghum breeders explicitly defined six sorghum research domains in Asia and SSA for the first time (Bantilan et al. 2004). However, its fundamental approach has been to develop various breeding materials, varieties, hybrid parents (A/B/R lines), segregating populations, lines and improved sources of diseases and insect resistance to strengthen the breeding programs of the national agricultural research systems (NARS) and the seed sector.

Over the journey of four decades, external environments, perceptions of donors and national agricultural research systems (NARS), changing crop requirements and opportunities, and NARS capacity are the most important factors that influenced these changes in breeding concepts, objectives and the research approaches. With the ultimate aim of increasing sorghum production worldwide, ICRISAT has made available its germplasm readily available for the NARS of developing and developed countries. Overall, these changes could be perceived at six different phases of ICRISAT's sorghum research (Reddy et al. 2008 and see Figure 2). They are:

Phase I : Breeding for wide adaptability and higher grain yield (1972-75)

Phase II : Breeding for wide adaptability and screening techniques (1976-79)

Phase III : Regional adaptation and resistance breeding (1980-84)

Phase IV : Specific adaptation and resistance breeding (1985-89)

Phase V : Trait based breeding and sustainable productivity (1990-1994)

Phase VI : Intermediate products and upstream research (1995 onwards)

In the initial years of ICRISAT's establishment the major emphasis was on developing improved populations and composites, and open pollinated varieties (OPVs) of sorghum. However, with the rapid development of the hybrid seed industry in Asia and the comparatively higher yields (25-30% more yields in hybrids than OPVs) and better adaptation to diverse climatic areas, ICRISAT-India (and to some extent ICRISAT programs in sub-Saharan Africa) re-oriented the sorghum improvement programs to breed hybrids. Since 1995, emphasis was laid on developing improved hybrid parents at ICRISAT, Patancheru for Asia, and finished products (varieties and hybrids) at other ICRISAT locations in Africa, through partnership research. In Asia, the breeding programs focused on developing improved breeding lines and parental lines of potential hybrids, and delegating the responsibility for development, testing and release of hybrids to public institutions and private sector seed companies. During the sixth phase, the emphasis has been on producing parental lines and gene pools. In the early 2000s, ICRISAT also started a new initiative by joining hands with private seed companies for undertaking collaborative research (see Box 1).

ICRISAT sorghum cultivar releases

ICRISAT does not release any improved cultivar directly in India or in any other country in the world. ICRISAT maintains close research collaborations with the NARS partners in a particular country and shares the breeding material with them. The partners put these materials in multi-location trials and release them as improved cultivars if they find them superior to check/local cultivars. Similarly in the case of India, ICRISAT has shared either the germplasm or advanced breeding material with NARS, SAUs and private seed companies since 1972.

The details of the total number of improved sorghum cultivars (varieties and hybrids) released by ICRISAT through the supply of germplasm and breeding materials to NARS in different regions of the world between 1975 and 2016 is summarized in Table 4. A total of 270 improved cultivars were made available in 45 countries of Asia, Africa and America. Almost 56% of these releases were concentrated in African countries followed by Asia (31.1%) and America (13%). The top three individual country beneficiaries of ICRISAT research and materials are India (40 cultivars) followed by Mali (38) and China (24). The presence

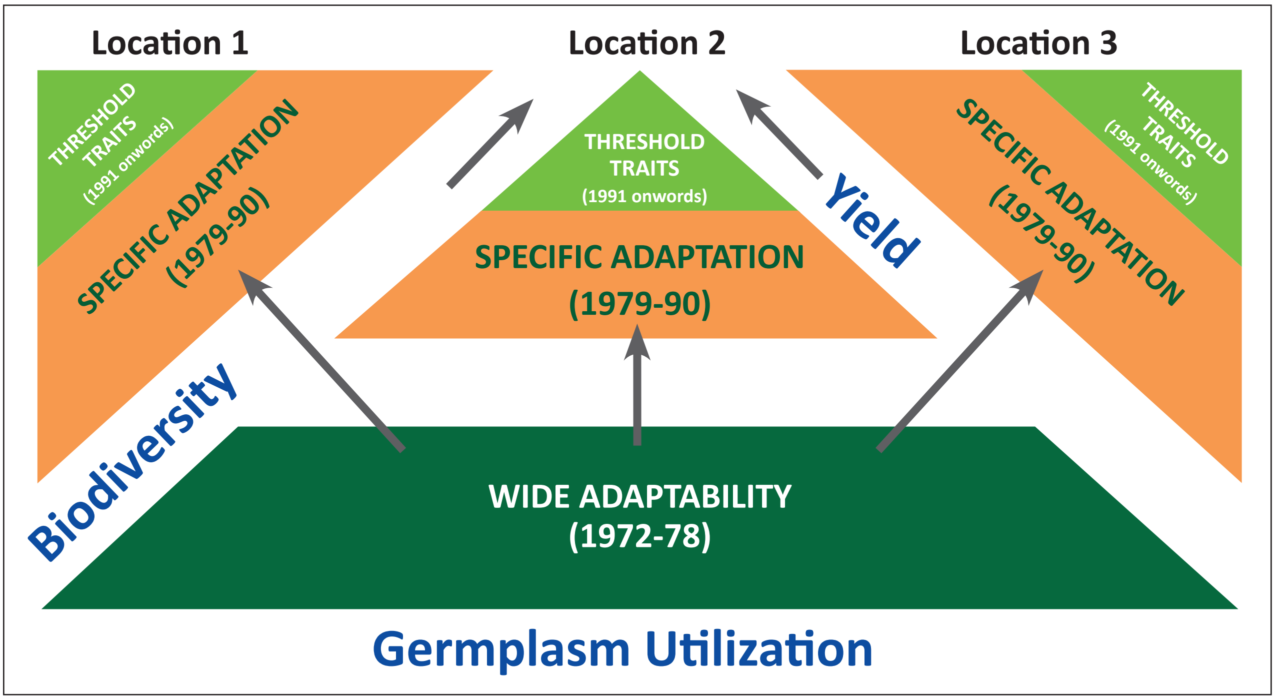

Figure 2. ICRISAT's sorghum breeding strategy from 1972 onwards.

Box 1: ICRISAT-Private Sector partnerships in sorghum improvement (2000-2016)

The Hybrid Parents Research Consortium (HPRC) is an initiative of ICRISAT that was formed in 2000 with the basic objective of increasing the scope of accessibility to better hybrids for poor farmers through effective public-private partnerships. The consortium was started with nine members and has grown up to 35 seed companies by 2012 in the case of sorghum. It 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 % of the total rainy season sorghum area) and one million ha of the summer season sorghum are planted with about 70 private sector-based hybrids, of which 54 are based on ICRISAT-derived parental lines or their derivatives. One of the most promising hybrids developed was JKSH22. At one point, it occupied more than 2 m ha of sorghum area and it ruled the sorghum production areas for nearly ten years. Another high-yield potential hybrid resulting from the ICRISAT-Private sector partnership, VJH 540, has been extremely popular. The area planted under it has increased from 650 ha in 1997 to 1,90,000 ha in 2003 (in the rainy season in major sorghum-growing areas) based on the increase in seed sales from 6.5 tons in 1997 to 1,420 tons in 2003. These examples illustrate the power of partnership between ICRISAT and the private sector to develop and deliver desired products to the farming community. Several other partnership private sector hybrids, such as MLSH 296, GK 4009 and GK 4013, have also been widely adopted in India. The high rate of adoption of ICRISAT-based hybrids is due to their large grain size, and high productivity of grain and fodder. 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 (Reddy et al. 2007).

of the ICRISAT headquarters at India and existence of a strong NARS to make use of breeding materials might have helped in gaining a relatively higher advantage. The country-wise releases during 1975-2016 are depicted in Figure 3. The releases were at their peak during the early 1990s across all the regions and contributed nearly 56 improved cultivars in all. After that, the number of releases has seen a decreasing trend over time but the number of countries with improved cultivars has been increasing.

Table 4. ICRISAT global releases of sorghum cultivars, 1975-2016.

Years	Africa	America	Asia	Total	India	Other Asia
1975-80	9	4	4	17	1	3
1981-85	5	7	11	23	3	9
1986-90	31	11	6	48	4	1
1991-95	28	9	19	56	9	8
1996-00	24	4	18	46	7	11
2001-05	21	0	10	31	3	7
2006-11	14	0	15	29	10	3
2012-16	19	0	1	20	3	2
Total	151	35	84	270	40	44
% share	55.9	13.0	31.1	100	14.8	16.3

The detailed break up (variety or hybrid) of the total releases across regions is summarized in Table 5. In total, ICRISAT has released 201 varieties and 69 hybrids during the period 1975-2016 among four regions. Within Africa, more releases took place in ESA (84) when compared with WCA (67) during the same period. Around 66.6% of the total varieties and 24.6% of the total hybrids have been released in Africa alone. The American region also received more varieties when compared to hybrids. In the case of Asia, this trend was reversed (17.9% of total varieties and 69.6% of total hybrids). NARS across the globe have evaluated hybrids/varieties developed in partnership with ICRISAT in their network or regional trials to select for region specific adaptation materials.

Table 5. ICRISAT global releases by region and type.

Region	Varieties	Hybrids	Total
WCA	58	9	67
ESA	76	8	84
America	31	4	35
Asia	36	48	84
Total	201	69	270

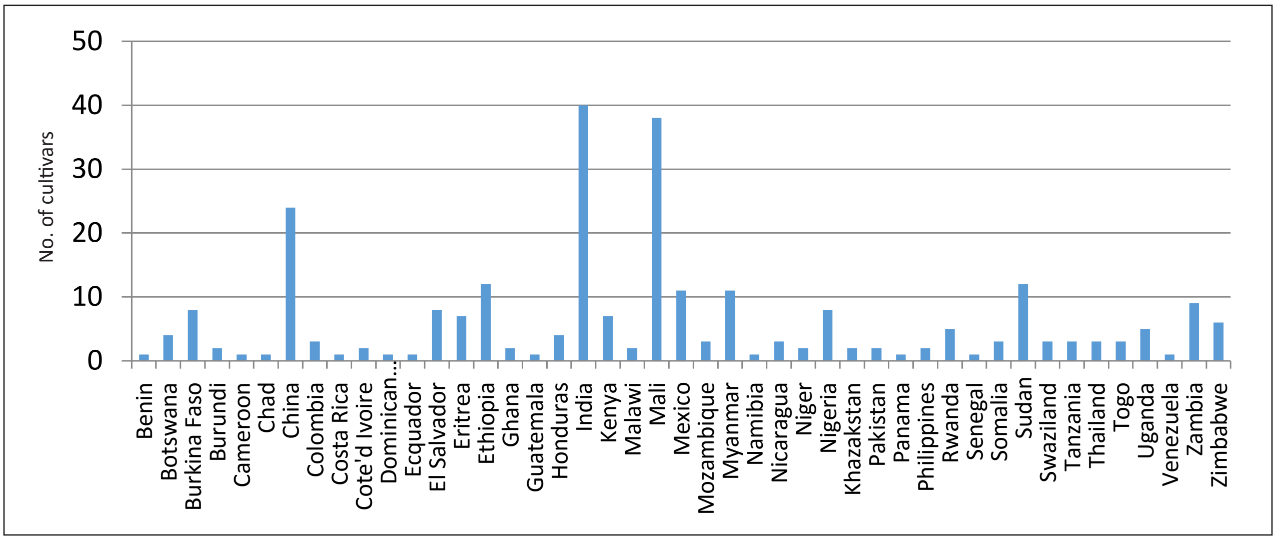

Figure 3. Country-wise sorghum cultivar releases (1975-2016).

4. ICRISAT sorghum research spillovers[6]

Research products aimed at a given location may spill across regions, nations or even across traditional agro-ecological zones. The potential for such spillovers depends on several factors like bio-physical and socio-economic similarities between locations. Agro-ecological similarities are essential for agro-biological technology spillovers across countries or regions, but they are by no means sufficient. The potential for spill-out and spill-in of agricultural technologies across geopolitical boundaries could also be disincentives for national programs to invest in agricultural research. Recent studies on inter-regional spillovers have shown that such benefits often account for up to half the measured growth in crop production in many countries (Shiferaw et al. 2004). To attain the goals of improving food security and ensuring more sustainable management of natural resources in the dryland tropics, ICRISAT has promoted the sharing and spillover of finished products, germplasm, knowledge, methods, tools etc. across national and regional borders by acting as a bridge, broker and catalyst. The inter-regional transfer of research products showed important spillovers within each region in Africa and Asia as well as a two-way transfer of germplasm and improved cultivars across the continents (see Appendix Table A2 for a detailed list of transfers).

The summary of sorghum spillovers of technologies is presented in Table 6. Until 2001, a total of 21 genotypes developed in Asia have been released in India. Another 23 genotypes from ICRISAT, Patancheru have also been released in five other Asian countries. About 29 genotypes from ICRISAT, Patancheru too have been released in 17 African countries across WCA and ESA. The most prominent examples of the transfer of sorghum technologies developed in Asia for Africa are ICSV 111, ICSV 112, S 35 (see Box 2) and SV 2. It is also important to note that about 13 genotypes from ICRISAT, Patancheru were also released in Latin American countries. Another prominent example within the ESA region is Macia (SDS 3220) (see Box 3). Figure 4 shows the global flow of selected sorghum technologies developed by ICRISAT and its partners.

In addition to the advanced progeny and varieties, a major spillover was effected through the transfer of germplasm accessions collected globally and distributed across countries and regions. ICRISAT holds in trust 39,000 germplasm accessions of sorghum collected from Africa (64%), India (17%), other Asian countries (11%) and the rest of the world (8%). This is an important International Public Good (IPG). However, there has been no recorded example of varietal transfer across the two major African regions. This is partly because the farmers of these two regions require sorghum varieties of different maturity groups (early to mid-maturing in ESA and late maturing in WCA).

Box 2: Variety S 35 Spillover (Asia to Africa)

Early breeding efforts in S 35 started in 1978 at ICRISAT, Patancheru and resulted in the development of F_4 progeny of a three-way cross. The ICRISAT sorghum breeder based at the Institute for Agricultural Research (IAR) at Samaru in Nigeria introduced an F_5 from ICRISAT, Patancheru into Nigeria in 1980. At Samaru, S 35 was selected from this progeny in 1981 and tested in preliminary yield trials at Samaru and Kano by the ICRISAT/IAR breeding program in 1982. The variety did not perform well and was never released for wider use (Rao 1983). Later in 1982, ICRISAT, Samaru sent S 35 seeds to a sorghum breeder at IITA in Cameroon. On-farm testing of S 35 commenced in 1983 with no stimulating results in comparison with local varieties. However, the 1984 trials across 88 test sites showed an 85% mean increase in yield with S 35 over farmers' local varieties (Johnson et al. 1986). The subsequent trial results in 1985, 86 and 87 showed the superiority of this variety (Yapi et al. 1999a). On the basis of its high and stable performance, S 35 was released in 1986 in Cameroon. In a good example of south-south collaboration, S 35 was introduced in Chad in 1986 by the national program from IRA's breeding program at Maroua. The variety was evaluated at Gassi research station in Chad and found to be early maturing, high yielding and resistant to long smut. The on-farm trials allowed a clear appreciation of the performance of the technology that led to its release in 1989. Farmers in Chari-Baguirmi and Mayo-Kebbi regions experienced increased yields of 46% and 53% respectively compared to local varieties. The on-farm surveys conducted by Yapi et al. (1999a; 1999b) indicated 33% and 27% adoption rates of S 35 respectively in Cameroon and Chad.

6 For detailed review on spillover studies refer Deb and Bantilan 2001; Bantilan et al. 2004; Deb and Bantilan 2006.

Box 3: Variety SDS 3220 (Macia) Spillovers (Within Africa)

Macia is an open-pollinated, early-maturing and high-yielding variety that was developed at ICRISAT-Bulawayo, Zimbabwe in 1989. It was released in Mozambique (as Macia in 1989), Botswana (as Phofu in 1994), Namibia (as Macia in 1998), Zimbabwe (as Macia in 1998) and Tanzania (as Macia in 1999). Obilana et al. 1997 confirmed that nearly 25% of total sorghum area in Botswana is occupied by this variety. The on-farm trials significantly out yielded the popular variety Segaolane by 39%.

The initial cross for developing SDS 3220 was made at ICRISAT, Patancheru. In 1984, a segregating F_3 bulk from ICRISAT, Patancheru was introduced to ICRISAT, Bulawayo, where it was further improved following modified pedigree selection at ICRISAT locations at Zimbabwe. This variety is easily identified by its green foliage and broad leaves after grain harvest. It was later found to possess the stay-green trait i e, resistance to terminal drought. The variety was most preferred and accepted by farmers, and it was subsequently released by several national programs in the Southern African Development Community (SADC) region.

There were also pre-releases and on-farm verifications in East Africa (Eritrea and Kenya) in recent years through the efforts of ICRISAT, Nairobi and in West Africa (Ghana). These spillovers were attained mainly due to the wide adaptability of Macia's regional germplasm exchanges and sustained multi-locational testing in potential areas for adoption in Africa.

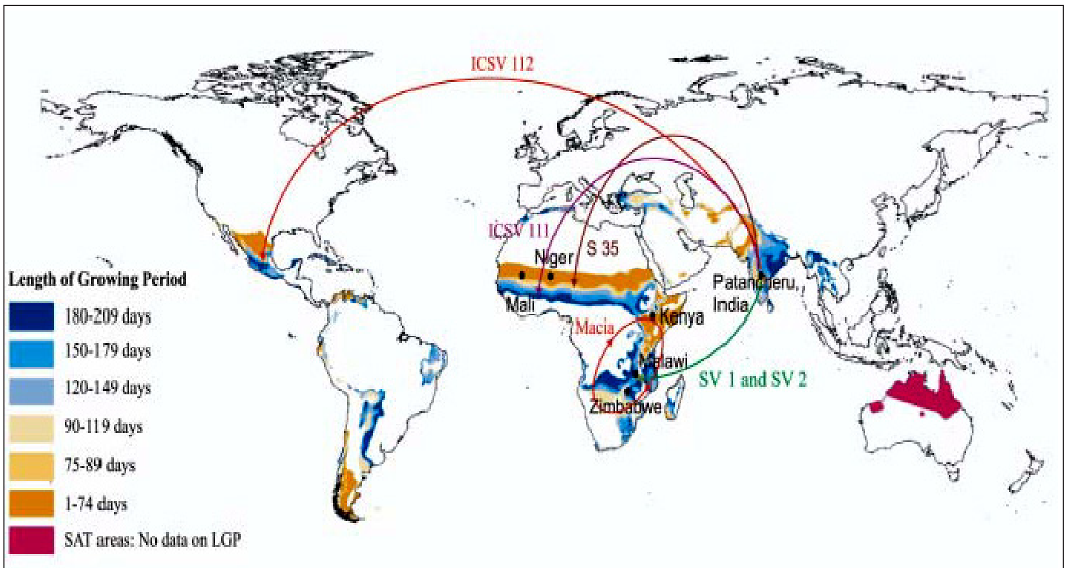

Figure 4. Flow of selected ICRISAT sorghum spillovers technologies.

Source: Shiferaw et al. 2004.

Table 6. Summary of inter- and intra-regional technology transfers (up to 2001).

Varieties (No.)	Developed by	Country of release
21	ICRISAT-Patancheru with partners	India
23	ICRISAT-Patancheru with partners	5 other Asian countries
29	ICRISAT-Patancheru with partners	17 African countries
13	ICRISAT-Patancheru with partners	7 Latin American countries
19	ICRISAT-Africa with African NARS partners	17 African countries
2	ICRISAT-Africa with NARS partners	2 Asian countries
8	ICRISAT-Mexico with partners	5 Latin American countries

Source: Shiferaw et al. 2004

5. Sorghum research domains in 1992

ICRISAT's research in sorghum improvement during the last four decades was conducted by multi-disciplinary teams of scientists located at its center at Patancheru (India), and at the regional centers at Bamako (Mali) and Kano (Nigeria) in West Africa, at Nairobi (Kenya) in Eastern Africa, at Bulawayo (Zimbabwe) in Southern Africa and at El Batan (Mexico) in Latin America. Special programs have been conducted at Cali (Colombia), in collaboration with the Centro International Agriculture Tropical (CIAT) and the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA). ICRISAT scientists are involved in global research on sorghum improvement in collaboration with NARS scientists and with other international programs such as the International Sorghum and Millet Collaborative Research Support Program (INTSORMIL).

The agro-ecologies, growing conditions and the market requirements are quite different in total sorghum growing counties across the world necessitating crop improvement for various adaptations, different uses and market preferences. Sorghum research activities at different locations were conducted under the implicit assumption of eight research domains delineated as homogeneous eco-regions in terms of soil and climatic conditions regardless of national boundaries. Thus, a research domain was defined as a somewhat homogeneous eco-region, where the relevance of strategic research is expected to be pervasive throughout the geographical areas that it comprises. The objective was to specify domains in such a way that it would be possible to directly relate the impact of potential research themes to one (or more) of the defined domains.

ICRISAT always develops and designs technologies that target certain problems or regions on a global basis with a clear focus on the semi-arid tropics. The applicability of a technology is generally supposed to be in the regions in which these problems are endemic or in those that have similar characteristics. In an attempt to define and formalize these homogenous zones ICRISAT developed so called domain maps of its mandate crops in the Medium Term Plan 1994-98 (ICRISAT 1992) in order to enhance the efficiency of its breeding program and to facilitate the "international mindset" of its staff. These domains were designed to reflect the main characteristics and group regions in Africa and Asia (the main target regions of ICRISAT) according to the most important characteristics (ICRISAT 1992). Table 7 summarizes the characteristics of sorghum research domains (SDRs) while Figure 5 shows the areas in different countries in Asia and Africa that falls under these domains.

These domains were: wide adaptability (SRD I), dual purpose with specific adaptability (SRD II), dual purpose with fodder emphasis (SRD III), forage sorghum (SRD IV), early-sown postrainy sorghum (SRD V), late-sown postrainy sorghum (SRD VI), irrigated sorghum (SRD VII) and extreme altitude sorghum (SRD VIII) (also see Bantilan et al. 2004).

The sorghum research domains identified during MTP (1994-98) era are very useful even today, though their accuracy is limited by the technology available during the early 1990s. Utilizing the progress in the area of Geographic Information Systems (GIS), they can be revised and improved in order to better guide scientists to analyze the climatic changes that took place in the recent times. Furthermore, the zones were defined separately for India and Africa based on the expertise available in each location as well as the assessment that these regions are rather different. However going by recent experience and the number of varieties adopted, and number of germplasms transferred in both regions this might not hold now-a-days and might need to be reconsidered. So, the present made a systematic effort to update these global sorghum research domains using highly sophisticated, publicly available resources and GIS tools.

Table 8 summarizes the ICRISAT Medium Term Plan (MTP), 1994-98 of the sorghum prioritization exercise done in 1992 across the SA, SSA and Latin America regions with involvement of bio-physical scientists and economists. Fourteen research constraints/research problems were identified across six research domains with primary and secondary domain focuses. The respective probabilities of their successes were also anticipated under optimum resource scenarios. Good progress has been made in addressing some of these traits over time.

Table 7. Characteristics of sorghum research domains, 1992 (SDRs).

Domain	Production system characteristics	Major constraints	Locations
SRD 1 (Wide adaptability)	Rainy season, multipurpose grain, stalk, fodder (fodder emphasis) and wide adaptability (June-Aug sowing)	Grain mold, shoot fly, headbug	West Africa (southern tier), India (Tamil Nadu, southern Karnataka, Andhra Pradesh)
SRD II (Dual purpose, specific adaptability)	Rainy season, dual purpose (grain and fodder), specific adaptation (June sowing) and medium-to-late-maturing types	Stem borer, grain mold, midge, shoot fly, drought	East and Southern Africa, India (Andhra Pradesh, northern Karnataka, Maharashtra, Madhya Pradesh, Gujarat), Latin America (some areas)
SRD III (Dual purpose, fodder emphasis)	Rainy season, dual purpose (fodder emphasis) and early maturing	Shoot fly, stem borer	West Africa (northern tier), East Africa (Yemen, Somalia), India (eastern Rajasthan), Latin America (some areas), China, Iran
SRD IV (Forage sorghum)	Rainy season, forage types (thin stalk, tillering) and late maturing	Stem borer, leaf diseases	India (northern Gangetic plain), Pakistan
SRD V (Early-sown postrainy)	Postrainy season, dual purpose (early:sown before Oct). Large grain types, dual purpose	Shoot fly, stalk rot and Aphids	India (southern Andhra Pradesh, southern Karnataka)
SRD VI (Late-sown postrainy)	Postrainy season (late sown:mid/ late Oct), large grain, photoperiod sensitivity required and temperature-insensitive	Shoot fly, stalk rot, droughts (shallow soils)	India (Gujarat, southern Maharashtra, northern Karnataka)
SRD VII (Irrigated)	Irrigated sorghum		Iran, Egypt, Wad Medani (Sudan)
SRD VIII (Extreme altitude)	Others		(I) High altitude: China; (ii) Low altitude: Indonesia, Brazil, Ecuador, Venezuela

source: ICRISAT (1992)

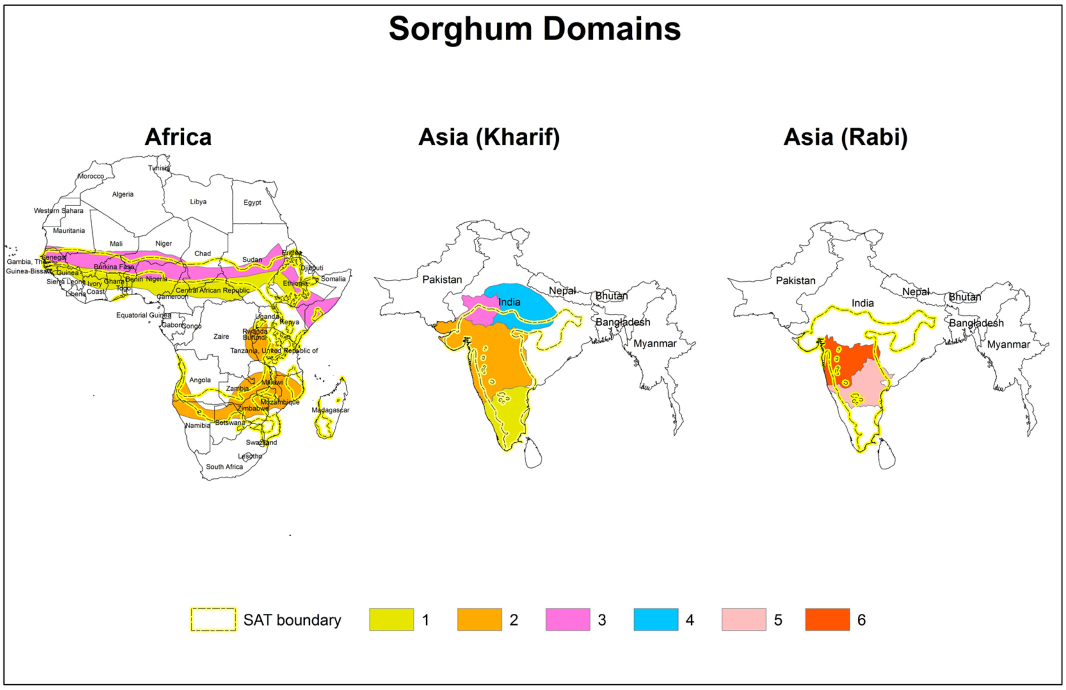

Figure 5. Sorghum research domains in Africa and India (MTP document, 1994-98).

Table 8. ICRISAT MTP, sorghum research prioritizations (1994-98).

	Research domain		Probability of success#	
Type of constraint	Primary	Secondary	Primary	Secondary
1. Improvement and control of *Striga*	III (SSA)	I & II	80%	80%
2. Improvement of grain and stover yield	Global	-	80%	80%
3. Improvement of resistance to stem borer	I, II, III & IV	Latin America and China	75%	50%
4. Resistance to grain mold	II (India)	I, II (SSA) and Latin America	80%	80%
5. Lack of adaptation to low temperature	ESA (Burundi, Ethiopia, Rwanda, Uganda, Kenya)	South Africa	90%	60%
6. Head bug, biology and resistance	I	III & II (SSA)	75%	60%
7. Resistance to Anthracnose	I & II (SSA), IV	III	80%	80%
8. Improvement of resistance to midge	I & III	II	90%	75%
9. Adaptation of sorghum to acid soils	Brazil, Colombia & Venezuela	South America and South Africa	70%	50%
10. Mechanisms for escape from drought	III	I, II, IV, V & VI	75%	70%
11. Resistance to leaf blight	II & III (SSA)	Central and Latin America	75%	75%
12. Improvement of foliar disease resistance for Latin American sorghum	Mexico, Central America, Panama, Caribbean	I & II (SSA), Argentina, Brazil, Colombia and Venezuela	85%	85%
13. Improvement of resistance to shoot fly	VI, V, III (India)	I, II & III	70%	70%
14. Improvement of forage sorghum	IV, II (Africa)	Latin America	80%	80%

under optimum resource scenario; Source: MTP, 1994-98

6. Updated homogenous research domains in 2012

In the 1990s the first and most crucial factor during the considerations was the length of the growing period across all locations. Groups were built along this most important indicator. After these basic delineations, the major cropping systems and some of the major constraints that are endemic across regions were attributed to the zones. This resulted in the zones mapped in Figure 4. From this, one can clearly see that an overlap exists between the Asian, West African and East African locations. This would clearly indicate that almost all disseminations from any one of these ICRISAT regions to another would have to be considered as spillover effects. In an effort to spread these zones to sorghum growing areas that were not covered in the initial attempt, consultations with leading ICRISAT sorghum scientists were held. Their assessment of the 1992 homogenous zones indicated that they do not cover the real situations and are rather rough drawings mainly based on the LGP which has changed today in many locations. Therefore, it was decided to redefine a new set of global homogenous zones for sorghum. The following main steps and layers were used in the process:

a. Sorghum suitability map[7]

Sorghum, like any other crop, can be grown in a very specific environment but not everywhere in the world. Different type of cultivars suit different micro-environments/eco-regions. The definition of

[7] See more details at http://gaez.fao.org/Main.html#

homogenous zones will be based on regions that are at least marginally suitable for rainfed sorghum production and are therefore potential target areas for breeding efforts. For this assessment the FAO (2000) sorghum suitability maps are utilized (Figure 6). This layer itself considers several other relevant environmental features and estimates suitability indices (SI).

b. The SPAM sorghum area and production maps

The Spatial Production Allocation Model (SPAM) identifies the current sorghum production and areas across the globe based on the crop secondary information consolidated by pixels (Figures 7 & 8). This additional layer helps in the formation of a base area for the delineation of the homogenous zones. It was developed by HarvestChoice (2010) and provides spatial estimates for sorghum production (year: circa 2000). The layer was integrated and developed based on crop national production statistics, production systems, Agro-ecological Zones, etc.

The combination of suitability (Figure 6) and actual production (Figure 7) is used as the basis for identifying the area considered for the generation of the sorghum homogenous zones.

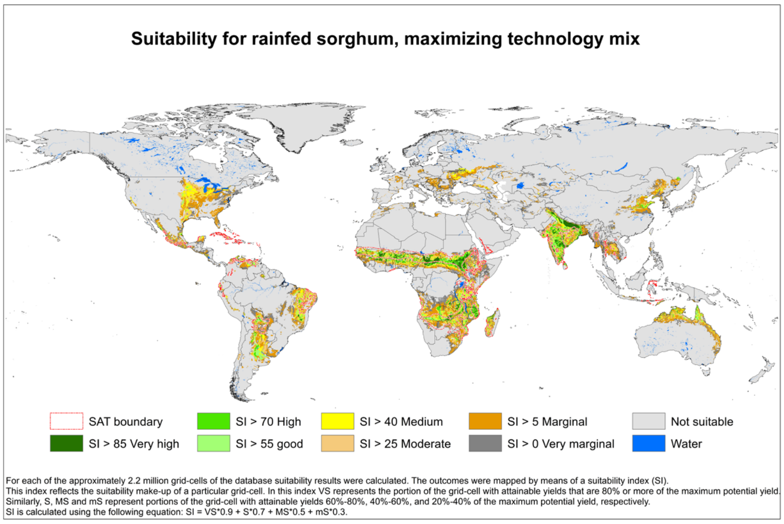

Figure 6. Sorghum suitability map.

Source: FAO, 2000a

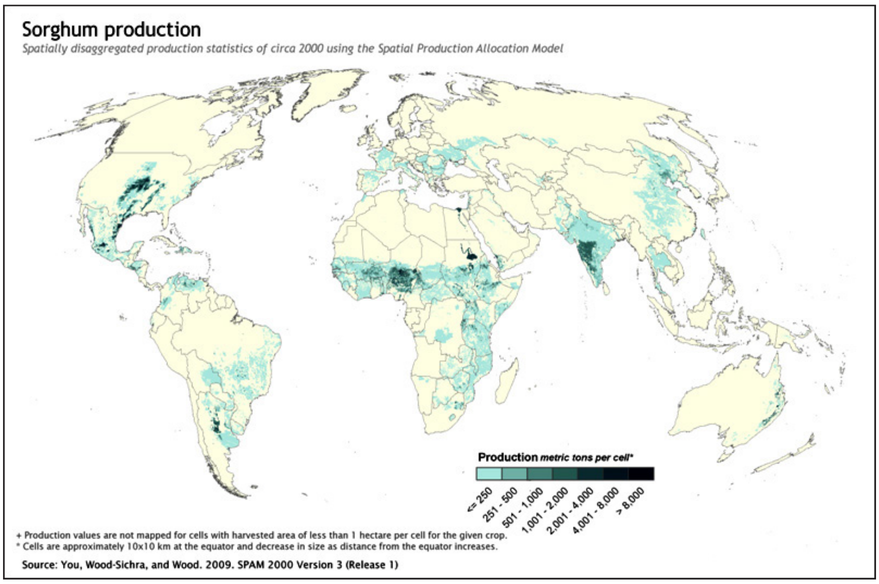

Figure 7. HarvestChoice sorghum production map (circa 2000).

Source: HarvestChoice, 2010

This layer (Figure 8) combination not only covers the current distribution of sorghum production but also includes potential areas where the crop can be produced in the future due to environmental changes or changes in the preferences of consumers/producers. Therefore, this base area for the classification gives a very broad assessment.

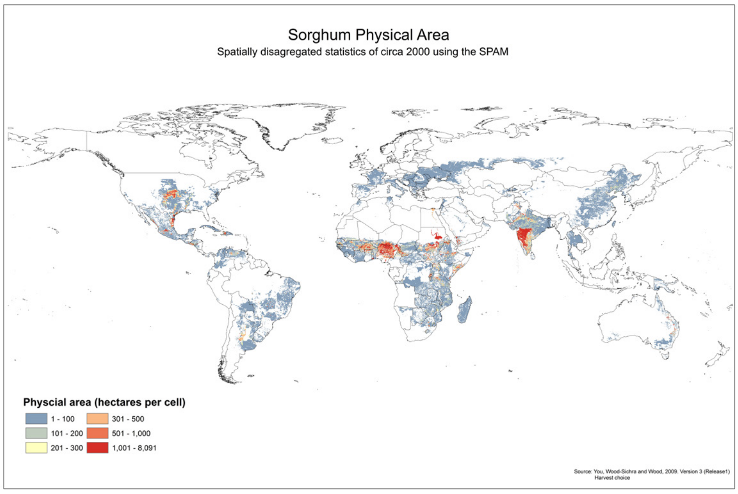

Figure 8. HarvestChoice sorghum physical area map.

Source: HarvestChoice, 2010.

c. Global agro-ecological zones (AEZs)

The broader features of agro-ecological zones (AEZ) developed by FAO (2000) were used to identify the different climate conditions across the globe (Figure 9). These zones are based on climate, soil and terrain conditions that are most relevant to agricultural production. Therefore, they represent a broad classification of regions according to their most basic agro-ecologic features (FAO 2000 & 2010). These broad zones can be used to sub-divide the base sorghum area into several zones as the conditions among these broad zones will be different to a certain extent. Nevertheless, similar AEZs can be found in several very different parts of the world.

d. The length of the growing period (LGP)

The aggregate Length of the Growing Period (LGP) also compiled by FAO (2000) represents the maximum available period in which crops can be grown in the region under rainfed conditions (Figure 10). The LGP

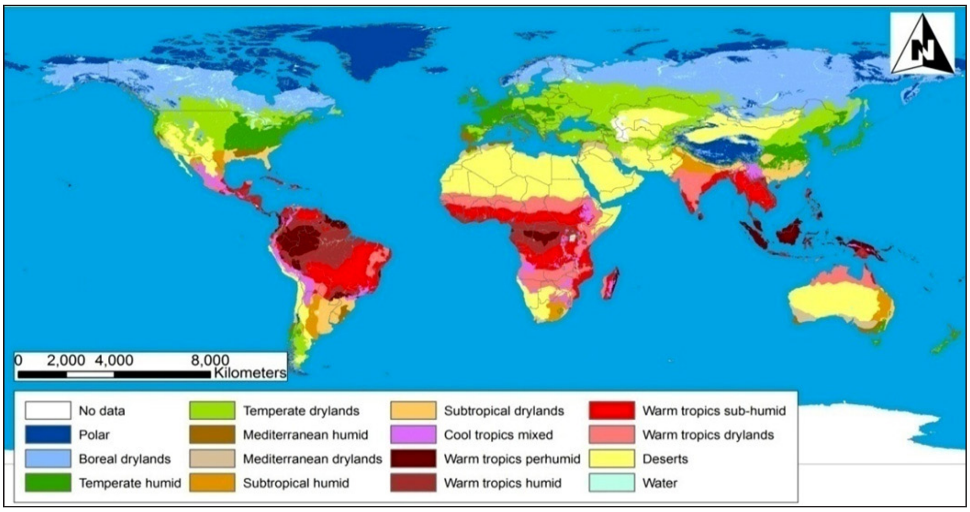

Figure 9. The global agro-ecological zones (AEZs).

Source: FAO, 2000b & 2010

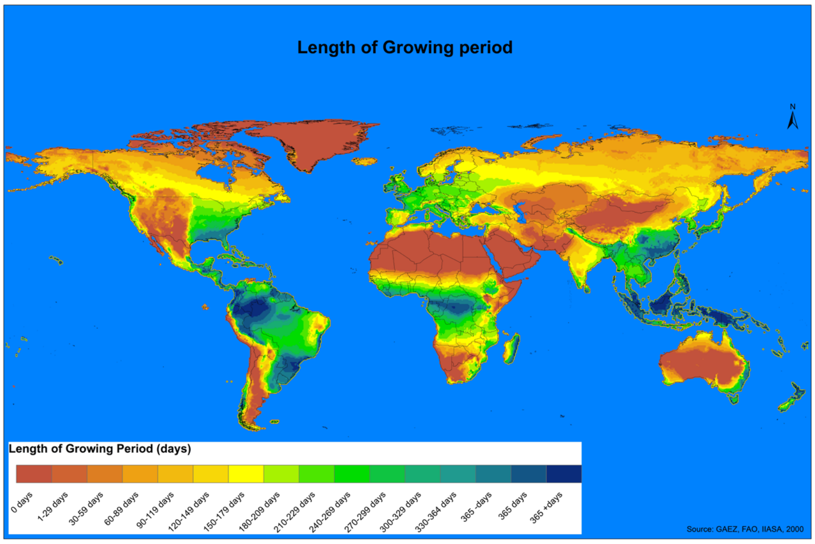

Figure 10. Length of Growing Periods.
Source: FAO 2000b

is the period of the year in which both the moisture levels and the temperatures are suitable for crop growth. The assessment is based on rainfall, soil profiles and, evapo-transpiration and relies crucially on the soil moisture storage capacity.

The length of the growing period has direct implications for the possibilities available for farmers and on the crop portfolio from which they can choose in their specific location. LGP is an important determinant for sorghum production as different varieties require different durations.

The global sorghum homogenous zones up-gradation process utilized all these four layers which are readily available from reliable sources. Using modern Geographic Information Systems (GIS) tools, all the layers were integrated with suitable controls. Several iterations and refinements were carried out to obtain the conformations from bio-physical scientists across the world. Finally, 13 homogenous research domains (earlier eight in 1992) were identified across the globe where sorghum is currently grown. These domains have huge potential for further expansion. During the process, some minor sorghum climatic environments were discarded for want of better visibility and clarity in research domains. The details are presented in Table 9 and Figure 11.

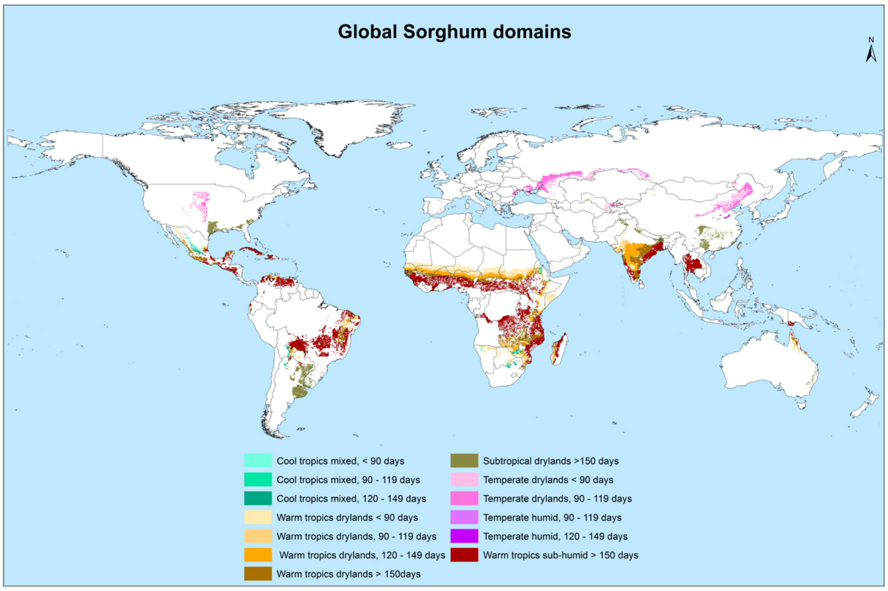

Figure 11. Global Sorghum Research Domains, 2012.

Table 9. Updated Research Domains and their characteristics.

S.No.	Research Domains (RD)	Climate type and Length of Growing Period (LGP)	Production ('000 tons)[1]	Production share (%)	Major Countries
1	RD1	Cool tropics mixed, < 90 days	36.6	0.11	Mexico, Eritrea, Ethiopia, Zimbabwe and South Africa
2	RD2	Cool tropics mixed, 90-119 days	111.9	0.33	Ethiopia, Mexico, Zimbabwe, Botswana, Argentina, Sudan
3	RD3	Cool tropics mixed, 120-149 days	752.4	2.21	Mexico, South Africa, Zimbabwe, Ethiopia, Tanzania, Argentina, Bolivia,
4	RD4	Warm tropics drylands, < 90 days	3169.6	9.29	Sudan, Nigeria, Niger, India, Mexico, Mali, Somalia, Mauritania, Kenya
5	RD5	Warm tropics drylands, 90-119 days	3184.4	9.33	Nigeria, Sudan, India, Ethiopia, Burkina Faso, Mexico, Mali, Niger, Kenya, Chad, Cameroon
6	RD6	Warm tropics drylands, 120-149 days	6780.5	19.88	India, Nigeria, Burkina Faso, Mexico, Sudan, Mali, Cameroon, Senegal, Chad
7	RD7	Warm tropics drylands, > 150 days	4971.3	14.57	India, Mexico, Nigeria, Sudan, Ethiopia, Chad, Burkina Faso, Mali, Tanzania, Cameroon
8	RD8	Sub-tropical drylands, > 150 days	3110.7	9.12	United States, Argentina, Australia, China, Pakistan, Uruguay
9	RD9	Temperate drylands, < 90 days	2603.6	7.63	United States, China, Uzbekistan, Mexico
10	RD10	Temperate drylands, 90-119 days	1031.1	3.02	China, United States, Uzbekistan
11	RD11	Temperate humid, 90-119 days	0.1	0.00	China, India
12	RD12	Temperate humid, 120-149 days	18.4	0.05	China, Spain
13	RD13	Warm tropics sub-humid, > 150 days	8342.7	24.46	Nigeria, Sudan, India, Tanzania, Brazil, Venezuela, Ghana, Ethiopia, Burkina Faso, Cameroon, Mozambique, Uganda, Haiti, Bolivia, Benin, Chad, Central African Republic

Note: [1]The SPAM (2010) spatial distributed production map of sorghum is used for estimating the production.

The characteristic details of research domains and their respective production shares are presented in Table 9. Research domain 13 alone contributes nearly 25% of global sorghum production in the world. It is followed by Research domains 6 and 7 with at 20 and 15% shares in total production respectively. Among the 13 domains, the lowest production share is observed in Research domain 11. The major countries covered in sorghum production, Research domain-wise are also highlighted. The visualization of the updated homogenous research domains (2012) is depicted in Figure 11.

Table 10. New research domains and their geographical coverage.				
Research Domain	RD no.	Actual area[1] (m ha)	Estimated domain area[2] (m ha)	% covered
Cool tropics mixed, < 90 days	1	0.1 (0.25)	0.053 (0.18)	53.01
Cool tropics mixed, 90-119 days	2	0.2 (0.49)	0.082 (0.28)	40.999
Cool tropics mixed, 120-149 days	3	0.4 (0.98)	0.185 (0.62)	46.299
Warm tropics drylands, < 90 days	4	8.3 (20.43)	4.68 (15.7)	56.383
Warm tropics drylands, 90-119 days	5	4.2 (10.34)	3.085 (10.35)	73.455
Warm tropics drylands, 120-149 days	6	8.5 (20.93)	7.757 (26.03)	91.254
Warm tropics drylands, > 150 days	7	5.6 (13.79)	4.797 (16.1)	85.654
Sub-tropical drylands, > 150 days	8	2.3 (5.66)	0.78 (2.62)	33.894
Temperate drylands, < 90 days	9	1.7 (4.19)	0.737 (2.47)	43.329
Temperate drylands, 90-119 days	10	0.6 (1.48)	0.369 (1.24)	61.571
Temperate humid, 90-119 days	11	0.001 (0)	0 (0)	3.6
Temperate humid, 120-149 days	12	0.018 (0.04)	0.008 (0.03)	41.939
Warm tropics sub-humid, > 150 days	13	8.7 (21.42)	7.285 (24.45)	83.736
Total	-	40.619 (100.00)	29.816 (100.00)	73.405

[1] 2010 FAOSTAT area [2] Estimated value using SPAM area map
Figures in the parenthesis indicate shares to the column totals

Table 10 summarizes the updated research domain-wise details and their extent of coverage respectively. Overall, 73.4% of the sorghum cropped area in the globe has been covered by 13 homogenous Research domains in the world. The highest coverage of actual cropped area was observed in the case of Research domain 6 (Warm tropics drylands, 120-149 days) followed by Research domain 7 (Warm tropics drylands, > 150 days) and Research domain 13 (Warm tropics sub-humid, > 150 days). The lowest representation of sorghum cropped area was visualized in the case of Research domain 11.

7. Theoretical framework for ex ante spillovers estimation

Interstate and international spillovers from public agricultural research and development investments account for a significant share of agricultural productivity growth. These spillovers across geopolitical boundaries have implications for measures of research impacts on productivity, and the implied rates of return to research, as well as for state, national, and international agricultural research policy. In studies of aggregate state or national agricultural productivity, interstate or international R&D spillovers might account for half or more than half of the total measured productivity growth. As a result, the stakes associated with the distortions in research policy caused by agricultural R & D spillovers are very large, probably much bigger than those for most other agricultural policy distortions.

Spillovers also have profound implications for the distribution of research benefits between consumers and producers and thus among countries, depending on their trade status and capacity to adopt the technology. It is not easy to measure these impacts, and the results can be sensitive to the specifics of the approach taken.

Even if the appropriability issue is ignored there have, been several studies which have addressed the spillover issue and have specifically focused on agriculture. The work done by Evenson (1978) which used aggregate productivity or production function specifications with public research expenditure, in an aggregate sense, determined the relationship between expenditures on research at one location and the output in others. Evenson (1989) reported a further refinement of this work. In general, the appropriate level of aggregation of any analysis clearly depends on the type of decision making the information generated has to support. The limitations of the study are mainly useful in policy discussions and in obtaining the disaggregated data.

Brennan (1986) estimated specific economic gains to Australia from CIMMYT wheat research. These studies have taken specific technologies and developed analyses specific to the particular situation or at the institutional level and have not generalized at a national or international level. The limitation is that the model does not give any generalized spillover impact.

In the first generally accepted economic surplus type research evaluation model, Edwards and Freebairn (1981, 1982 and 1984) developed a two region trade model which included an allowance for spillovers between two politically defined regions. Later, Mullen et al. (1989) used a similar model between two regions for processing sector research. They applied hypothetical guesses of a zero to one spillover index to weigh the unit cost reduction estimates.

Davis et al. (1987) extended the Edwards and Freebairn model to include many regions and used agro-climatic zonation work to identify agricultural production environments. The similarities in these environments were used to subjectively assess spillover effects (0 to 1) for different commodities. A spillover index vector or matrix was developed and used.

Later, the need to separate assessments of the impact of technologies in different arbitrary geographical/political boundaries became apparent. Technologies are invariably developed to suit some locations and may not be suitable for others locations. Sometimes, different technologies may exist within the same geographical boundary. Finally an urgent need to relate spillover modelling to these production environment factors was recognized by Davis et al. 1987.

Multi-region, single commodity economic surplus model

A framework was developed using a multi-regional international trade model using the concepts of economic surplus and is employed to derive ex ante measures of the relative economic benefits of alternative commodity and regional research portfolios and the distribution of these benefits among consumers, producers, importers and exporters. Davis (1991) was successful in modifying the model of Davis et al. (1987) where geographical/political boundary based available data were transformed to homogenous agro-ecological unit and research strategies which were focused on the basis of the production environment. This took many forms but with respect to spillover modelling and subjective estimation of the research applicability and spillover impact, Davis (1991) provides a good summary. Davis et al. (1989) and Fearn and Davis (1991) outline how this expanded framework was applied to the forestry and fisheries sectors which were an important part of ACIAR's priority setting focus. This set of information has been used in the multi-regional research evaluation model to estimate possible research benefits associated with the different options. This ACIAR model (Davis 1991) was adopted and suitably modified for the ICRISAT research spillover estimation (see more details in Bantilan et al. 2013).

Management has decided to adapt the framework summarized in equations (1) to (4) to suit these decision making requirements. This adapted framework can be represented in slightly revised form as:

$$
\begin{aligned}
E[PV(GB_{gw})] = & \sum_{t=1}^{T}\sum_{f=1}^{n}\frac{p_{gt}\,a_{gft}\,x_{gft}\,k_{gft}}{(1+d)^{t}}Q_{sft} \\
& + \sum_{t=1}^{T}\sum_{f=1}^{n}\frac{p_{gt}\,\beta_{f}(\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git})^{2}}{2(1+d)^{t}(\sum_{i=1}^{n}(\beta_{i}+b_{i}))^{2}} \\
& + \sum_{t=1}^{T}\sum_{f=1}^{n}\frac{p_{gt}\,\beta_{f}}{2(1+d)^{t}}[a_{gft}\,x_{gft}\,k_{gft} - [\frac{\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git}}{\sum_{i=1}^{n}(\beta_{i}+b_{i})}]]^{2} \\
& + \sum_{t=1}^{T}\sum_{f=n+1}^{N+m}\frac{p_{gt}\,a_{gft}\,x_{gft}\,k_{gft}}{(1+d)^{t}}Q_{sft} \\
& + \sum_{t=1}^{T}\sum_{f=n+1}^{N+m}\frac{b_{f}\,\beta_{f}\,p_{gt}\,a_{gft}^{2}\,x_{gft}^{2}\,k_{gft}^{2}}{2(1+d)^{t}\,(\beta_{f}+b_{f})} \qquad \text{..........} \quad (5)
\end{aligned}
$$

The individual national benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally traded environment (f = 1 ... n) are given as:

$$
\begin{aligned}
E[PV(G_{gf})] = & \sum_{t=1}^{T}\sum_{f=1}^{n}\frac{p_{gt}\,a_{gft}\,x_{gft}\,k_{gft}}{(1+d)^{t}}Q_{sft} \\
& + \sum_{t=1}^{T}\frac{p_{gt}(Q_{dft} - Q_{sft})\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git}}{(1+d)^{t}\sum_{i=1}^{n}(\beta_{i}+b_{i})} \\
& + \sum_{t=1}^{T}\frac{p_{gt}\,b_{f}\,(\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git})^{2}}{2(1+d)^{t}(\sum_{i=1}^{n}(\beta_{i}+b_{i}))^{2}} \\
& + \sum_{t=1}^{T}\frac{p_{gt}\,\beta_{f}}{2(1+d)^{t}}[a_{gft}\,x_{gft}\,k_{gft} - \frac{\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git}}{\sum_{i=1}^{n}(\beta_{i}+b_{i})}]^{2} \qquad \text{..........} \quad (6)
\end{aligned}
$$

Consumer benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally traded environment (f = 1 ... n) are given as:

$$
\begin{aligned}
E[PV(G_{cgf})] = & \sum_{t=1}^{T}\frac{p_{gt}\,Q_{dft}\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git}}{(1+d)^{t}\sum_{i=1}^{n}(\beta_{i}+b_{i})} \\
& + \sum_{t=1}^{T}\frac{p_{gt}\,b_{f}\,(\sum_{i=1}^{n}\beta_{i}\,a_{git}\,x_{git}\,k_{git})^{2}}{2(1+d)^{t}[\sum_{i=1}^{n}(\beta_{i}+b_{i})]^{2}} \qquad \text{..........} \quad (7)
\end{aligned}
$$

Producer benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally traded environment (f = 1 ... n) are given as:

$$E[PV(G_{pgf})] = \sum_{t=1}^{T} \frac{p_{gt} Q_{sft}}{(1+d)^t} \left[a_{gft} x_{gft} k_{gft} - \frac{\sum_{i=1}^{n} \beta_i a_{git} x_{git} k_{git}}{\sum_{i=1}^{n} (\beta_i + b_i)} \right]$$

$$+ \sum_{t=1}^{T} \frac{p_{gt} \beta_f}{2(1+d)^t} \left[a_{gft} x_{gft} k_{gft} - \frac{\sum_{i=1}^{n} \beta_i a_{git} x_{git} k_{git}}{\sum_{i=1}^{n} (\beta_i + b_i)} \right]^2 \quad \text{........ (8)}$$

National benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally non-traded environment (f = n+1 ... N+m) are given as:

$$E[PV(G_{gf})] = \sum_{t=1}^{T} \sum_{f=1}^{n} \frac{p_{gt} a_{gft} x_{gft} k_{gft}}{(1+d)^t} Q_{sft}$$

$$+ \sum_{t=1}^{T} \frac{p_{gt} b_f \beta_f a_{gft}^2 x_{gft}^2 k_{gft}^2}{2(1+d)^t (\beta_i + b_i)} \quad \text{........ (9)}$$

Consumer benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally non-traded environment (f = n+1 ... N+m) are given as:

$$E[PV(G_{cgf})] = \sum_{t=1}^{T} \frac{p_{gt} \beta_f a_{gft} x_{gft} k_{gft}}{(1+d)^t (\beta_f + b_f)^2} Q_{dft}$$

$$+ \sum_{t=1}^{T} \frac{p_{gt} b_f \beta_f^2 a_{gft}^2 x_{gft}^2 k_{gft}^2}{2(1+d)^t (\beta_f + b_f)^2} \quad \text{........ (10)}$$

Producer benefits for country/region ‘f’ from ICRISAT research focused on research domain/production environment ‘g’ with an internationally non-traded environment (f = n+1 ... N+m) are given as:

$$E[PV(G_{pgf})] = \sum_{t=1}^{T} \frac{p_{gt} b_f a_{gft} x_{gft} k_{gft}}{(1+d)^t (\beta_f + b_f)} Q_{sft}$$

$$+ \sum_{t=1}^{T} \frac{p_{gt} \beta_f b_f^2 a_{gft}^2 x_{gft}^2 k_{gft}^2}{2(1+d)^t (\beta_f + b_f)^2} \quad \text{........ (11)}$$

Where:

p_{yt} is the probability of success of innovative research undertaken in country ‘y’ in year ‘t’ ($0 \leq p_{yt} \leq 1$);

a_{yft} is the probability of success of adaptive research undertaken in country ‘f’ on a technology developed by innovative research in country ‘y’ in year ‘t’ ($0 \leq a_{yft} \leq 1$). Note that in the early applications of this framework this parameter was used to adjust the spillover index before calculation of the final unit cost reduction, k_{yft}; see Davis et al (1987; pp37-39). It has been included in equation (1) to make this adjustment more transparent;

x_{yft} is the expected level of adoption of the technology developed in country 'y' by producers in country 'f' (f = 1 … N) in year 't' ($0 \le x_{yft} \le 1$);

k_{yft} is the cost reducing effect from research in country 'y' in country 'f' (f = 1 … N) in year 't'. For the country where the research takes place this 'k_{yyt}' is the direct effect of the research; for the remaining N-1 countries producing and/or consuming the commodity the k_{yft} will be the spillover effects of research. For many countries this could be zero.

d is the social discount rate in real terms.

Q_{sft} is the quantity of the commodity produced in country 'f' in time period 't' without research, that is, the initial equilibrium output.

b_f and b_i are the slope parameters (dQ/dP) of the demand function in country/region 'f' or 'i'. Note that $b_i = e_{di}$ [Q_{dit}/P_{it}], where e_{di} is the elasticity of demand for the commodity in country 'i' evaluated at the original equilibrium prices and quantities, Q_{dit} and P_{dit}. Note because negative signs are included in the demand specification the absolute value for these parameters are entered in the formulae.

$ß_f$ and $ß_i$ are the slope parameters (dQ/dP) of the supply function in country/region 'f' or 'i'. Also note, $ß_i = e_{si}$ [Q_{sit}/P_{it}] where e_{si} is the elasticity of supply.

N is the total number of countries/regions (aggregations of some countries) in the world.

n is the number of countries/regions where the commodity of concern is produced or consumed and is internationally traded.

N-n is the number of countries/regions where the commodity is only traded domestically (that is, closed economies) if any.

The changes to the model are relatively subtle but important. Instead of the innovative research being undertaken by a country it is now undertake through an ICRISAT research strategy 'g'. This involves focusing the research on a specified research domain/production environment. While the number of these can be as many as required it is expected that g= 1....m, but perhaps less than this. Recall 'm' is the number of production environments appropriate to a particular commodity (crop) and research issue. With the flexibility available for ICRISAT the number of production environments will most likely be different between crops and research issues.

Notice now instead of N countries and regions the model now includes N+m. These should now be referred to as countries, regions and research strategies. Adapting the framework requires adding these 'm' rows and/or columns to the matrices K, K*, S, R and F. These are not repeated here since they only involve a change in matrix sizes. Importantly, though the entries in the R matrix for the 'm' ICRISAT strategies are directly focused on each research domain/production environment and although not required will be set so r_{ii}=1 and r_{ij}=0 for each 'g'. In addition the unit cost reductions in K* for the 'g' th ICRISAT production environment research strategy will be specific to that research domain rather than a country level weighed unit cost reduction as in most other applications.

8. Minimum dataset requirements

The following minimum dataset variables are required for estimation of ex ante sorghum research spillovers across regions:

a. Select the commodity and collect data on area, production and consumption

b. Define the agro-climatically homogenous research regions/Research domains (it is important for the assumption of a parallel supply shift due to research)

c. Estimate the probability of success of research for each commodity under each region/domain

d. Estimate the expected ceiling levels of adoption, lags in the availability of research results and adoption

e. Construct the applicability matrix (C matrix)

f. Estimate unit cost reduction across research domains

g. Collect data on prices, price elasticities of supply and demand, research investment costs, etc.

For collection of each minimum dataset variable to be used in the analysis, the following methods or approaches were attempted.

8.1 Commodity data

The present study has chosen the sorghum crop explicitly for assessing the quantity of research spillovers across regions. Most of the sorghum data on area, production and consumption were accessed from FAOSTAT. The country-wise area, production and consumption data used in the present study are based on 2008-10 averages. With the aim of harmonization of model input parameters across time period, the sorghum area and production of triennium average (2008-10) was used a baseline data in the model. The country-wise average production and consumption data for 2008-10 are furnished in Table 12.

8.2 Identification of homogenous zones

An innovative aspect of the approach to determining research priorities in this study is the identification of the way in which production of sorghum crop is distributed among homogenous zones. The objective of this zonation is to be able to identify the benefits of research, not only to the country or countries in which the research is actually undertaken, but also to other regions with ecological affinities, to which some of the knowledge or materials derived from research elsewhere might be relevant (spillover). As indicated in Figure 11, the world sorghum area has been divided in to 13 homogenous zones based on their similar agro-ecology, sorghum crop suitability mix and length of growing period etc. It is very important to understand the step by step process used here along with incorporation of feedback obtained from respective sorghum crop improvement scientists located at across the world. It is necessary to bear in mind that sorghum zones with the same length of growing period can exist under quite different temperature and moisture regimes, and therefore in different/major thermal regions, depending on the factors limiting growth. These are principally rainfall (too much or too little) in the lowland tropics; and temperature, as determined by altitude and/or latitude. Thus some areas in both the tropics and the temperate zones may have a year-round growing season. Overall it is the specific nature and location of a sorghum crop within a country which determines its zonal definition, and consequently the affinity it may have with other producing countries for identification of spillover potential. Sometimes a country may derive part of its sorghum production from several LGP (Length of Growing Period) zones in the warm tropics, and from zones with similar or different length of growing period in the cooler tropics, or another major climatic zone. In general, the bulk of agricultural production in the developing countries is located in the warm sub-humid to semi-arid tropics, and in the cooler tropics modified by altitude in Africa and Latin America.

8.3 Estimation of probability of success

The unit-cost reducing impact of research discussed previously assumes that research objectives are fully achieved. However, there are many reasons why all research in a country will not achieve the stated objectives. In addition, there are likely to be substantial differences in the probability of success of achieving research objectives among countries and commodities due to factors such as the history of previous research and the current level of research intensity. This probability of success was subjectively estimated as a result of inspection of quantitative and qualitative data on national research system for each selected country in the study, including information on the actual no. of research workers engaged on sorghum crop improvement in each country. Although final probability of success estimates for each country were subjectively derived, the judgements used were made on the basis of a common underlying relationship between factors it is believed influence research success. The probability of success of current research systems is likely to take the full probability range, that is, zero to one.

Probability of success of innovative research undertaken (in the present study it is ICRISAT) in particular country (p_{yt}) or institution is the prime deriving factor for generating the direct and spillover benefits. Identification of right research problem which has more impact on major production environments/ research domains should be prioritized in any innovative research. Similarly, it should also have higher probability of success. In general, International Agricultural Research Centres (IARCs) will undertake this type of research because of strong research capacities (a_{yft}) as well as financial support. The probability of success of adaptive research could undertake in a country determined by the national agricultural research systems (NARS) capacity in that country. The strength of NARS and extent of use of gene pools/ intermediate materials generated by IARCs will in turn help in quick generation of improved cultivars in any country. The time lag should be shorter from innovative research in a country/institution to adaptive research and to reap the maximum benefits from it.

The probability of success of innovative research was assumed as one in all the iterations of the model because ICRISAT as an external entity generating the technologies and transferring these materials to different locations in the world unconditionally. ICRISAT has been transferring these materials (germplasms and intermediate materials like gene pools and hybrid parents) not only to the NARS in different countries but also equally to private seed companies since 1972 to till now. The probability of success of adaptive capacity undertaken in a country was assessed based on the NARS strength (FTEs) working on a particular crop (sorghum) in a country as well as on the number of improved cultivars released during a particular period. ICRISAT has put concerted efforts and collated this historic information from reliable sources like ISNAR (Pardey et al. 1989), Evenson and Gollin (2003) and Agricultural Science and Technology Indicators (ASTI) Reports. Recently, ICRISAT also initiated massive diffusion studies (sequel to 1998 baseline) in sub-Saharan Africa (SSA) and South-Asia with the support of SPIA and BMGF respectively. This activity has provided enough advantage to ICRISAT to update the 1998 CGIAR baseline as well as to add new potential crops in various countries. The information/data generated from all the sources have helped ICRISAT to estimate this parameter in different countries. However, ICRISAT also validated this information with bio-physical scientists through various workshops and conferences. The crop-wise estimated parameters were summarized in the annexure Table 4 respectively.

8.4 Estimation of ceiling level of adoption and research lags

Ceiling level of adoption is defined as the maximum attainable adoption rate given the current conditions facing the most important institutional and infrastructure conditions like market structure, road network or trader preferences. These are the basic conditions that influence adoption to a large extend but also take long time to be changed and therefore can be assumed fixed for this exercise. The initial 1998 baseline to determine the extent of adoption of improved cultivators was established by Evenson and Gollin (2003). As a partner in this study, ICRISAT has generated this information for Sorghum, Pearl millet and Groundnut crops in major countries in South Asia and sub-Saharan Africa. However, this baseline is now ten years old and needs to be deepened and widened. Recently, ICRISAT (as a lead center in the World) also put substantial effort in the Dryland Cereals and Grain Legumes projects supported by the Bill and Melinda Gates Foundation (BMGF) to update this information through various monitoring and adoption surveys under taken in different countries with the help of NARS partners. However, the recent initiate of diffusion studies carried out in SSA and SA have generated huge datasets to complement the on-going effort in different projects (Walker and Alwang 2015). By integrating all these sources of information (both primary and secondary), ICRISAT has estimated extent of adoption of improved cultivators and probable research lags under five mandate crops in different countries. The crop-wise estimations were summarized in the annexure Table 4 respectively.

8.5 Construction of applicability matrix

In the absence of large historical datasets across countries, expert judgements are the main tools we have to rely on to estimate the applicability of sorghum technology developed at particular production environment to other PEs or applicability of particular sorghum technology across homogenous zones. Similar to the procedure utilized for the capacity levels, in a stepwise procedure, these judgements were validated using multiple discussion rounds with experts from different zones and from different backgrounds (economists, breeders and agronomists) which were along the process backed with available data from various countries. This process made sure that estimates are consistent across countries as starting from pure expert estimates the rates given were cross-checked against available data for adjustments. The information on national level multi-location trials (AICSIP in case of India), international trials (ISVHAT) etc. were used for judging the performance of improved sorghum technology and arriving the consensus. Based on those adjustments the relativities were revisited and it was made sure that these are still in line with the real picture on the ground.

Similarly, the sorghum scientists in the African locations (both in ESA and WCA) were contacted through series of Skype calls, telephonic discussions and follow-up visits. This massive effort led to derivation of applicability matrix among the thirteen sorghum production environments identified for the present study (see Table 12). The applicability index value ranges between 0 and 1. This value indicates how the varieties/hybrids developed for one particular production domain is likely to outperform than the best local variety in each of the other production domains. The applicability value become 'zero' when a particular cultivar/hybrid developed for specific production domain cannot be grown or adopted in any other crop production domains. In the absence of applicability, a specific technology generated in a particular production environment could able to generate only direct welfare benefits. The spillover benefits of that technology will become zero.

8.6 Estimation of unit cost reductions

K_{yft} is the cost reducing effect from research in country 'y' in country 'f' in year't'. For the country where the research takes place is the direct effect of the research; for the remaining countries (which are producing or consuming the commodity) it will be spillover effects of research. The present study has assumed a 10% reduction in the cost of sorghum production with increased yield due to access to improved sorghum technology. Sorghum FAO prices (2008) available for respective targeted countries were used for estimating the potential unit cost reductions due to applicability of improved sorghum technology in different production environments. Table 11 summarizes the 2008 FAO prices of sorghum in different study countries.

8.7 Price elasticity of demand and supply

The first step in determining elasticities was a literature search related to sorghum. In some cases it was possible to find the estimates of direct elasticities for some commodities and countries from FAO or World Bank data. For the present study, the estimates for all countries were adopted from IFPRI-IMPACT model (see Table 11).

Assumptions underlying this framework are often simple and, are usually clearly identified. It is also assumed that supply shifts resulting from research affect neither the prices of other commodities or services, nor the macro-economic variables such as exchange and employment. World price effects are accommodated for commodities experiencing technological change. However linear demand and supply schedules are assumed along with parallel supply shifts resulting from research. The model assumes static demand and abstract distortions caused by government taxes and subsidies. Appendix Table A4 illustrates the country-wise data on NARS Strength, adaptive and research capacities and extent of adoption of improved cultivars of sorghum used in the subsequent analysis.

The details of production proportions across different sorghum producing climates or homogenous production environments are summarized in Figure 12. It is clear from the figure that sorghum can be grown broadly in six major climatic conditions in the world. Among the six climates, Warm tropics dryland alone contributes more than 50% of the global production. It is followed by Warm tropics sub-humid (24%) and temperate drylands (10%). These three environments put together are supplying nearly 85% of the world sorghum production. So, the present study has included these environments while updating the homogenous PEs.

Country/Region	Production[1] '000 tons	Consumption[1] '000 tons	Prices[2] (USD/ton)	Supply Elasticity[3]	Demand Elasticity[3]
India	7341.57	7316.33	198	0.53	0.46
China PDR	2356.98	2496.00	217	0.43	0.26
Pakistan	167.53	167.67	177	0.43	0.33
Other S & SEA	72.74	93.16	200	0.41	0.49
Other developing	24.36	796.66	200	0.42	0.49
Sudan	4776.00	3431.33	330	0.53	0.50
Ethiopia	2228.96	2230.33	447	0.53	0.50
Tanzania	804.19	780.33	280	0.77	0.67
Uganda	448.33	531.33	280	0.77	0.67
South Africa	177.33	339.67	215	0.67	0.47
Mozambique	163.18	187.00	175	0.70	0.63
Rwanda	193.10	218.00	186	0.77	0.63
Other ESA	519.79	772.88	280	0.42	0.67
Nigeria	9367.33	9371.67	371	0.65	0.68
Burkina Faso	1525.28	1557.33	226	0.53	0.50
Niger	952.67	874.00	155	0.53	0.50
Mali	766.53	698.33	198	0.53	0.50
Chad	617.57	568.33	340	0.53	0.50
Cameroon	554.49	527.67	270	0.74	0.68
Ghana	258.28	326.33	515	0.74	0.68
Senegal	121.90	123.67	340	0.74	0.68
Togo	212.50	212.33	630	0.74	0.68
Other WCA	395.90	406.67	340	0.42	0.34
Egypt	861.28	861.00	265	0.63	0.34
Yemen PDR	471.83	498.67	650	0.63	0.34
Saudi Arabia	231.54	231.54	458	0.63	0.34
Other WANA	35.02	79.35	458	0.63	0.34
Mexico	5748.61	8256.33	208	0.72	0.37
Argentina	2672.36	2136.00	124	0.77	0.40
Brazil	1522.07	1468.67	53	0.72	0.35
Bolivia	270.33	264.33	53	0.72	0.35
Uruguay	102.92	105.67	200	0.70	0.42
Venezuela	450.64	451.33	253	0.70	0.42
Other C &SA	653.53	813.00	149	0.70	0.42
USA	9882.72	4826.33	126	0.60	0.51
Australia	1741.86	1814.00	217	0.70	0.44
France	285.81	249.33	207	0.86	0.52
Italy	200.03	305.67	195	0.86	0.52
Canada	0.00	4.00	195	0.60	0.47
Other developed	73.51	1837.00	220	0.65	0.47

Table 11. Minimum dataset requirements for sorghum spillover estimation.

[1] 2008-10 mean collected from FAOSTAT, 2012; [2] FAO 2008 Prices; [3] Adopted from IFPRI-IMPACT model

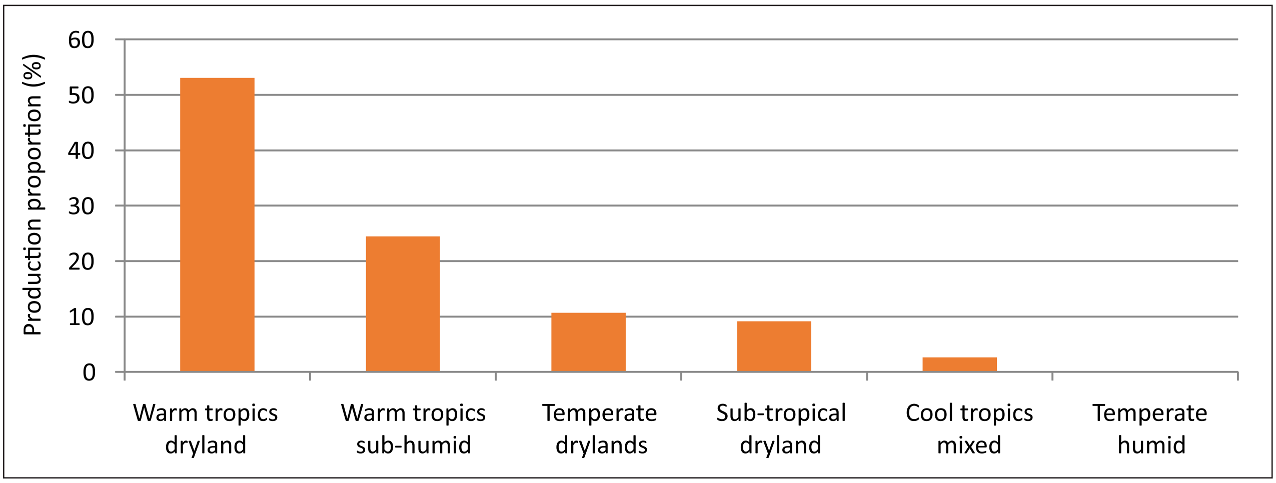

Figure 12. Production proportions across different sorghum growing climates.

Figure 13 presents the shares of production portions across the 13 updated homogenous research domains in the world. The single largest domain with nearly a 25% share in production was Research domain 13. Research domains 6 and 7 occupy the next places with 20 and 15% respectively. All the remaining research domains contribute less than 10% to the total production. The details of country-wise production proportions for each Research domain are summarized in appendix Table A1. Similarly, the impact of various improved cultivars of sorghum on yield gains, that has been assessed in different studies in South Asia and Africa are summarized in appendix Table A3.

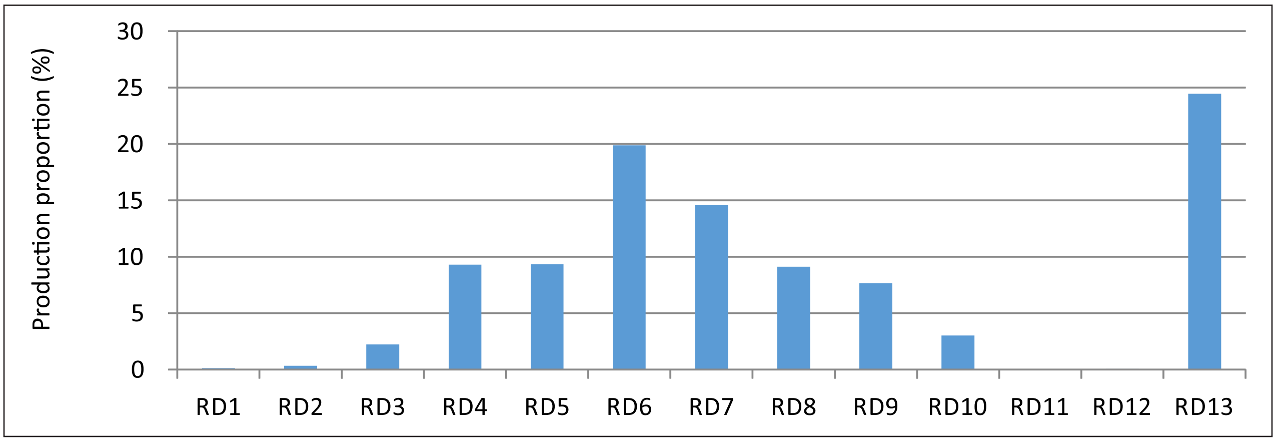

Figure 13. Production proportions across research domains.

Table 12. Applicability matrix (C matrix).

Research Domain name	RD1	RD2	RD3	RD4	RD5	RD6	RD7	RD8	RD9	RD10	RD11	RD12	RD13
Cool tropics mixed, < 90 days (RD1)	1	0	0	0	0	0	0	0	0	0	0	0	0
Cool tropics mixed, 90-119 days (RD2)	0	1	0	0	0	0	0	0	0	0	0	0	0
Cool tropics mixed, 120-149 days (RD3)	0	0	1	0	0	0	0	0	0	0	0	0	0
Warm tropics drylands, < 90 days (RD4)	0.6	0.6	0.6	1	0.3	0.2	0.2	0.5	0	0	0	0	0.1
Warm tropics drylands, 90-119 days (RD5)	0.2	0.3	0.3	0.4	1	0.6	0.5	0.2	0.2	0.3	0.3	0	0.4
Warm tropics drylands, 120-149 days (RD6)	0.1	0.2	0.2	0.3	0.5	1	0.6	0.1	0.1	0.2	0	0	0.5
Warm tropics drylands, > 150 days (RD7)	0	0	0.1	0.2	0.4	0.5	1	0.2	0	0	0	0	0.6
Subtropical drylands, > 150 days (RD8)	0	0	0	0	0.1	0.2	0.2	1	0.6	0.7	0	0	0
Temperate drylands, < 90 days (RD9)	0	0	0	0	0.3	0.2	0.1	0.4	1	0.3	0	0	0
Temperate drylands, 90-119 days (RD10)	0	0	0	0.5	0.4	0.2	0.1	0.7	0.4	1	0	0	0
Temperate humid, 90-119 days (RD11)	0	0	0	0	0	0	0	0	0	0	1	0	0
Temperate humid, 120-149 days (RD12)	0	0	0	0	0	0	0	0	0	0	0	1	0
Warm tropics sub-humid, > 150 days (RD13)	0	0	0	0.1	0.3	0.4	0.6	0	0	0	0	0	1

The research applicability matrix or 'C' matrix developed across 13 research domains is summarized in Table 12. This was developed in close collaboration with bio-physical scientists, especially those who were working on sorghum crop improvement in the major regions of ICRISAT (Asia, ESA and WCA). Repeated iterations were conducted to obtain those indices while maintaining a clear understanding of the various issues in the ACIAR model. However, the general perception of bio-physical scientists was that the applicability of materials from Asia to ESA was relatively high when compared to WCA. This is because of the nature of the endosperm consumption preferences and photo-sensitivity issues. But, they agreed that there were huge spillover applications within each region. There was large history of evidence about the transfer of research materials from Asia to Africa and vice-versa (see appendix Table A2). On the other hand, the spillover transfers from ESA to WCA and vice-versa were minimal or almost negligible.

The details of unit cost reduction in improved sorghum technologies in India and Africa are summarized in Tables 13 and 14 respectively. These evidences were documented by ICRISAT through conduct of various technology adoption and impact studies in India and sub-Saharan Africa. The results aptly prove that the extent of unit cost reduction ranges from 20-40% in different states in India. Deb et al. 2005 also established the relationship between the adoption of improved cultivars and grain yield instability in respective states in India. Similarly, the studies carried out in Cameroon and Chad (WCA Region) indicated huge unit cost reductions of up to 25% due to adoption of sorghum improved technologies, especially S 35.

Table 13. Unit cost reductions in improved sorghum technologies in India, 1971-95

	Average real cost (Rs per ton[1])			Cost reduction (%) compared to the early 1970s	
States	Early 1970s[2]	Early 1980s[3]	Early 1990s[4]	Early 1980s	Early 1990s
Andhra Pradesh	270	NA[5]	286	NA	-6
Karnataka	224	192	231	14	-4
Madhya Pradesh	223	169	208	24	7
Maharashtra	253	188	153	25	40
Rajasthan	309	264	195	14	37

Source: Bantilan et al. 2004; Deb et al. 2005;

1. All costs are real costs of production. For Rajasthan, the real cost is computed on the basis of 1992 prices and for all the other states it is based on 1989 prices.
2. Early 1970s indicate for Andhra Pradesh (average of 1973-74), Karnataka (average of 1972-74), Madhya Pradesh (1976), Maharashtra (average of 1972-74) and Rajasthan (average of 1972-74).
3. Early 1980s indicate for Karnataka (average of 1981-83), Madhya Pradesh (average of 1981-83), Maharashtra (average of 1981-83) and Rajasthan (average of 1981-83).
4. Early 1990s indicate for Andhra Pradesh (average of 1994-95), Karnataka (1991), Madhya Pradesh (average of 1994-95), Maharashtra (1995) and Rajasthan (1992).
5. NA = Not Available.

Source: Estimated from CACP Reports, Ministry of Agriculture, GOI.

Table 14. Impacts of improved sorghum cultivar S 35 in Cameroon and Chad, 1995.

Country	Region	Unit variable costs (CFA Francs/t)		Unit cost reduction (%)
		Local	Improved	
Cameroon	Mayo-Sava	77500	57700	26
Cameroon	Diamare	63500	58900	7
Cameroon	Mayo-Danay	50000	49300	1
Cameroon		63161	55607	12
Chad	Guera	89296	65825	26
Chad	Mayo-Kebbi	45994	37903	18
Chad	Chari-Baguirmi	67765	49947	26
Chad		80805	60817	25

Source: Yapi et al. 1999a & b

Kumara Charyulu et al. 2014 also attempted to estimate the impact of adoption of sorghum improved cultivars on unit cost of production (1993 real prices) between 1986 and 2008 across major sorghum growing states in India. The study has concluded that the unit cost reduction was visible up to early 2000s from 1986-87. But, during the late 2000s the unit of production went up significantly when compared to 1986-87. This may be one of the reasons that farmers are moving out of sorghum crop in many states in India.

Assumptions in the model

The following assumptions were considered for different parameters while estimating the ex ante global sorghum spillovers benefits across countries and regions.

Parameter	Assumption
Baseline sorghum production and consumption levels	Country-level FAOSTAT triennium average of 2008-10 data was used as a baseline
Innovative research	It will be carried out by ICRISAT as International Public Good (IPG) nature of research with global research investments
Research focus	Entire ICRISAT sorghum research keeps focus (100%) on one specific research domain
Real (business as usual) world	Situation where actual adaptive capacity, adoption and 10% unit cost reduction on FAO 2008 price on respective country-wise were estimated and used.
Ideal world	Situation where adaptive capacity=1 (means 100%), adoption=1 (means 100%) and 10% unit cost reduction on FAO 2008 price on respective country-wise were assumed.
ICRISAT Focus benefits	It includes the gross benefits derived from Asia, ESA and WCA regions only
ROW benefits	Gross benefits derived from Rest of the World (total benefits exclude of Asia, ESA and WCA regions)
Total benefits	Sum of ICRISAT focus benefits plus ROW benefits
Costs of undertaking sorghum research at ICRISAT	Costs of undertaking sorghum research at ICRISAT were not included in this study
Period of study benefits estimated	30 years of research benefits assumed i e, from 2013 to 2043
Research lag assumed	12 years (No of years from start of the project to start of adoption)
Welfare benefits	Sum of both producer and consumer surplus. These are gross benefits derived in the model.

9. Research results and discussions

Multi region, single commodity economic surplus model adapted and modified from ACIAR was used for quantification of ICRISAT sorghum spillover benefits globally. The sorghum research domains defined in 1992 (eight) were updated (to 13) using GIS tools. The details about research domain wise global sorghum cropped area coverage are furnished in Table 10. In terms of sorghum cropped area, RD 13 is the biggest domain followed by RD 6 and RD 4. The estimation of gross welfare benefits (M USD) across research domains for each individual research focus are summarized in Table 15. It is assumed that ICRISAT is undertaking the innovative research at a higher level with global research investments and sharing those intermediate materials across the targeted regions and countries. These results were obtained under real world scenario (where the actual adaptive and adoption levels for each country are applied with 10% unit cost reduction on 2008 FAO prices) conditions with research applicability between research domains. The benefits are arranged in descending order based on ICRISAT focus (which includes benefits from Asia, ESA and WCA only) values. Research domain 6 (Warm tropics drylands, 120-149 days) stood on the top with 1095 M USD (ICRISAT focus) and 1793 M USD (total benefits) between 2013 and 2043. It was followed by Research domains 7, 5 and 13 respectively. The top three welfare benefits in research domains were observed only in one agro-climate i e, Warm tropics drylands with different LGPs. These results clearly conclude that RD 6 is a high payoff research domain for ICRISAT focus sorghum research. It is closely followed by RD 7 and RD 5.

Similarly the estimation of gross welfare benefits under real world scenario without applicability (where applicability matrix contains zero values) across research domains for each individual research focus is presented in Table 16. The total and ICRISAT focus benefits have gone down significantly across research domains because only the direct benefits were considered in targeted regions. Research domains 6 and 7 were on the top of the order respectively. But, total and ICRISAT focus research benefits had declined to 40 and 55% respectively in the case of Research domain 6. Once again the results clearly confirm that RD 6 is a high payoff domain even though applicability was not considered.

The details of gross welfare benefits across different Research domains with and without applicability conditions are summarized in Figure 14 under real world scenario. Among all Research domains, RD 8 showed the highest (M USD 2166) total research benefits. But, its ICRISAT focus benefits (M USD 485) are lower than those of RD 6, 7 and 5. However, the gross welfare benefits are the same in RD 3, 2, 12, 1 and 11 both with and without the applicability criterion (Figure 14). In absolute terms, RD 5 exhibited the highest spillover benefits (M USD 1577) followed by RD 10 (M USD 1479) and RD 8 (M USD 1175) (Table 17 and Figure 15). RD 6 and RD 7 have nearly 40% benefits as direct benefits and the remaining 60% as indirect benefits (spillovers). To derive maximum spillover benefits or applicability of sorghum research materials across research domains, more research focus should be concentrated on RD 5.

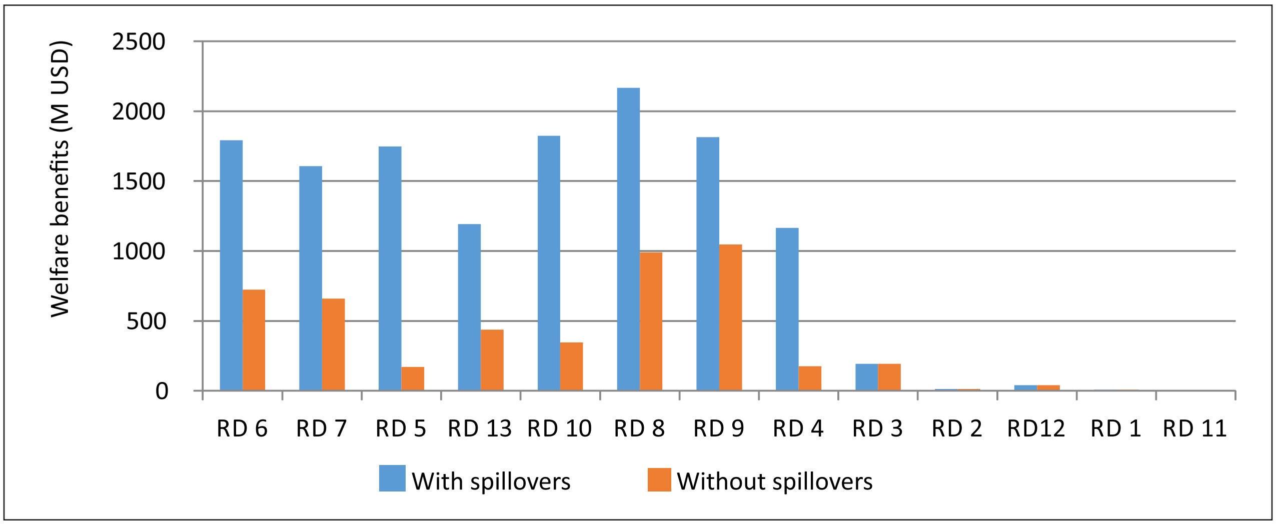

Figure 14. Welfare benefits across research domains (with Vs without applicability) in real world.

Table 15. Welfare benefits (with spillovers) (M USD) from individual research focus in real world*.

RD no.	Research Domains	Area ('000 ha)	Production ('000 tons)	Total[c]	ICRISAT –focus[a]	Asia	ESA	WCA	ROW[b]
RD 6	Warm tropics drylands, 120-149 days	8500	6780.5	1793.1	1094.9	900.1	86.1	108.7	698.3
RD 7	Warm tropics drylands, > 150 days	5600	4971.3	1606.2	898.2	703.7	95.6	98.9	708.0
RD 5	Warm tropics drylands, 90-119 days	4200	3184.4	1747.0	874.4	686.4	86.0	102.1	872.6
RD 13	Warm tropics sub-humid, > 150 days	8700	8342.7	1192.7	770.2	554.7	115.9	99.6	422.4
RD 10	Temperate drylands, 90-119 days	600	1031.1	1823.8	538.3	476.8	24.6	37.0	1285.5
RD 8	Sub-tropical drylands, > 150 days	2300	3110.7	2166.4	485.6	451.3	14.5	19.8	1680.8
RD 9	Temperate drylands, < 90 days	1700	2603.6	1815.4	383.0	348.2	12.3	22.5	1432.4
RD 4	Warm tropics drylands, < 90 days	8300	3169.6	1164.1	359.2	251.6	55.1	52.5	804.9
RD 3	Cool tropics mixed, 120-149 days	400	752.4	193.6	16.6	0.0	16.5	0.0	177.0
RD 2	Cool tropics mixed, 90-119 days	200	111.9	12.6	5.3	0.0	5.3	0.0	7.3
RD12	Temperate humid, 120-149 days	18	18.4	40.5	3.8	3.8	0.0	0.0	36.8
RD 1	Cool tropics mixed, < 90 days	100	36.6	8.1	0.8	0.0	0.8	0.0	7.3
RD 11	Temperate humid, 90-119 days	1	0.1	0.1	0.0	0.0	0.0	0.0	0.1

* Real World defined as the condition where actual adaptive capacity, adoption and 10% unit cost reduction on FAO 2008 prices on the respective country-wise estimated

[a] ICRISAT Focus includes benefits from Asia, ESA and WCA regions

[b] ROW: Rest of the World

[c] Total (gross) benefits includes ICRISAT Focus and ROW for the period between 2013 and 2043.

Source: Author's own estimates of this paper

Table 16. Welfare benefits (without spillovers) (M USD) from individual research focus in real world*.									
RD no.	Research Domains	Area ('000 ha)	Production ('000 tons)	Total[c]	ICRISAT –focus[a]	Asia	ESA	WCA	ROW[b]
RD 6	Warm tropics drylands, 120-149 days	8500	6780.5	724.5	601.4	553.7	6.3	41.4	123.1
RD 7	Warm tropics drylands, > 150 days	5600	4971.3	660.0	368.5	317.4	23.5	27.6	291.6
RD 13	Warm tropics sub-humid, > 150 days	8700	8342.7	436.2	274.9	128.4	92.0	54.5	161.3
RD 10	Temperate drylands, 90-119 days	600	1031.1	344.6	228.1	228.0	0.0	0.0	116.5
RD 9	Temperate drylands, < 90 days	1700	2603.6	1047.8	111.0	109.6	0.5	0.9	936.8
RD 5	Warm tropics drylands, 90-119 days	4200	3184.4	169.5	81.5	31.5	18.5	31.5	88.1
RD 4	Warm tropics drylands, < 90 days	8300	3169.6	175.2	73.0	31.5	18.2	23.3	102.2
RD 8	Sub-tropical drylands, > 150 days	2300	3110.7	990.6	56.4	50.1	5.5	0.8	934.2
RD 3	Cool tropics mixed, 120-149 days	400	752.4	193.6	16.6	0.0	16.5	0.0	177.0
RD 2	Cool tropics mixed, 90-119 days	200	111.9	12.6	5.3	0.0	5.3	0.0	7.3
RD12	Temperate humid, 120-149 days	18	18.4	40.5	3.8	3.8	0.0	0.0	36.8
RD 1	Cool tropics mixed, < 90 days	100	36.6	8.1	0.8	0.0	0.8	0.0	7.3
RD 11	Temperate humid, 90-119 days	1	0.1	0.1	0.0	0.0	0.0	0.0	0.1

* Real world defined as the condition where adaptive capacity, adoption and 10% unit cost reduction on FAO 2008 prices on the respective country-wise estimated

[a] ICRISAT focus includes benefits from Asia, ESA and WCA regions

[b] ROW: Rest of the World

[c] Total (gross) benefits includes ICRISAT focus and ROW for the period between 2013 and 2043.

Source: Author's own estimates of this paper

Table 17. Total direct and indirect (spillover) benefits (M USD) for individual research focus under real world.				
RD no.	Research Domains	Total benefits*	Direct benefits	Spillover benefits
RD 6	Warm tropics drylands, 120-149 days	1793.1	724.5	1068.6
RD 7	Warm tropics drylands, > 150 days	1606.2	660.0	946.2
RD 5	Warm tropics drylands, 90-119 days	1747.0	169.5	1577.5
RD 13	Warm tropics sub-humid, > 150 days	1192.7	436.2	756.5
RD 10	Temperate drylands, 90-119 days	1823.8	344.6	1479.2
RD 8	Sub-tropical drylands, > 150 days	2166.4	990.6	1175.8
RD 9	Temperate drylands, < 90 days	1815.4	1047.8	767.6
RD 4	Warm tropics drylands, < 90 days	1164.1	175.2	988.9
RD 3	Cool tropics mixed, 120-149 days	193.6	193.6	0.0
RD 2	Cool tropics mixed, 90-119 days	12.6	12.6	0.0
RD12	Temperate humid, 120-149 days	40.5	40.5	0.0
RD 1	Cool tropics mixed, < 90 days	8.1	8.1	0.0
RD 11	Temperate humid, 90-119 days	0.1	0.1	0.0

Total benefits = Direct benefits + spillover benefits (indirect benefits)
* benefits are derived for the period 2013 to 2043 (30 years)
Source: Author’s own estimates of this paper

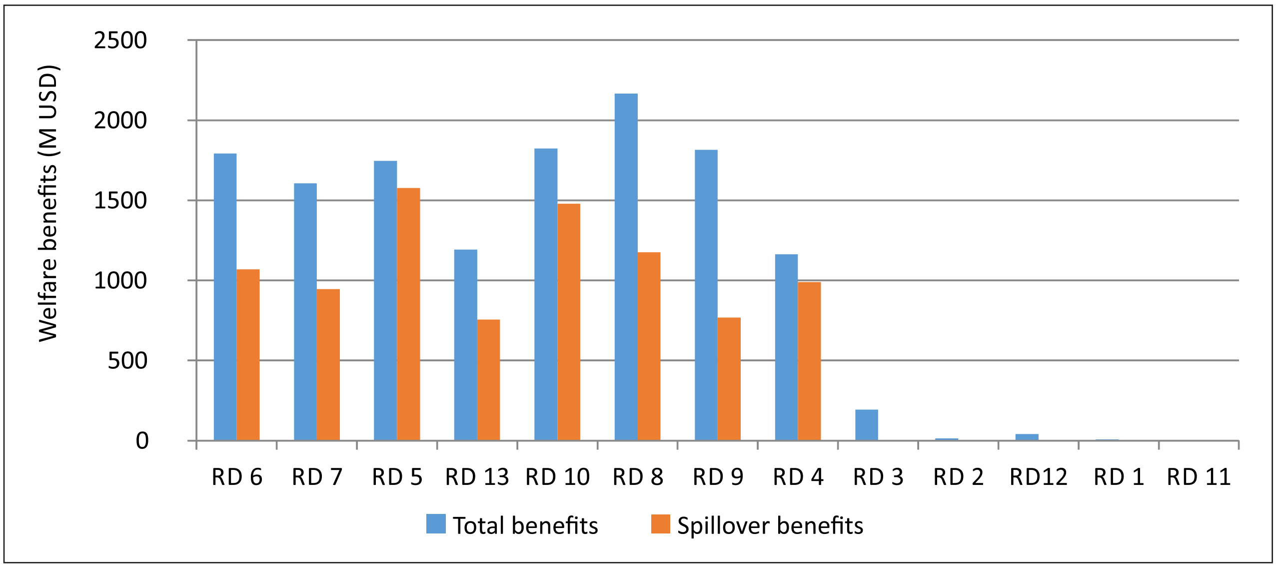

Figure 15. Total and spillover (indirect) benefits across research domains in the real World.

The details of the top five ICRISAT focuses and their relative benefits to the Rest of the World (ROW) are summarized in Figure 16. Unlike other crops, sorghum is a global crop and grown in all the regions of the world. In terms of total benefits, RD 10 secured the top position among the five research focuses. But, the share of ICRISAT Focus is lower and the maximum benefits are reaching the Rest of the World. Even though the ROW regional area share was lower, their contribution to global production was much higher. Among all the five research focuses, ROW is benefitting as much as the ICRISAT focus. ICRISAT sorghum research program wants to derive maximum welfare benefits, we need to keep our research focus either on RD 6 or 7.

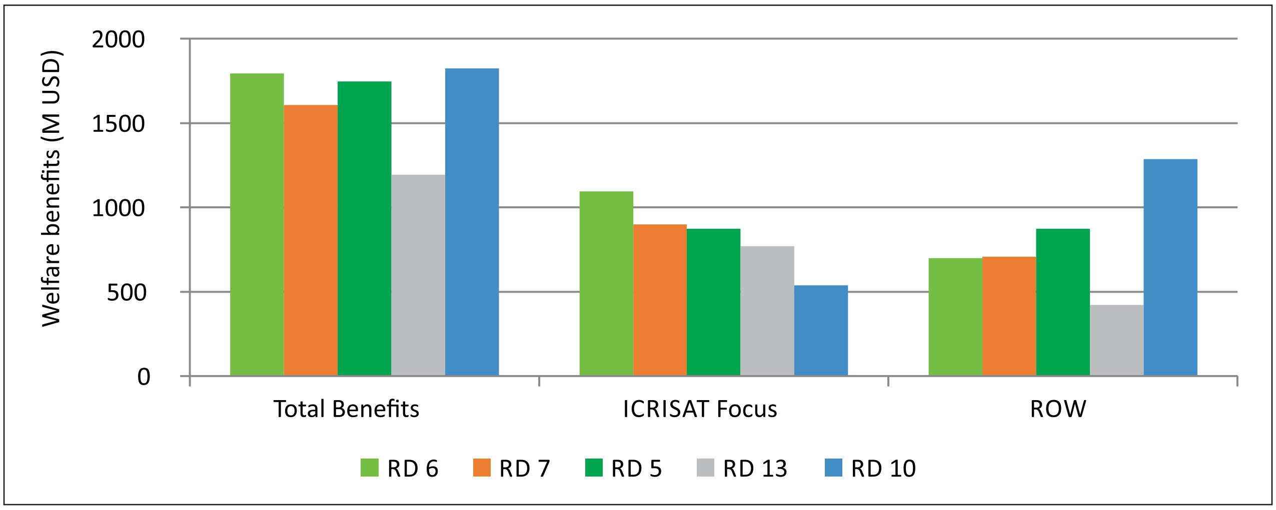

Figure 16. Total benefits among the top five ICRISAT research focuses in the real world.

The region-wise break up of gross welfare benefits are presented in Figure 17 for the top five research focuses under a Real world scenario. The results were clearly indicated that the highest benefits were derived in Asia followed by the WCA and ESA regions. More than 70-90% of the welfare benefits are accruing in Asia alone, especially in India. This may be because of the quicker and higher adoption rate of improved cultivars in India when compared to the WCA and ESA regions. Lack of NARS strategic and adaptive capacities may be another reason for lower research benefits in those regions.

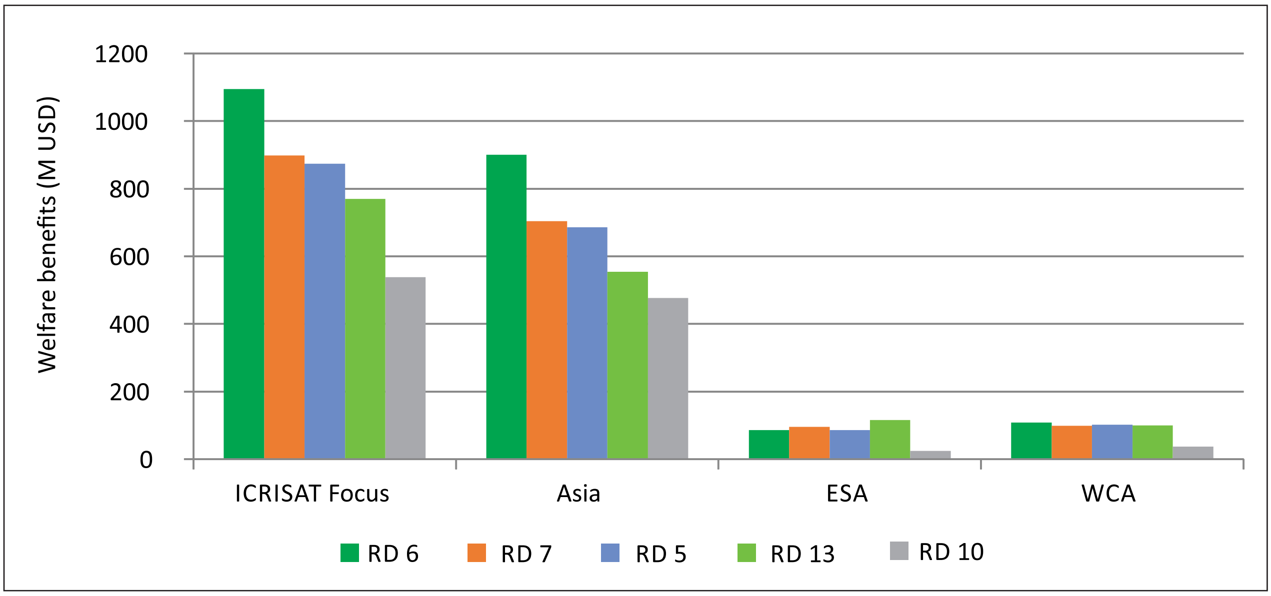

Figure 17. Region-wise welfare benefits under the top five ICRISAT research focuses in the real world.

The country-wise gross welfare benefits are estimated under high payoff (RD 6) research focus and summarized in Table 18. These results have been obtained with research applicability criteria and a Real world scenario. Among the four regions, Asia got the lion's share in the total benefits. Within Asia, nearly 94% benefits were accrued to India and only 7% to China. ROW secured the second highest research benefits under high-pay off research focus. Mexico (56%), USA (24%) and Brazil (5%) are the major beneficiaries in the ROW region. However, these countries were not belonging to ICRISAT focus countries. The research benefits were marginal in both the African (WCA and ESA) regions. Nigeria and Mali were the dominant beneficiaries in the WCA region while Ethiopia, Tanzania, Sudan and Uganda are the top recipients of spillovers in the ESA region.

The reasons for low marginal benefits observed in both African regions were: a) low adaptive capacity of NARS to absorb the innovative research capacity developed and provided by ICRISAT b) extent of adoption of improved cultivars were very low. Even though the applicability of research technology is very high between these regions, both these parameters limiting to reach the full potential available in those regions. To fully understand the influence of these parameters in the spillover estimation, a sensitivity analysis was undertaken.

Table 18. Country-wise welfare benefits shares under high-payoff research focus.

South Asia region (900.07 M USD)		ESA region (86.14 M USD)	
Country	Benefits (% share)	Country	Benefits (% share)
India	838.15 (93.1)	Ethiopia	26.8 (31.1)
China	59.66 (6.6)	Tanzania	17.7 (20.5)
Pakistan	1.21 (0.1)	Sudan	14.8 (17.2)
Others	1.05 (0.1)	Uganda	10.7 (12.5)
-	-	South Africa	6.8 (7.9)
-	-	Rwanda	3.1 (3.6)
-	-	Mozambique	1.5 (1.7)
		Others	4.7 (5.4)
WCA region (108.65 MUSD)		**ROW region (698.28 M USD)**	
Country	Benefits (% share)	Country	Benefits (% share)
Nigeria	53.2 (48.9)	Mexico	388.1 (55.58)
Mali	24.3 (22.4)	USA	168.9 (24.19)
Burkina Faso	7.5 (6.9)	Brazil	36.2 (5.18)
Cameroon	6.3 (5.8)	Australia	32.8 (4.70)
Chad	5.8 (5.4)	Egypt	15.7 (2.24)
Ghana	3.1 (2.9)	Saudi Arab	11.5 (1.65)
Togo	2.5 (0.9)		

Sensitivity Analysis

A sensitivity analysis was performed to see the extent of influence of different parameters on ex ante welfare estimation under high-payoff research focus (RD 6) with the research applicability criterion. Three additional scenarios were assumed along with Real world estimations and the results were compared for their extent of sensitivity. The results clearly showed that the influence of different parameters is quite significant in different regions. The details of the three additional scenarios are as follows:

1. When the adaptive capacities of all the countries are assumed as equal and one (Adaptive capacity = 1)
2. When the adoption rate of improved cultivars are assumed as equal and one among all the countries (Adoption rate=1)
3. When adaptive capacity and rate of adoption are assumed as equal to one (it is called ideal world) (Adaptive capacity = 1 and Adoption rate = 1)

For further clarity in the analysis, the benefit patterns were analyzed under different research focuses in the Ideal world (when adaptive capacity and adoption rate are equal to one) scenario using both with and without spillovers criteria. The details of the results are summarized in Tables 19 and 20.

Table 19. Welfare benefits (with spillovers) (M USD) from individual research focus in the ideal world*.

RD no.	Research Domains	Production ('000 tons)	Total[c]	ICRISAT –focus[a]	Asia	ESA	WCA	ROW[b]
RD 6	Warm tropics drylands, 120-149 days	6780.5	4171.6	3113.5	997.5	712.7	1403.2	1058.1
RD 5	Warm tropics drylands, 90-119 days	3184.4	4122.7	2842.5	757.1	729.8	1355.6	1280.2
RD 7	Warm tropics drylands, > 150 days	4971.3	3906.0	2772.2	788.1	735.7	1248.4	1138.8
RD 13	Warm tropics sub-humid, > 150 days	8342.7	3604.8	2771.2	624.6	856.6	1289.9	833.7
RD 4	Warm tropics drylands, < 90 days	3169.6	2816.5	1570.1	285.5	550.8	733.8	1246.4
RD 10	Temperate drylands, 90-119 days	1031.1	2992.0	1289.0	506.1	286.8	496.1	1702.9
RD 8	Sub-tropical drylands, > 150 days	3110.7	2949.8	787.7	486.3	89.8	211.6	2162.1
RD 9	Temperate drylands, < 90 days	2603.6	2384.6	740.8	371.0	98.3	271.6	1643.8
RD 2	Cool tropics mixed, 90-119 days	111.9	43.5	34.3	0.0	34.3	0.0	9.2
RD 3	Cool tropics mixed, 120-149 days	752.4	251.8	30.0	0.0	29.9	0.1	221.8
RD 1	Cool tropics mixed, < 90 days	36.6	13.4	4.3	0.0	4.3	0.0	9.1
RD12	Temperate humid, 120-149 days	18.4	55.1	3.8	3.8	0.0	0.0	51.4
RD 11	Temperate humid, 90-119 days	0.1	0.2	0.0	0.0	0.0	0.0	0.2

* Ideal world defined as the condition where adaptive capacity =1, Adoption =1 and 10% unit cost reduction on FAO 2008 prices on the respective country-wise assumed

[a] ICRISAT Focus includes benefits from Asia, ESA and WCA

[b] ROW: Rest of the world

[c] Total (gross) benefits includes ICRISAT Focus and ROW for the period 2013-2043

Source: Author's own estimates of this paper

Table 20. Welfare benefits (without spillovers) (M USD) from individual research focus in the ideal world*.

RD no.	Research domains	Production ('000 tons)	Total[c]	ICRISAT –focus[a]	Asia	ESA	WCA	ROW[b]
RD 13	Warm tropics sub-humid, > 150 days	8342.7	1984.2	1513.9	152.8	631.6	729.6	470.3
RD 6	Warm tropics drylands, 120-149 days	6780.5	1387.0	1230.7	615.3	92.8	522.7	156.3
RD 7	Warm tropics drylands, > 150 days	4971.3	1187.8	810.1	352.6	165.1	292.4	377.7
RD 4	Warm tropics drylands, < 90 days	3169.6	949.6	728.3	35.1	331.6	361.6	221.3
RD 5	Warm tropics drylands, 90-119 days	3184.4	847.0	675.3	35.1	183.4	456.9	171.8
RD 10	Temperate drylands, 90-119 days	1031.1	348.1	228.1	228.0	0.0	0.0	120.0
RD 9	Temperate drylands, < 90 days	2603.6	1048.0	111.0	109.6	0.5	0.9	937.0
RD 8	Sub-tropical drylands, > 150 days	3110.7	1474.7	86.5	66.0	18.6	1.9	1388.2
RD 2	Cool tropics mixed, 90-119 days	111.9	43.5	34.3	0.0	34.3	0.0	9.2
RD 3	Cool tropics mixed, 120-149 days	752.4	251.8	30.0	0.0	29.9	0.1	221.8
RD 1	Cool tropics mixed, < 90 days	36.6	13.4	4.3	0.0	4.3	0.0	9.1
RD12	Temperate humid, 120-149 days	18.4	55.1	3.8	3.8	0.0	0.0	51.4
RD 11	Temperate humid, 90-119 days	0.1	0.2	0.0	0.0	0.0	0.0	0.2

* Ideal world defined as the condition where adaptive capacity =1, Adoption =1 and 10% unit cost reduction on FAO 2008 prices on the respective country-wise assumed

[a] ICRISAT focus includes benefits from Asia, ESA and WCA

[b] ROW : Rest of the world

[c] Total (gross) benefits includes ICRISAT focus and rest of the world for the period 2013-2043

Source: Author's own estimates of this paper

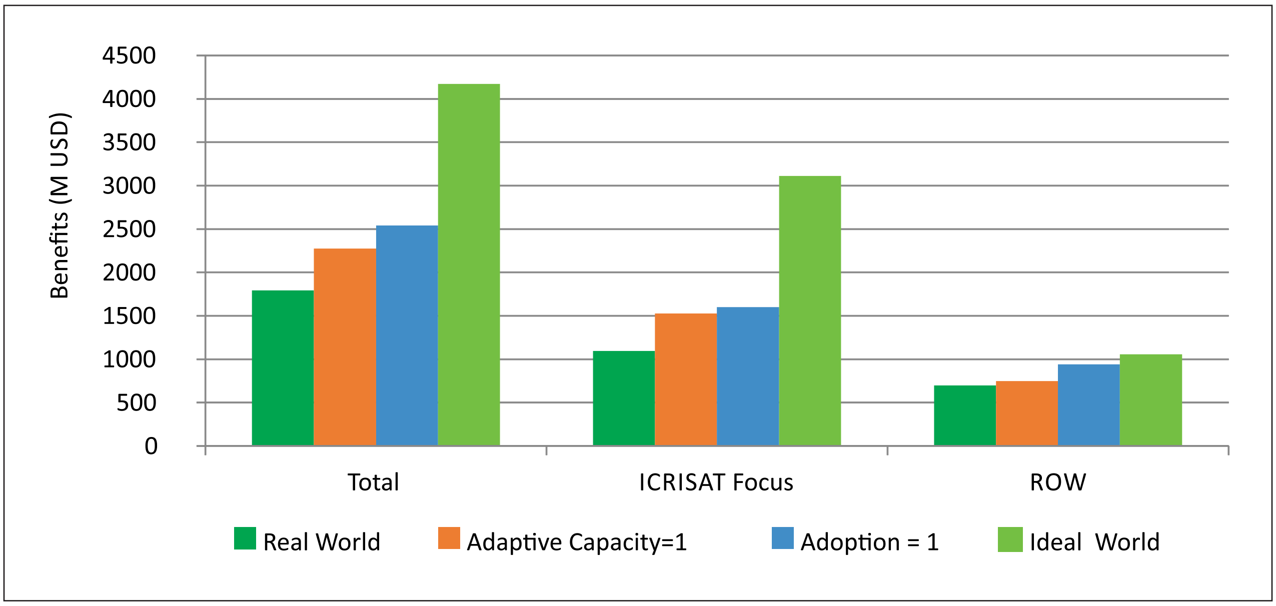

Figure 18. Welfare benefits under different scenarios in high-payoff (RD 6) research focus.

The distribution of welfare benefits among ICRISAT Focus and ROW under high-payoff research focus (RD 6) is summarized in Figure 18. There is a huge gap exists between real and ideal world scenarios in total benefits and ICRISAT Focus. In the case of ROW, the gap was marginal which clearly reveals better adaptive and adoption levels in the region. The welfare benefits for ICRISAT focus doubled with enhancement of NARS capacity and adoption rates in SSA and SA.

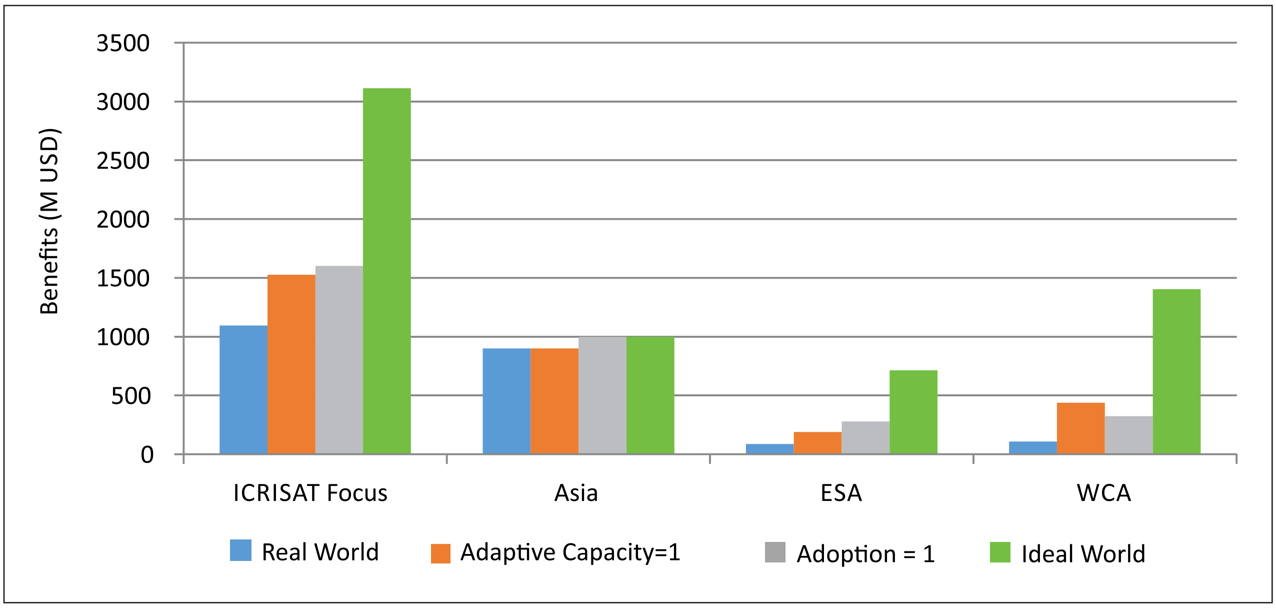

Figure 19. Region-wise welfare benefits under different scenarios (RD 6 research focus).

The region-wide distribution of welfare benefits under the high payoff zone (RD 6) is summarized in Figure 19. Among the three regions in ICRISAT Focus, Asia alone is contributing more than 80% of the total real benefits. However, the difference between the real and ideal world scenarios is marginal in Asia when compared with the other regions. The second highest welfare benefits were observed in the WCA region in the real world scenario. But, there is a huge gap between Real and Ideal world scenarios. This indicates the vast sorghum potential in the region when compared with other regions. If we do more research investments to improve the adaptive capacity and rate of adoption in WCA, the welfare benefits will go up nearly 13 times. The ESA region is the lowest beneficiary under the business-as-usual (real world) scenario, but has good scope for further improvement of sorghum in the region. While moving from a real to an ideal world scenario it was noticed that research benefits increased nearly eight times.

Country-wise welfare benefits under different scenarios (RD 6 research focus)

The details of the country-wise distribution of welfare benefits are furnished in Figures 20 to 23 respectively for the Asia, ESA, WCA and ROW regions under high-payoff research focus (RD 6) along with the spillover criterion. The country-wise distribution of welfare benefits in Asia is presented in Figure 20. Among the three major beneficiary countries in Asia, India got the lion's share (>90%) followed by China and Pakistan. There is a marginal difference in welfare benefits in India between the real and ideal world scenarios. This is because of India's high adaptive capacity as well as high adoption rate (nearly 80%). In the case of China, the research benefits are already in their peak (real and ideal are almost equal).

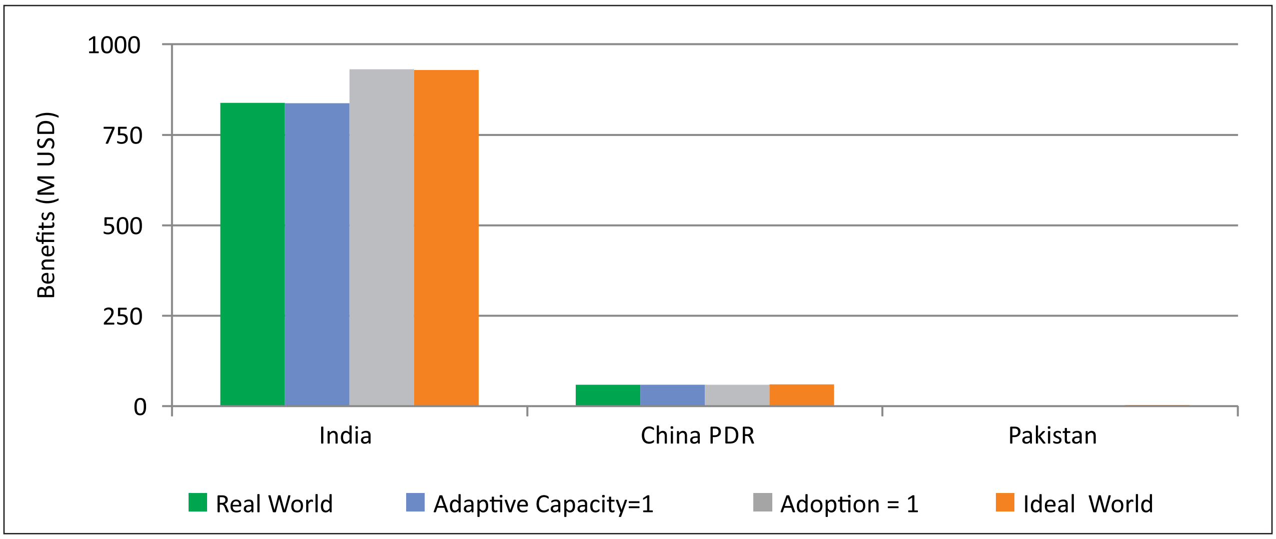

Figure 20. Country-wise distribution of welfare benefits in Asia (RD 6 research focus).

The spread of country-wise research benefits in the ESA region are summarized in Figure 21. Countries like Sudan, Ethiopia, Tanzania and Uganda were securing very marginal real research benefits when compared to the existing potential (ideal). Huge differences in welfare benefits between these two scenarios were observed in almost all the ESA countries. The main reasons were low adaptive capacities and adoption rates of improved cultivars in the region. Sudan and Ethiopia especially have exhibited huge scope for sorghum spread in these countries. If ICRISAT invest more on strengthening the NARS's research capacities and to improve the rate of adoption, Sudan alone can increase research benefits from 14.8 to 362.3 M USD (nearly 24 times). Similarly, Ethiopia could increase research benefits by nearly seven times.

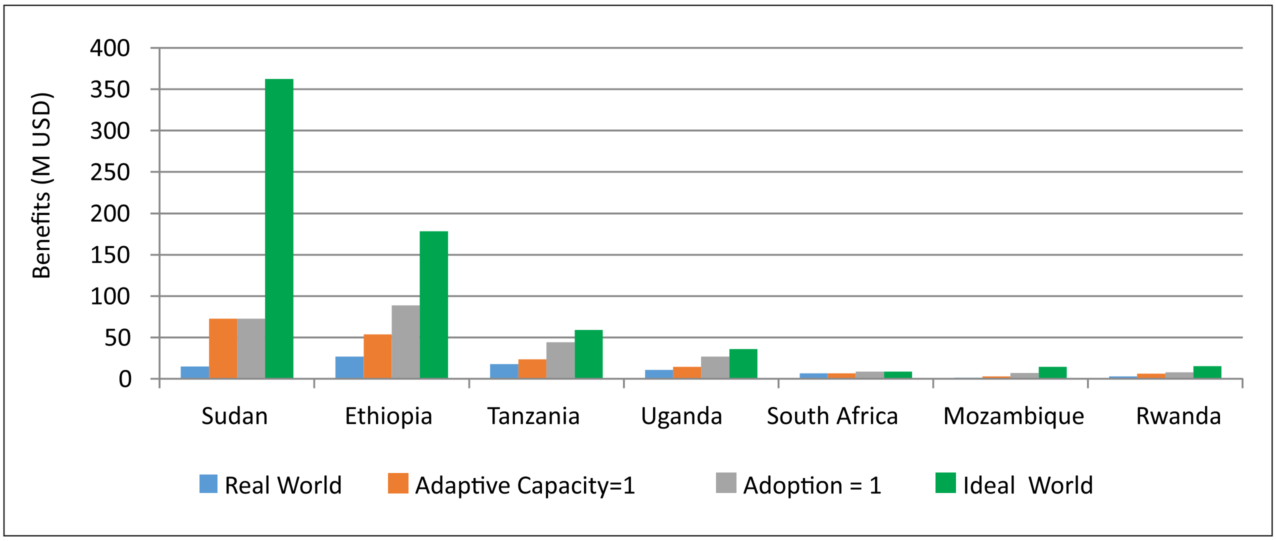

Figure 21. Country-wise distribution of welfare benefits in ESA (RD 6 research focus).

The breakup of country-wise research benefits in the WCA region is depicted in Figure 22. Nigeria, Burkina Faso, Mali, Chad and Cameroon are the major beneficiaries in the region in descending order. However, the real benefits received in the region were meagre when compared with its potential. Lack of NARS research capacity and availability of improved sorghum cultivars were the major constraints minimizing the research benefits. Among the different countries in the region, Nigeria and Burkina Faso have huge potential for derive sorghum technology adoption benefits. If we adopt institutional innovations and lift the constraint in these countries, the welfare benefits would go up by 16 and 24 times respectively for Nigeria and Burkina Faso. The research benefits have already been experienced in Chad and Cameroon through high adoption of S 35 improved cultivars (Yapi et al. 1999a & 1999b).

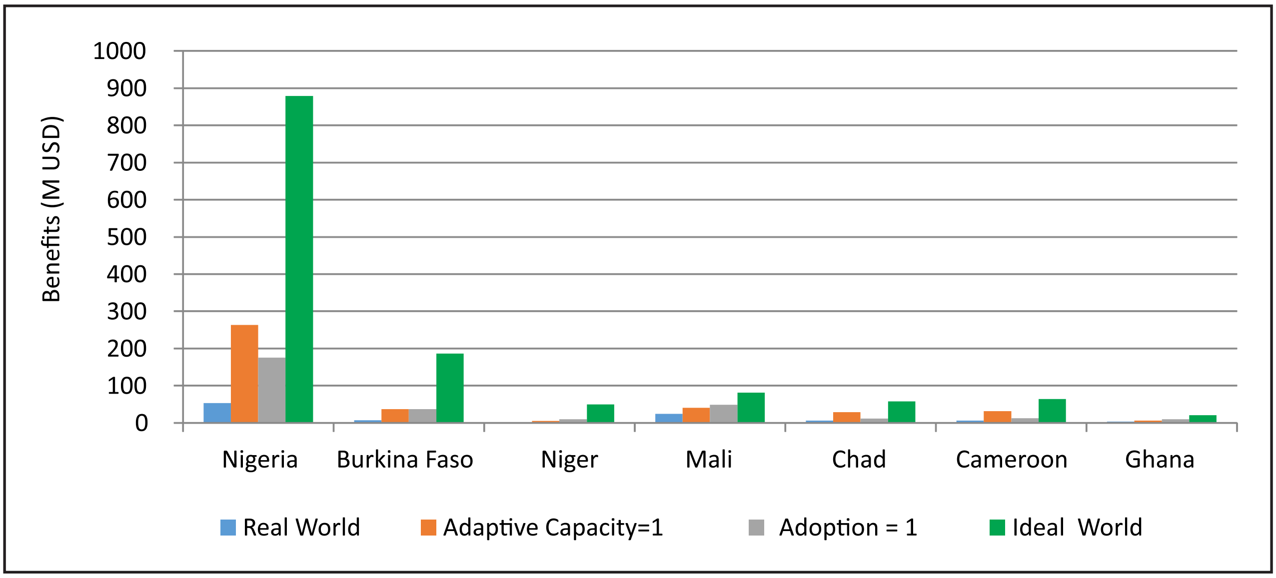

Figure 22. Country-wise distribution of welfare benefits in WCA (RD 6 research focus).

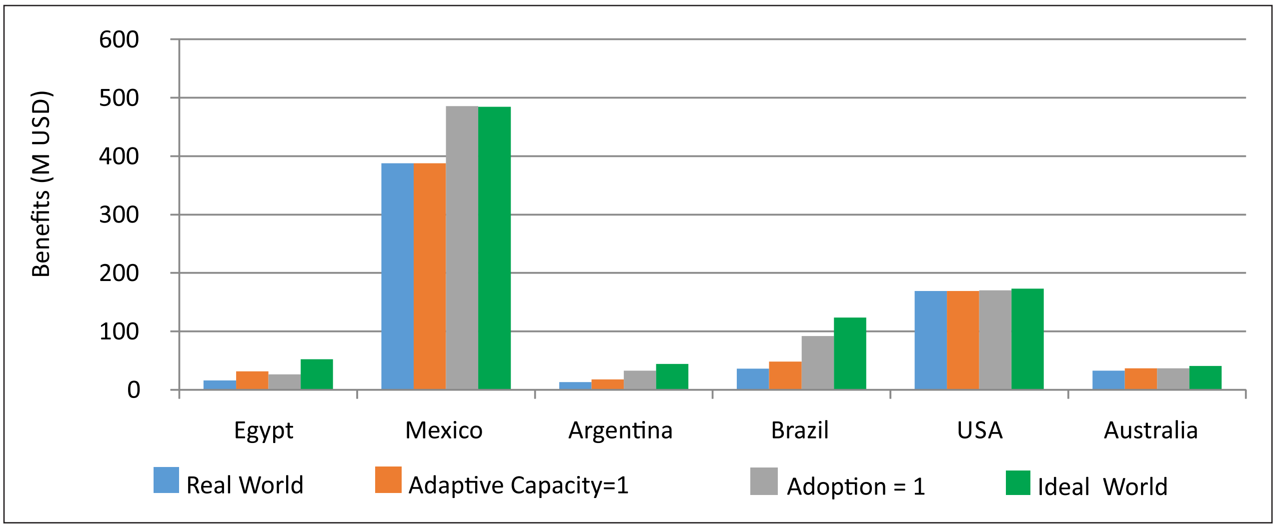

Figure 23. Country-wise distribution of welfare benefits in ROW (RD 6 research focus).

The details of country-wise research benefits in the ROW region are summarized in Figure 23. The major sorghum growing countries in the region are Mexico followed by USA, Brazil, Australia, Egypt and Argentina. All the countries in this region are realizing maximum research benefits because of high adaptive capacities and adoption rates when compared with other regions. There is a little scope for further increase in the benefits in Mexico and Brazil while they are almost saturated in the case of USA and Australia.

The detailed break-up of total spillover benefits under RD 6 research focus along with applicability criterion are summarized by country-wise in Table 21. Further, the split of both producer and consumer surpluses in the total economic surplus were also furnished. In case of Asia region, sorghum producers gained maximum benefits than consumers because the demand for consumption is low. In case of both ESA and ROW regions, the producer surplus is slightly higher than the consumer surplus. But in case of WCA region, consumer surplus is much higher than the producer surplus.

10. Implications on research prioritization

The results from this exercise clearly indicated that more than 50% of global sorghum production is contributed by Warm-tropics dryland environment (53%) followed by Warm-tropics sub-humid (24%) and Temperate drylands (10%). Across the 13 new research domains, Warm tropics sub-humid, > 150 days (RD 13) has the highest share of production (25%) followed by Warm tropics drylands, 120-149 days (RD 6) (20%) and Warm tropics drylands, > 150 days (RD 7) (15%). Multi-region, single commodity economic surplus model developed by ACIAR was adapted and modified to suit the needs of ICRISAT research on sorghum spillover estimation. As highlighted in the previous

Table 21. Break-up of economic surplus by country under RD 6 research focus.

Country	Economic surplus (USD M)	Producer surplus (USD M)	Consumer surplus (USD M)
India	838.15	728.47	109.67
China PDR	59.66	20.62	39.04
Pakistan	1.21	-0.18	1.39
Other S & SEA	1.05	0.81	0.25
Asia total	**900.07**	**749.71**	**150.36**
Sudan	14.82	-1.17	15.99
Ethiopia	26.80	15.67	11.13
Tanzania	17.70	12.33	5.37
Uganda	10.75	7.76	2.99
South Africa	6.84	4.49	2.36
Mozambique	1.47	0.92	0.55
Rwanda	3.09	1.80	1.29
ESA total	**86.14**	**44.70**	**41.44**
Nigeria	53.16	6.23	46.92
Burkina Faso	7.55	2.41	5.13
Niger	1.15	-0.51	1.65
Mali	24.28	17.90	6.39
Chad	5.83	0.70	5.13
Cameroon	6.33	1.71	4.62
Ghana	3.10	1.81	1.29
Senegal	0.93	0.32	0.61
Togo	2.54	0.78	1.76
WCA total	**108.65**	**32.51**	**76.14**
Egypt	15.65	7.08	8.57
Yemen PDR	2.88	1.31	1.57
Saudi Arabia	11.51	4.42	7.09
Mexico	388.10	311.80	76.30
Argentina	13.19	-4.70	17.89
Brazil	36.18	25.87	10.31
Bolivia	6.67	4.83	1.84
Uruguay	2.47	1.79	0.69
Venezuela	0.76	-0.75	1.51
USA	168.90	4.65	164.25
Australia	32.85	6.82	26.02
France	0.05	-4.23	4.27
Italy	2.30	-0.69	2.99
Canada	0.00	0.00	0.00
ROW total	**698.28**	**368.83**	**329.45**

sections, at global level, ICRISAT will undertake the innovative research to cater the needs of different regions and targeted countries. The NARS/advanced research institutes located in different countries will adapt this research quickly and fine tune to meet their requirements. The level of adaptive capacity of respective countries will critically determine the extent of spillover benefits due to introduction of a particular technology. Another important parameter which also played a key role in the model are: extent of adoption of the technology. Technology adoption is the primary condition for assessing the impact of any specific technology. Both adoption lag and ceiling level of adoption will significantly influence the extent of welfare benefits to be derived from a specific technology in a given period of time.

The estimated welfare benefits across research domains for each individual research focus concluded that Warm tropics drylands, 120-149 days (RD 6) has the highest potential in ICRISAT focus in the real world scenario both with and without the research applicability criterion. The research domain 7 (Warm tropics drylands, > 150 days) stood at the second place in the domain list. This clearly reveals that ICRISAT sorghum research should focus more on RD 6 for attaining higher (high payoff) welfare benefits in the South Asia and sub-Saharan Africa regions. In terms of total benefits, RD 8 has higher benefits than RD 6. But, RD 8 contributes relatively fewer benefits to ICRISAT's focus and more benefits to ROW. In absolute terms, RD 5 exhibited the highest spillover (indirect) benefits followed by RD 10 and RD 8. RD 6 and RD 7 have nearly 40% benefits as direct benefits and the remaining 60% as indirect benefits (spillovers).

Table 22. Potential research benefits and priority countries.

Region	Country	Potential benefits[1] (USD M)	Realized benefits[2] (USD M)	Difference (USD M)	Total gap (USD M)	Priority rating[$]
Asia	India	929	838	91	92.5	***
	China PDR	59	59	0		*
	Pakistan	2.7	1.2	1.5		*
ESA	Sudan	362.3	14.8	347.5	565.5	***
	Ethiopia	178.2	26.8	151.4		***
	Tanzania	59.1	17.7	41.4		**
	Uganda	35.9	10.7	25.2		**
WCA	Nigeria	878.6	53.2	825.4	1238	***
	Burkina Faso	186.7	7.5	179.2		***
	Niger	49.9	1.1	48.8		***
	Mali	81.5	24.3	57.2		**
	Chad	58.3	5.8	52.5		***
	Cameroon	63.7	6.3	57.4		***
	Ghana	20.6	3.1	17.5		**
ROW	Egypt	52.2	15.7	36.5	231.9	*
	Mexico	484.4	388.1	96.3		*
	Brazil	123.3	36.2	87.1		*
	USA	172.8	168.9	3.9		*
	Australia	40.9	32.8	8.1		*

[1] estimated under ideal world scenario
[2] estimated under real world scenario
[$] defined as high priority - ***; medium priority - **; low priority - *

If ICRISAT sorghum research is to derive maximum spillover benefits or applicability of research materials across research domains, more research should be concentrated on RD 5. In terms of regional shares, nearly 70-90% benefits were accruing in Asia alone, especially in India. The next beneficiary regions in the row are the WCA and ESA regions respectively. In Asia, India (93%) is the prime beneficiary followed by China and Pakistan. Nigeria (48.9%), Mali (22.4%) and Burkina Faso (6.9%) are the major beneficiaries in the WCA region. Ethiopia (31.1%), Tanzania (20.5%), Sudan (17.2%) and Uganda (12.5%) are the top countries that have benefitted in descending order in the ESA region. In the case of ROW, Mexico (56%) and USA (25%), the major producers have benefitted under this research focus.

The sensitivity analysis also showed huge scope for gaining sorghum welfare benefits in ICRISAT focus as compared to the ROW. Among the three regions in ICRISAT focus, WCA has indicated vast potential (M USD 1238) in the region when compared with the ESA region (M USD 565). ROW also exhibited significant potential but ignored because as it will not fall under ICRISAT focus. The potential (M USD 900.1) and actual realized (M USD 997.5) benefits are pretty closer in case of Asia because of strong NARS capacity and high rate of adoption of improved cultivars.

Table 22 summarizes the country-wise potential and actual realized sorghum research spillover benefits during the study period. Countries like Nigeria, Burkina Faso, Niger, Mali, Chad and Cameroon in the WCA region and Sudan, Ethiopia and Tanzania in the ESA region have exhibited enormous potentials for sorghum welfare benefits in the analysis under different iterations. The rationality for research prioritization was the differences between the potential and actual realized spillover research benefits. The huge differences between these benefits used as basis for identification of priority countries (larger the difference the more was the priority) in that region. The innovative sorghum research undertaken at ICRISAT plans to maximize its spillover benefits, we need to target those countries where there are huge gaps. When we observe closely, this gap was much higher in the case of WCA targeted countries followed by the ESA regional countries. This difference was much lower in the case of South Asia (except in India) countries. Even though Rest of the World (ROW) also has good potential, but it was not prioritized because as it was not the focus region for ICRISAT sorghum research. However, ROW region is used to enjoy the research spillover benefits through ICRISAT innovative research due to applicability of different intermediate materials among homogenous research domains.

The results from sensitivity analysis have clearly concluded that there are two major parameters at country-level influencing for realizing these additional benefits. They are: a) adaptive research capacity of NARS partners at country level b) Ceiling level of adoption of improved cultivars in a particular country. The targeted countries in both ESA and WCA regions could not able to realize the fullest potential due to their poor NARS adaptive research capacity and low ceiling level of adoption of improved technologies (see appendix Table A4). Even though ICRISAT has been providing the intermediate research materials through innovative research, these countries could not able to efficiently use them in their respective breeding/crop improvement programs. Even if they use these materials to some extent and develop few improved cultivars, the cropped area occupied by them is very low or marginal. So, the above analysis clearly visualizes that the future research and developmental efforts in these countries should focus more on establishing institutions and mechanisms for enhancing the adoption of improved cultivars as well as strengthening NARS scientific research capacity. The International Public Goods (IPGs) nature of ICRISAT research has more interest to reduce the poverty and malnutrition in its focused regions such as South Asia, Eastern and Southern Africa (ESA) and West and Central Africa (WCA). Rest of the world (ROW) is not the current ICRISAT research focus for enhancing research spillovers.

The entire exercise and results emanated from this study not only benefits the ICRISAT sorghum research prioritization but also guide the future research investments across activities and regions. Finally, the study also suggested that the ICRISAT Management has to work closely with national governments, international donors and community based organizations (CBOs) to mobilize more resources for enhancing research towards WCA and ESA regions while continuing the existing support to Asia region.

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Appendix tables

Table A1. Production proportions across sorghum research domains and sorghum growing countries.

Country	RD-1	RD-2	RD-3	RD-4	RD-5	RD-6	RD-7	RD-8	RD-9	RD-10	RD-11	RD-12	RD-13
Argentina	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Australia	0.00	0.00	0.00	0.01	0.02	0.02	0.02	0.91	0.00	0.00	0.00	0.00	0.02
Azerbaijan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.00	0.23	0.00
Bangladesh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.74
Belize	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Benin	0.00	0.00	0.00	0.00	0.00	0.10	0.22	0.00	0.00	0.00	0.00	0.00	0.68
Bolivia	0.00	0.00	0.01	0.02	0.00	0.02	0.08	0.00	0.00	0.00	0.00	0.00	0.87
Botswana	0.08	0.51	0.06	0.24	0.08	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Brazil	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.03	0.00	0.00	0.00	0.00	0.92
Burkina Faso	0.00	0.00	0.00	0.07	0.14	0.52	0.14	0.00	0.00	0.00	0.00	0.00	0.13
Burundi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Cameroon	0.00	0.00	0.00	0.04	0.12	0.42	0.11	0.00	0.00	0.00	0.00	0.00	0.31
Central African Republic	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.95
Chad	0.00	0.00	0.00	0.14	0.13	0.16	0.38	0.00	0.00	0.00	0.00	0.00	0.19
China	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.29	0.59	0.00	0.01	0.00
Colombia	0.00	0.00	0.00	0.00	0.01	0.04	0.10	0.00	0.00	0.00	0.00	0.00	0.85
Congo, DRC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Cote d'Ivoire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Cuba	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.98
Dominican Republic	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.97
Ecuador	0.00	0.00	0.00	0.06	0.05	0.37	0.35	0.00	0.00	0.00	0.00	0.00	0.17
El Salvador	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Eritrea	0.20	0.00	0.00	0.76	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethiopia	0.01	0.09	0.02	0.04	0.22	0.04	0.26	0.00	0.00	0.00	0.00	0.00	0.32
Ghana	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Greece	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Guatemala	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Guinea	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.99
Guinea-Bissau	0.00	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.00	0.00	0.00	0.00	0.16
Haiti	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.98
Honduras	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
India	0.00	0.00	0.00	0.03	0.03	0.52	0.30	0.00	0.00	0.00	0.00	0.00	0.12
Iraq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.88	0.00	0.07	0.00
Italy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Kenya	0.00	0.00	0.00	0.26	0.33	0.13	0.13	0.00	0.00	0.00	0.00	0.00	0.14
Kyrgyzstan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.79	0.00	0.00	0.00
Lebanon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Lesotho	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Madagascar	0.00	0.00	0.00	0.01	0.11	0.07	0.15	0.00	0.00	0.00	0.00	0.00	0.67
Malawi	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.42

Table A1. Production proportions across sorghum research domains and sorghum growing countries.

Country	RD-1	RD-2	RD-3	RD-4	RD-5	RD-6	RD-7	RD-8	RD-9	RD-10	RD-11	RD-12	RD-13
Mali	0.00	0.00	0.00	0.21	0.13	0.35	0.28	0.00	0.00	0.00	0.00	0.00	0.02
Mauritania	0.00	0.00	0.00	0.88	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	0.01	0.01	0.25	0.07	0.07	0.16	0.38	0.00	0.00	0.00	0.00	0.00	0.06
Moldova	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Morocco	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.78	0.11	0.00	0.00
Mozambique	0.00	0.00	0.00	0.00	0.00	0.08	0.16	0.00	0.00	0.00	0.00	0.00	0.75
Namibia	0.01	0.00	0.00	0.21	0.63	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nicaragua	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Niger	0.00	0.00	0.00	0.89	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nigeria	0.00	0.00	0.00	0.11	0.24	0.19	0.11	0.00	0.00	0.00	0.00	0.00	0.36
Pakistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Papua New Guinea	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Paraguay	0.00	0.00	0.00	0.41	0.25	0.00	0.00	0.29	0.00	0.00	0.00	0.00	0.04
Peru	0.00	0.82	0.04	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Romania	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.98	0.00	0.00	0.00
Russia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.69	0.00	0.00	0.00
Rwanda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Senegal	0.00	0.00	0.00	0.06	0.18	0.56	0.20	0.00	0.00	0.00	0.00	0.00	0.00
Sierra Leone	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Somalia	0.00	0.00	0.00	0.89	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South Africa	0.01	0.01	0.65	0.06	0.07	0.01	0.15	0.01	0.00	0.00	0.00	0.00	0.03
Spain	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.84	0.00
Sri Lanka	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.95
Sudan	0.00	0.00	0.00	0.38	0.12	0.09	0.06	0.00	0.00	0.00	0.00	0.00	0.35
Swaziland	0.00	0.00	0.00	0.00	0.47	0.02	0.36	0.00	0.00	0.00	0.00	0.00	0.15
Syria	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.70	0.00	0.00	0.00
Tajikistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.88	0.00	0.00	0.00
Tanzania	0.00	0.00	0.00	0.00	0.00	0.06	0.12	0.00	0.00	0.00	0.00	0.00	0.81
Thailand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
The Gambia	0.00	0.00	0.00	0.00	0.00	0.27	0.73	0.00	0.00	0.00	0.00	0.00	0.00
Togo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Uganda	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Ukraine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.96	0.00	0.00	0.00
United States	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.58	0.07	0.00	0.00	0.00
Uruguay	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
Uzbekistan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.00	0.00	0.00
Venezuela	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.96
Zambia	0.00	0.00	0.00	0.00	0.00	0.10	0.71	0.00	0.00	0.00	0.00	0.00	0.19
Zimbabwe	0.01	0.03	0.33	0.10	0.14	0.37	0.03	0.00	0.00	0.00	0.00	0.00	0.00

Source: Author’s own estimations using SPAM production map

Table A2. Summary of sorghum research spillovers across regions.

Sorghum research spillovers from Asia to Africa			
ICRISAT name	**Released country**	**Release name**	**Year**
M19019-6	Cameron	S35	1986
	Chad	S35	1989
ICSV400	Nigeria	ICSV400	1996
ICSV 111	Nigeria	ICSV 111	1996
	Ghana	Kapala	1997
	Benin	ICSV 111	1999
ICSV112	Zimbabwe	SV1	1987
	India	CSV13	1987
	Kenya	ICSV112	1988
	Swaziland	MRS 12	1992
	Mozambique	Chokwe	1993
	Malawi	PIRIRA 2	1993
SRN 39	Sudan	SRN 39	1991
	Niger	SRN 39	1993
ICSV401	Mali	ICSV401	1994
ICSV 1	India	CSV11	1984
	Ethiopia	Dinkmash	1988
	Malawi	PIRIRA 1	1993
ICSV 2	Zambia	ZSV1	1983
A,6460	Zimbabwe	SV2	1987
ICSV 210	Eritrea	Bushuka	2000
M90393	Sudan	INGAZI	1992
M90038	Niger	SEPON 82	1993
IS 29415 germplasm	Eritrea	Shiketi	2000
**	Eritrea	Shambuko	2000
**	Eritrea	Shieb	2000
**	Eritrea	Laba	2000
**	Ethiopia	Melkamash	1998

** Varieties developed by national programs based on ICRISAT lines

Sorghum research spillovers from Africa to Asia			
ICRISAT name	**Released country**	**Release name**	**Year**
IS 30468	India	NTJ-2	1990
IRAT-408 germplasm ***	Pakistan	PARC-SS2	1991
**	Colombia	Sorghica PPH 302	1992
**	Colombia	HE 241	
**	Costa Rica	ESCAMEKA	1991

Sorghum research spillovers within Africa			
ICRISAT name	**Released country**	**Release name**	**Year**
SDS3220 (M91057 derivative)	Mozambique	Macia	1989
	Botswana	Phofu	1994
	Namibia	Macia	1998
	Zimbabwe	Macia	1998
	Tanzania	Macia	1999
SDS 2293-6	Tanzania	Pato	1995
IS 18758(E-35-1)	Ethiopia	Gambella 1107	1980
	Burkina Faso	E -35-1	1983
	Burindi	Gambella 1107	1990
SDSV 1513	Swaziland	MRS 13	1990
SDS 2583	Botswana	Mahube	1994
SDSV1594-1	Swaziland	MRS 94	1990
SDSH 48	Botswana	BSH 1	1994
ICSV 1007 BF	Sudan	Mugawim Buda 1	1991
ICSV 1063 BF	Ivory Coast	a	2000
	Mali	a	1993
ICSV 1079 BF	Mali	Yagare	2001
**	Kenya	KARI MATAMA 1	1994
**	Kenya	KARI MATAMA 3	2001
**	Rwanda	5 D x 160	1980
	Burundi	5 D x 160	1989
**	Tanzania	Tegemeo	1988
	Uganda	Equripur	1995
**	Zambia	Kuyuma	1989
**	Zambia	WSH 287	1987
**	Zambia	MMSH 413	1990
**	Togo	SORVATO 1	1998
**	Togo	SORVATO 28	1998

[a] Data not available
** Varieties developed by national programs based on ICRISAT lines
*** ICRISAT collected, conserved and facilitated the exchange of germplasm

Sorghum research spillovers within Asia			
ICRISAT name	Released country	Release name	Year
ICSV 735	Myanmar	YEZIN 6	1996
ICSV 758	Myanmar	YEZIN 7	1996
ICSV 804	Myanmar	YEZIN 5	1996
ICSV 107	Pakistan	PARC-SS 1	1991
ICSV126	Philippines	IES Sor 4 (PSB SG 94-02)	1994
M 90906	Myanmar	YEZIN 1(Schwephyu 1)	1984
M 36248	Myanmar	YEZIN 2	1984
M36335	Myanmar	YEZIN 3	1984
M 36172	Myanmar	YEZIN 4	1984
IS 8965	Myanmar	Shwe-ni-1	1980
IS 2940	Myanmar	Shwe-ni-2	1981
A 3681	China	YUAN 1-98	1982
A 3872	China	YUAN 1-28	1982
A 3895	China	YUAN 1-505	1982
A 6072	China	YUAN 1-54	1993
ICSV 93046	Kazakhstan	ICSV 93046	2016
**	Philippines	IES Sor-1(PSB SG 93-20)	1993
**	China	Liao 4	1988
**	China	Liao Za 4	1995
**	China	Liao 5	1996
**	China	Liao Za 6	1996
**	China	Liao Za 7	1996
**	China	Jinza 94	1996
**	Thailand	Suphanburi 1	1996

** Varieties developed by national programs based on ICRISAT lines

Sorghum research spillovers from Asia to Latin America			
ICRISAT name	Released country	Release name	Year
ICSV 112	Mexico	UANL 1-87	1987
	Mexico	Pacifico- 301	1990
	Nicaragua	Pinollnero 1	1990
ISIAP DORADO(M 91057)	El Salvador	ISTMENNO	1981
	Mexico	Blnaco 86	1986
	Mexico	ISIAP DORADO	1991
	Panama	AlanjeBlanquito	1991
	Paraguay	a	a
	Honduras	a	a
	Egypt	a	a
M 90362	Mexico	UNAL-1-287	1987
	El Salvador	Agroconsa-1	1987
M 62641	Mexico	COSTENO 201	1989
M90812	Mexico	Tropical 401	1991
M90975	Guatemala	ICTA MILTAN 85	1985
M90361	El Salvador	Centa Oriental	1987
M62650	Honduras	SURENO	1985
SEPON 77	Nicaragua	NICA- SOR(T43)	1985
A 3895	Colombia	Icayanuba	1992
IS 18484	Honduras	TORTILLERO 1	1984
Sorghum research spillovers within Latin America			
ICRISAT name	Released country	Release name	Year
Hybrid	Honduras	Catracho	1984
IS 9468	Mexico	Maravilla No. SOF0430201092	2000
ICSV-LM 90502	El Salvador	Soberano	1996
ICSV-LM 90503	El Salvador	R.C.V	1996
ICSV-LM 90508	El Salvador	Jocoro	1997
ICSV-LM 90501	Dominion Rep	SURENNA-1	1993

[a] Data not available
* ICRISAT locations: Patancheru (India), Bulawayo (Zimbabwe), Nairobi (Kenya), Kano/Samaru (Nigeria), Bamako (Mali), and Mexico
** Varieties developed by national programs based on ICRISAT lines
*** ICRISAT collected, conserved and facilitated the exchange of germplasm

Table A3. Impact of ICRISAT sorghum research technologies in different regions.

Country	Region	Year	Improved cultivar	Yield (kg per ha) Local	Yield (kg per ha) Improved	Yield gain (%)
Cameroon	Mayo-sava	1995	S 35	1220	1650	36
Cameroon	Diamare	1995	S 35	1450	1540	6
Cameroon	Mayo-Danay	1995	S 35	1420	1470	4
Cameroon		1995	S 35	1360	1550	14
Chad	Guera	1995	S 35	710	1090	54
Chad	Mayo-Kebbi	1995	S 35	780	1190	53
Chad	Chari-Baguirmi	1995	S 35	810	1180	46
Chad		1995	S 35	760	1150	51
Nigeria	Kano	1996	ICSV 400	875	1165	33
Nigeria	Katsina	1996	ICSV 400	1003	1073	7
Nigeria	Jigawa	1996	ICSV 400	865	1398	62
Nigeria		1996	ICSV 400	914	1212	33
Nigeria	Kano	1996	ICSV 111	875	1221	40
Nigeria	Katsina	1996	ICSV 111	1003	1274	27
Nigeria	Jigawa	1996	ICSV 111	865	1406	63
Nigeria		1996	ICSV 111	914	1300	42

Source: For Cameroon and Chad, Yapi et al., 1999a; For Nigeria, Ogungbile et al., 1998

Table A4. Estimates of parameters used in the ACIAR model.

Country	NARS Strength (FTE) in Sorghum		Sorghum Cultivar releases		Final adaptive capacities considered[3]	Final adoption estimates	
	FTE in 1999[1]	FTE in 2011[2]	1998[1]	2011[2]		1999[1]	2011[2]
China	200.00		24.00	30	1.00	98.00	1.00
India	150.00	80.00	182.00	256	1.00	69.00	1.00
Indonesia			13.00	13	0.40		0.20
Myanmar			21.00	20	0.60	10.00	0.30
Pakistan	14.00		11.00	13	0.40	21.00	0.40
Thailand	36.00		7.00	7	0.40	NA	0.30
Benin				1	0.20		0.10
Burkina Faso	8.00	2.96	5.00	8	0.50		0.20
Cameroon	4.00		1.00	1	0.20	-	0.45
African Republic					0.00		0.00
Chad			1.00	2	0.30	-	0.45
Ghana	4.00		1.00	3	0.40		0.40
Mali	7.00	7.75	4.00	18	0.80	29.00	0.50
Niger	6.00	3.00	2.00	4	0.50		0.20
Nigeria	6.00	2.50	4.00	22	0.50	0.18	0.40
Rwanda	3.00		2.00	7	0.40		0.10
Senegal		3.20	1.00	1	0.50		0.20
Ethiopia	50.00		7.00	12	0.70		0.30
Kenya	18.00		10.00	13	0.70		0.40
Malawi	3.00		3.00	3	0.40	10.00	0.30
South Africa					1.00	77.00	0.95
Sudan	21.00		6.00	10	0.30	22.00	0.40
Uganda	5.00		10.00	10	0.30		0.25
Tanzania				6	0.70		0.30
Egypt	25.00		8.00	7	0.40	35.00	0.50
USA	-			-	1.00		1.00
Mexico	-			-	1.00		0.80
Australia	-			-	0.90		0.90
Brazil	-			-	0.80		0.40

[1]Evenson and Gollin (2003) estimates
[2] DIVA and TRIVSA Project (Diffusions Studies) estimates
[3] Expert judgements generated in various workshops and meetings

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