Chapter 14

Sorghum Genetic Enhancement for Climate Change Adaptation

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Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is the fifth most important cereal crop and is the dietary staple of more than 500 million people in over 90 countries, primarily in the developing world. It is grown on 47 m ha in 104 countries in Africa, Asia, Oceania, and the Americas (Table 14.1). United States, Nigeria, India, Mexico, Sudan, China, and Argentina are the major sorghum producers globally (http://faostat.fao.org/site/567/default.aspx#ancor, accessed February 11, 2010). Sorghum grain is mostly used directly for food (55%) and is consumed in the form of porridges (thick or thin) and flat breads; however, sorghum is also an important feed grain (33%), especially in Australia and the Americas. Stover (crop residue after grain harvest) is an important source of dry matter to both milch and draft animals in mixed crop-livestock systems. Sorghum is also an effective source of green fodder due to its quick growth and high yield and quality. Of late, sorghum with sugar-rich juicy stalks (called sweet sorghum) is emerging as an important biofuel crop. Thus, sorghum is a unique crop with multiple uses as food, feed, fodder, fuel, and fiber.

Yield and quality of sorghum is influenced by a wide array of biotic and abiotic constraints. Significant biotic constraints include the insects, such as shoot fly, stem borer, midge, head bug, aphid, army worms, and locusts, and the diseases, such as grain mold, charcoal rot, downy mildew, anthracnose, rust, and leaf blight. Striga (*Striga asiatica*, *Striga densiflora, Striga hermonthica*) is a devastating parasitic weed found in many regions of Africa and India. Abiotic constraints include: problematic soils, drought, and temperature extremes. Climatic and edaphic changes including variable precipitation, higher soil and air temperatures, and increased soil alkalinity and acidity driven by increasing anthropogenic activities are becoming major global concerns threatening sorghum production.

This chapter examines the implications of climate change for major sorghum-growing areas and production. Inherent characteristics of sorghum to cope with climate change effects, the genetic options to mitigate climate change

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Crop Adaptation to Climate Change, First Edition. Edited by Shyam S. Yadav, Bob Redden, Jerry S. Hatfield, Hermann Lotze-Campen and Anthony Hall.

Table 14.1. Sorghum area, production, and productivity in 2007 for countries with substantial area.

	Area (m ha)	Production (m t)	Yield (t ha^{-1})
World	46.9	63.4	1.4
Africa	29.5	26.1	0.9
Americas	6.5	24.6	3.8
Asia	10.1	10.8	1.1
Europe	0.2	0.7	3.6
Oceania	0.6	1.3	2.1
Sudan	9.0	5.8	0.7
India	8.5	7.2	0.8
Nigeria	7.8	9.1	1.2
Niger	2.8	1.0	0.3
USA	2.7	12.6	4.6
Mexico	1.8	6.2	3.5
Burkina Faso	1.6	1.6	1.0
Ethiopia	1.5	2.2	1.5
Mali	1.1	0.9	0.8

Source: http://faostat.fao.org/site/567/default.aspx#ancor.

effects and future strategies for genetic improvement are discussed.

Climate change impacts on sorghum production

Global warming due to climate change will affect grain and stover yields in crops, more so in tropical Africa and Asia where sorghum is a major food crop. Most climate change models predict rises in air and soil temperatures and sea levels, and increased frequencies of extreme weather events leading to unprecedented changes in agricultural production in the years to come (IPCC 2007). Although both developed and developing countries will be affected, developing countries with little adaptive capacity and limited resources are more vulnerable to climate change effects. Desertification, shortages of fresh water, soil erosion, increased salinity, changed pest and disease scenarios, and biodiversity loss are some of the factors that adversely affect agricultural productivity. Detailed implications of climate change effects, resilience of populations, and coping mechanisms are not fully understood in most countries in the semiarid tropics (SAT) of Asia and Africa (Dar 2007; Cooper et al. 2008), which are traditional sorghum belts.

Predicted climate change effects on crop growth and yield in major sorghum growing areas

The world climate is continuing to change at rates that are projected to be unprecedented in recent human history. Global average surface temperature increased by about 0.6°C during the twentieth century (IPCC 2007). According to the Fourth Assessment Report (IPCC 2007), most of the observed increase in the global average temperature since the mid-twentieth century has been attributed to the observed increase in anthropogenic greenhouse gas concentrations. The Intergovernmental Panel on Climate Change (IPCC) climate models predict an increase in global average surface temperature of between 1.4°C and 5.8°C from 2001 to 2100, the range depending largely on the scale of fossil fuel burning between now and then and on the different models used. At the lower range of temperature rise (1–3°C), global food production might actually increase, but above this range, it would probably decrease (IPCC 2007). However, broad trends will be overshadowed by local differences, as the impacts of climate change are likely to be highly spatially variable (Cooper et al. 2008). Table 14.2 describes predicted changes in

Table 14.2. Predicted changes in temperature and rainfall in the major sorghum growing areas (based on regional predictions for A1B scenario for the end of the twenty-first century).

Region	Season	Temperature response (°C)	Precipitation response (%)
East Africa	Oct–Dec	+3.1	+11
	Mar–May	+3.2	+6
Southern Africa	Oct–Mar	+3.1	−10
West Africa	Jul–Oct	+3.2	+2
South Asia	Jun–Feb	+3.3	+11

Source: IPCC 2007.

temperature and rainfall in major sorghum-growing areas.

Disaggregated effects of predicted changes in temperatures and rainfall on sorghum yields

Preliminary cropping simulations exercises were conducted at ICRISAT to assess the impacts of climate change on sorghum yields in SAT areas of Africa and Asia. The following four scenarios were examined: potential grain yield with current cropping constrained only by climate; percent change in yield with current climate modified for predicted changes in rainfall; percent change in yield with current climate modified for predicted changes in temperature; and percent change in yield with current climate modified for predicted changes in both temperature and rainfall (Table 14.3).

Initial simulations predicted that for any given climate change scenario, the impact of climate change could vary both in nature and in magnitude from location to location, from crop to crop, from cultivar to cultivar, and from season to season. In general, the sorghum maturity period of current varieties decreases with increased temperatures. Climate change effects in terms of high temperatures and erratic rainfall may drastically reduce sorghum yields in South Asia, Southern Africa, and West Africa (Cooper et al. 2008; Table 14.3).

The impact of climate change on insect pests will be felt in terms of increased production losses and reduced efficacy of management strategies (Chakraborty et al. 2000). For all insect species, higher temperatures below the species' upper lethal limit could result in faster development rates, leading to rapid increase of pest populations as the time to reproductive maturity is reduced. For example, an increase of 1°C and 2°C in daily maxima and minima will cause codling moth (*Cydia pomonella*) to become active about 10–20 days earlier than expected. Overwintering of pests will increase as a result of climate change, producing larger spring populations as a base for a build-up in numbers in the following season. There will be increased dispersal of airborne pest species in response to atmospheric disturbances. Many insects are migratory and therefore may be well adapted to exploit new opportunities by moving rapidly into those areas, which becomes increasingly favorable as a result of climate change (Hill and Dymock 1989). All these possibilities have a significant bearing on crop productivity.

Characteristics of sorghum that help in coping with climate change

Sorghum is a C_4 plant with an extensive and fibrous root system enabling it to draw moisture from deep layers of soil. Sorghum requires less moisture for growth compared to other major cereal crops; for example, in some studies, sorghum required 332 kg of water per kg of accumulated dry matter, whereas maize required 368 kg of water, barley required 434 kg, and wheat required 514 kg. Sorghum has the capacity

Table 14.3. Disaggregated effects of climate change on sorghum yields.

Region	Potential grain yield (kg ha^{-1})	Rainfall effect on yield	Temperature effect on yield	Climate change effect on yield
East Africa short rains	3244	+10%	+11%	+21%
East Africa long rains	2232	+6%	+42%	+48%
Southern Africa	2753	−6%	−16%	−22%
West Africa	1896	+6%	−20%	−14%
South Asia	2800	+1%	−38%	−37%

Source: Cooper et al. 2008.

to survive some dry periods and resume growth upon receipt of rain (House 1985). Sorghum also withstands wet extremes better than many other cereal crops, especially maize. Sorghum continues to grow, though not well, in flooded conditions; maize by contrast will die. Sorghum produces grain even when temperatures are high. Inflorescence development and seed-set are normal at temperatures of 40–43°C and at 15–30% relative humidity, if soil moisture is available. Sorghum is not as tolerant of cool weather as some maize cultivars. Sorghum grows slowly below 20°C, but germination and growth will occur in some varieties at temperature as low as 12°C (House 1985).

Climate change adaptation and genetic options

Climate change being a threat multiplier, suitable strategies need to be urgently integrated into national and regional sorghum improvement programs. Some of the adaptation strategies to address climate change impacts include development of better weather forecasting systems, crop husbandry technologies and pest forecasting and pest management technologies, and changes in land use and water management systems. Mitigation strategies may also include development of technologies to achieve improved input use efficiencies (such as fertilizer microdosing and need-based application of pesticides for pest management) but these involve recurring costs. Genetic management is considered as the most cost-effective and eco-friendly option to mitigate the adverse impact of climate change on sorghum production. Unlike other adaptation strategies, genetic options do not involve recurring costs. Genetic options should focus on redeployment of trait-specific germplasm and breeding for plant defense traits.

Redeployment of germplasm

Climate change will cause changes in the length of the growing period (LGP) in some regions. The LGP is defined as the number of days in any given rainfall season, when there is sufficient water stored in the soil profile to support crop growth. The impact of climate change on the likely change in the average LGP across Africa has been comprehensively mapped by ICRISAT using the General Circulation Model HadCM3.B1 for the period 2000–2050 (Cooper et al. 2009). The study showed that the extent of global SAT areas will be changed through (1) SAT areas being "*lost*" from their driest margins and become arid zones due to LGPs becoming too short or (2) SAT areas being "*gained*" on their wetter margins from subhumid regions through the reduction in the current LGPs in those zones. It means sorghum could be grown in new areas of the currently humid tropics where sorghum is not grown at present. Large scale adaptation studies will be required to understand soil and climate conditions, pest scenarios, cropping systems, consumptions patterns, and markets in the new areas. International agricultural research centers (IARCs), agricultural research institutes (ARIs), and national agricultural research system (NARS) with large reservoirs of sorghum germplasm, breeding material, and commercial cultivars could play a significant role in deploying suitable germplasm to the new areas. Several trait-specific, non-milo, and high-yielding female lines developed at ICRISAT, in a range of plant heights and maturities can be utilized in producing the hybrids that are of value to different agroecological zones (Table 14.4). Development of crop cultivars with a maturity duration that matches the prevailing LGP will be one of the best strategies to cope with changes in LGP. Retargeting of traits of local importance should be undertaken by the NARS with the help of other partners.

Drought tolerance

Four growth stages in sorghum have been considered as vulnerable to drought: germination and seedling emergence, postemergence or early seedling stage, midseason or preflowering, and

Table 14.4. Details of the sorghum trait-specific (*milo*) and non-*milo* A-/B-pairs developed at ICRISAT-Patancheru.

S. No.	ICSA numbers	Traits	Total lines
1	1–103	High yielding	77*
2	88,001–88,026	High yielding	15*
3	89,001–89,004	High yielding	4
4	90,001–90,004	High yielding	4
5	91,001–91,010	High yielding	10
6	94,001–94,012	High yielding	12
7	201–259	Downy mildew resistant	59
8	260–295	Anthracnose resistant	36
9	296–328	Leaf blight resistant	33
10	329–350	Rust resistant	22
11	351–408	Grain mold resistant	58
12	409–436	Shoot fly resistant (rainy)	28
13	437–463	Shoot fly resistant (postrainy)	27
14	464–474	Stem borer resistant (rainy)	11
15	475–487	Stem borer resistant (postrainy)	13
16	488–545	Midge resistant	58
17	546–565	Head bug resistant	20
18	566–599	*Striga* resistant	34
19	600–614	Acid soil tolerant lines	15
20	615–637	Early maturity lines	23
21	638–670	*Durra* (large grain) lines	33
22	671–687	Tillering and stay-green lines	17
23	688–738	Non-*milo* (A_2) cytoplasmic lines	51
24	739–755	Non-*milo* (A_3) cytoplasmic lines	17
25	756–767	Non-*milo* (A_4) cytoplasmic lines	12
Total			*689*

Source: Reddy et al. 2006.
*The number of lines being maintained.

terminal or postflowering. Terminal drought is the most limiting factor for sorghum production worldwide. In sub-Saharan Africa drought at both seedling establishment and terminal stages is very common. In India, sorghum is grown during both rainy and postrainy seasons. The variable moisture availability at both preflowering and postflowering stages during the rainy season can have severe impact on grain and biomass yield. Climatic variability and associated genotype × environment interactions do not permit clear definition of target environments. Opportunities to make progress in breeding for drought tolerance occur both in understanding the environmental control of crop growth and in developing simplified approaches to modeling effects of climate change (Bidinger et al. 1996).

Drought and/or heat stress at the seedling stage often results in poor emergence, plant death, and reduced plant stands. Severe preflowering drought stress results in drastic reduction in grain yield. Postflowering drought stress tolerance is indicated when plants remain green and fill grain normally. A stay-green trait has been associated with postflowering drought tolerance in sorghum. Genotypes with the stay-green trait are also reported to be resistant to lodging and charcoal rot (Reddy et al. 2007; Fig. 14.1).

Genetic enhancement of sorghum for drought tolerance would stabilize productivity and contribute to sustainability of production systems in drought-prone environments. The extent of grain yield losses due to drought stress depends on the stage of the crop and the timing,

Fig. 14.1. Expression of stay-green trait (in sorghum) under receding soil moisture conditions in a vertisol (Photo courtesy: C Tom Hash, Santosh Deshpande and Vincent Vadez, ICRISAT).

duration, and severity of drought stress. Sorghum responses to moisture stress at all four growth stages have been well characterized. Variation in these responses has been observed and found to be heritable (Reddy et al. 2009). Since the phenotypic responses of genotypes differing in drought tolerance can be masked if drought occurs at more than one stage, screening techniques have been developed to identify drought-tolerant genotypes at each of the growth stages, separately (Reddy 1986; Blum et al. 1989; Muchow et al. 1996; Haussmann et al. 1998; Borrell et al. 2000a, 2000b; Harris et al. 2007). Of the several mechanisms to circumvent drought stress in sorghum, drought escape (related to shorter maturity durations), drought avoidance (maintenance of higher leaf water potential, LWP), and drought tolerance (related to greater osmotic adjustment, OA) are important and have been well characterized (Reddy et al. 2009). However, LWP and OA did not correlate well enough with grain yield in field conditions to merit selection based on them; in addition, screening techniques developed based on LWP and OA were not cost effective in sorghum breeding. Empirical screening based on imposing drought at various growth stages and measuring plant morphological and yield responses was the most effective approach. Long mesocotyl in seedling establishment and recovery from midseason stress after release by rains are important traits that can be easily deployed in lines. The stay-green trait has been well exploited to enhance postflowering drought tolerance in sorghum (Reddy et al. 2009).

At ICRISAT, growth-stage-specific breeding for drought tolerance, which involves alternate seasons of screening in specific drought and well-watered environments, has been used to breed sorghum that can yield well in both high-yield-potential environments as well as in drought-prone environments (Reddy et al. 2009). Since hybrids have exhibited relatively better performance than open pollinated cultivars for grain yield under water-limited environments, hybrid cultivar development (including their parents) should be given strategic importance for enhancing sorghum production in water-scarce environments (Reddy et al. 2009). The progress in enhancing drought tolerance in sorghum through conventional approaches is limited by the quantitative inheritance of drought tolerance and yield coupled with the complexity of the timing, severity, and duration of drought. Biotechnology appears to offer promising tools, such as marker-assisted selection, for genetic enhancement of drought tolerance in sorghum. Four stable and major QTLs were identified for the stay-green trait and are being introgressed through marker-assisted selection (MAS) into elite genetic backgrounds at ICRISAT, QDPI, Purdue University, and Texas A&M University (Reddy et al. 2009).

Integration of the sorghum genetic map developed from QTL information with the physical map will greatly facilitate the map-based cloning and precise dissection of complex traits such as drought tolerance in sorghum. Sorghum has a compact genome size ($2n = 20$) and can be an excellent model for identifying genes involved in drought tolerance to facilitate their use in other crops. Paterson et al. (2009) reported that with respect to withstanding drought, sorghum has four copies of a regulatory gene that activates a key gene family that is present in a wide variety of plants. Sorghum also has several genes for proteins called expansins, which may be involved in helping sorghum to recover from droughts. In addition, it has 328 cytochrome P450 genes, which may help plants respond to drought stress, whereas rice has only 228 of these genes.

Some of the drought-tolerant sources identified in sorghum at ICRISAT include Ajabsido, B35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS12568, IS22380, IS12543C, IS2403C, IS3462C, CSM-63, IS11549C, IS12553C, IS12555C, IS12558C, IS17459C, IS3071C, IS6705C, IS8263C, ICSV 272, Koro Kollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414-12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000, and Tx7078 (www.icrisat.org). ICRISAT has identified lines that are tolerant to drought at various growth stages (Table 14.5). Drought tolerance of M 35-1, a highly popular postrainy season adapted landrace in India, has been amply demonstrated (Seetharama et al. 1982).

Table 14.5. Sorghum germplasm and breeding lines tolerant to drought at specific growth stages, ICRISAT-Patancheru, India.

Growth stage	Tolerant sources/improved lines
Seedling emergence	IS 4405, IS 4663, IS 17595 and IS 1037, VZM1-B and 2077 B, IS 2877, IS 1045, D 38061, D 38093, D 38060, ICSV 88050, ICSV 88065, and SPV 354
Early seedling	ICSB 3, ICSB 6, ICSB 11 and ICSB 37, ICSB 54, and ICSB 88001
Midseason	DKV 1, DKV 3, DKV 7, DJ 1195, ICSV 272, ICSV 273, ICSV 295, ICSV 378, ICSV 572, ICSB 58, and ICSB 196
Terminal drought	E 36-1, DJ 1195, DKV 3, DKV 4, DKV 17, DKV 18, and ICSB 17

Source: ICRISAT 1982; Reddy et al. 2004a.

Heat tolerance

Sorghum flowers and sets seed under high temperatures (up to 43°C) provided soil moisture is available (House 1985). In many regions of the world, sorghum production encounters heat and drought stress concurrently, thus initial efforts in breeding for temperature stress emphasized heat tolerance. Jordan and Sullivan (1982) reported heat and drought tolerance to be unique and independent traits. Despite the level of adaptation of sorghum in the SAT, seedling establishment is still a major problem. Failure of seedling establishment due to heat stress is one of the key factors that limits yields and affects stability of production (Peacock 1982).

Understanding the genetic control of heat tolerance in sorghum is a prerequisite for formulating an appropriate breeding program. Thomas and Miller (1979) reported that sorghum seedlings respond differently when exposed to varying temperatures, and genetic variation for thermal tolerance in sorghum has been shown to exist in certain lines that are capable of emerging at soil temperature of about 55°C. Peacock et al. (1993) and Howarth (1989) discussed the need for greater diversity in sorghum seedling tolerance to heat in superior genotypes, as this will improve crop establishment in the SAT. Genetic variability for heat tolerance among the genotypes at the seedling stage was demonstrated by Wilson et al. (1982). Using screening techniques such as the leaf disc method (Jordan and Sullivan 1982) and leaf firing ratings by ICRISAT breeders, genetic variability past the seedling stage was demonstrated and positive correlations were found between grain yield and heat tolerance, thus making breeding for heat tolerance a viable option. Genetic variability for heat tolerance in sorghum was also reported by other researchers (Sullivan and Blum 1970; Jordan and Sullivan 1982; Seetharama et al. 1982).

Khizzah et al. (1993) studied four sorghum parental lines RTx430, BTx3197, RTx7000, and B35 and their F_1s and F_2 progenies during their reproductive phases to assess the genetic basis of heat tolerance in sorghum. They reported that parents were more heat tolerant compared to their F_1s and the heat tolerance is associated with two genes with a simple additive model and epistatic interaction. Khizzah et al. (1993) also stated that cultivars with good late-season drought tolerance were also heat tolerant, suggesting a possible relationship between drought and heat responses. Low to high heritability of heat tolerance found in sorghum suggests the feasibility of genetic enhancement of this trait. B35 and BTx3197 could be used as sources for heat tolerance in sorghum improvement programs (Khizzah et al. 1993). The importance of additive gene effects over dominance effects for heat tolerance index was reported by Setimela et al. (2007). Further studies are needed to better understand the inheritance of heat tolerance in sorghum.

Selection for heat tolerance in sorghum has had limited success as (1) laboratory techniques to screen for heat tolerance have not been effective in increasing heat tolerance expressed in field conditions and (2) field screening for heat tolerance is difficult to manage and is often confounded with drought tolerance (Rooney 2004).

Resistance to pests and diseases

Sorghum is affected by an array of insects and diseases worldwide. Genetic options for shoot fly resistance and grain mold tolerance in sorghum are discussed because of their global importance.

Shoot fly resistance

Among the insects, shoot fly (*Atherigona soccata*) is a major grain-yield-limiting insect pest that causes damage when sowing is delayed in the rainy or postrainy seasons. Shoot fly infestation is high when sorghum sowings are periodic due to erratic rainfall, which is common in the SAT. Greater incidence of shoot fly incidence is expected with the predicted increases in temperature due to climate change. Agronomic practices, synthetic insecticides, and host plant resistance have been employed for shoot fly management to minimize losses. Host plant resistance can play a major role in minimizing the extent of losses and is compatible with other tactics of pest management, including bio-control measures. ICRISAT contributed to development and refinement of the interlard fish meal technique and no-choice-cage technique for screening for resistance against shoot fly and several resistant lines with desirable genetic backgrounds have been identified (ICSV 702, ICSV 705, ICSV 708, PS 21318, PS 30715-1, and PS 35805) as well as other sources (IS 18551) (Sharma et al. 1992). Interestingly, some of these lines turned out to be sweet sorghums with higher Brix%, juice volume, and stalk yield. Following a trait-based pedigree breeding approach, a large number of shoot-fly-resistant seed parents for both rainy season (ICSA/B 409 to ICSA/B 436) and postrainy season (ICSA/B 437 to ICSA/B 463) adaptations were developed (Reddy et al. 2004b; http://test1.icrisat.org/gt-ci/Newsletters/ISMN_Specialissue/Text/ISMN-47_SpecialIssue_text.pdf, Accessed Feb 17, 2010). More recently, additional sources of resistance viz., IS 923, IS 1057, IS 1071, IS 1082, IS 1096, IS 2394, IS 4663, IS 5072, IS 18369, IS 4664, IS 5470, and IS 5636 are being used in the development of shoot-fly-resistant hybrid parents. In a B-line development program, the shoot fly resistance levels in the advanced lines (BC_7s and BC_9s) was high, with low shoot dead hearts % (33–46%) compared to the susceptible check 296B (59% SFDH) and significantly higher grain yield (up to 10%) compared to 296B (4.11 t ha^{-1}) (Table 14.6). New B-lines with high grain yield and shoot fly resistance were identified during the 2008 rainy season at ICRISAT-Patancheru. Marker-assisted backcrossing has been attempted at ICRISAT-Patancheru to transfer five putative QTLs from the donor parent IS 18551 into the genetic backgrounds of elite shoot-fly-susceptible B-lines BTx623 and 296B, and the introgression lines are being evaluated (Tom Hash, unpublished).

Table 14.6. Performance of advanced sorghum B-lines for agronomic traits and shoot fly resistance in 2008 rainy season at ICRISAT-Patancheru, India.

Genotype	Days to 50% flowering	Plant height (m)	Shoot fly dead hearts (%)	Grain yield (t ha^{-1})
SP 97041	68	1.5	33	4.50
SP 97029	70	1.4	38	3.51
ABT 1007	68	1.6	39	4.52
SP 97033	70	1.6	40	3.57
SP 97035	69	2.1	45	6.09
SP 97037	68	1.5	46	5.33
Controls				
IS 18551	72	3.0	31	2.57
296B	70	1.5	59	4.11
Swarna	69	1.8	44	4.86
Mean	*69*	*1.73*	*46.02*	*4.28*
CV (%)	*2.95*	*21.33*	*53.93*	*14.00*
CD (5%)	*3.47*	*0.63*	*42.02*	*1.00*

Considering the potential risk of using a single source of CMS for developing hybrids, several A-lines based on diverse alternative CMS sources—A_2, A_3, A_4 (M), A_4 (VZM), and A_4 (G)—have been developed. Conclusive studies have been conducted at ICRISAT to establish the suitability of hybrids based on CMS sources other than A_1, the widely used CMS system. Evaluation of hybrids developed involving isonuclear alloplasmic A-lines (A_1, A_2, A_3, A_4 (M), A_4 (G), and A_4 (VZM) cytoplasms) each in six nuclear genetic backgrounds (ICSA 11, ICSA 37, ICSA 38, ICSA 42, ICSA 88001, and ICSA 88004) for 2 years indicated no significant differences between the cytoplasms for shoot fly resistance in rainy and postrainy seasons (Sanjana Reddy, ICRISAT–Patancheru, unpublished).

In the shoot fly resistance program at ICRISAT in 2009 rainy season, 11 elite sweet sorghum hybrids with 11–42% less, 12 advanced hybrids with 5–14% less, 10 B-lines with 5–51% less, and 24 R-lines showed 5–52% less shoot fly dead hearts than the control (SSV 84: 88–93% dead hearts) (Sharma HC, unpublished).

Author: The sense in sentence "In the shoot fly resistance program ..." is unclear. Please check.

Grain mold resistance

Grain mold (caused by a complex of Fusarium and many other pathogenic and saprophytic fungi) is a major disease of sorghum caused by a complex of fungi that affects grain production and quality. The disease is particularly important in the case of improved, short- and medium-duration sorghum cultivars, such as the improved/released cultivars that mature during the rainy season in humid, tropical, and subtropical climates. With increase in temperature and more intensive rains due to climate change, mold infection is expected to be more severe than at present. Photoperiod-sensitive cultivars that mature after the rains (or at the end of rainy season) often escape grain mold infection. Sorghum cultivars with the white grain pericarp (used as food in India) are particularly more vulnerable to grain mold than those with brown or red grain pericarps. Both greenhouse and field screening techniques have been standardized by ICRISAT and NARS partners for effective screening for grain mold resistance, and new sources of resistance have been identified for use in breeding programs (Thakur et al. 2006). A total of 156 grain mold tolerant/resistant lines were identified by screening 13,000 photoperiod-insensitive sorghum germplasm lines (Bandyopadhyay et al. 1988). Resistance has been found mostly in colored grain sorghums with and without tannins and also in a few white-grain sorghums (Thakur et al. 2006; Bandyopadhyay et al. 1988, 1998). Using the grain-mold-resistant white-grained germplasm sources, a couple of hybrid parents and varieties were developed. PVK 801 is one such variety developed by Marathwada Agricultural University (MAU), India, in partnership with ICRISAT. PVK 801 is quite popular in the rainy season in India. Studies on ICRISAT-developed B-lines in multilocation trials by the Indian national program showed that 11 entries (ICSB 355, -376, -377, -383, -388, GM 3, ICSB 355-1-10, -393-7-1, -401-4-2, -403-4-1, and SGMR 33-1-8-3-2) have stable grain mold resistance across five locations, with mean panicle grain mold rating (PGMR) = 2.0 (PGMR represents the percentage of grain molded on a panicle, recorded on a 1–9 scale, where 1 = highly resistant and 9 = highly susceptible) during 2006−07 (http://nrcjowar.ap.nic.in/aicsip06/reports/pathology.pdf, Dec 12, 2009). Recent studies at ICRISAT-Patancheru indicated that it is possible to breed grain-mold-resistant hybrids with grain yields comparable to popular high grain yielding hybrids. Table 14.7 depicts

Table 14.7. Performance of selected advanced sorghum B-lines for grain mold tolerance and agronomic traits in 2008 rainy season at ICRISAT-Patancheru, India.

Genotype	Days to 50% flowering	Plant height (m)	Panicle grain mold rating (PGMR)^2	Grain yield (t ha^{-1})
SP 97047	71	1.9	6.0	5.13
SP 97051	71	1.8	6.0	4.79
SP 97045	70	1.9	6.7	6.37
SP 97065	69	1.7	6.7	5.19
SP 97067	73	1.7	7.0	4.94
SP 97053	68	1.8	7.0	3.81
SP 97055	71	2.0	7.0	5.24
SP 97057	70	1.8	7.0	5.68
SP 97069	70	1.6	7.0	3.57
SP 97073	73	1.5	7.0	5.14
SP 97059	72	1.6	7.3	3.58
Controls				
Bulk Y (susceptible check)	50	1.3	9.0	5.54
296 B (susceptible check)	71	1.4	9.0	4.52
IS 14384 (resistant check)	72	3.1	2.0	6.58
Mean	*69.50*	*1.75*	*6.98*	*4.95*
CV (%)	*1.94*	*7.57*	*7.74*	*9.44*
CD (5%)	*2.23*	*0.22*	*0.88*	*0.77*

Source: Ashok Kumar, ICRISAT (Unpublished).

PGMR represents the percentage of grain molded on a panicle, recorded on a 1–9 scale, where 1, highly resistant; 9, highly susceptible.

the grain mold tolerance and agronomic traits of some of the recently developed sorghum B-lines. In addition to these efforts, SSR marker-based diversity assessment of grain mold resistance sources has been conducted and identification of QTLs for grain mold resistance is underway at ICRISAT-Patancheru and Indian national programs.

Increased grain microdensity

Malnutrition due to micronutrient deficiency (Fe and Zn) is alarming in Southeast Asia including India, especially in preschool children and pregnant women. The intensity of micronutrient malnutrition is high in the SAT, the home for millions of resource-poor people. The people of SAT depend upon sorghum along with other food staples for their calorie and micronutrient requirement. Droughts and water scarcity diminish dietary diversity and reduce overall food consumption and this may lead to malnutrition (http://www.fao.org/docrep/010/ai799e/ai799e00.HTM, Feb 17, 2010). Biofortification, i.e., development and deployment of micronutrient-dense sorghum cultivars using the best conventional plant breeding methods complemented by biotechnology tools, has been recognized as an effective strategy to mitigate dietary micronutrient deficiency. Research efforts at ICRISAT and elsewhere showed that there is considerable genetic variability and high heritability for grain Fe and Zn contents, and it is possible to genetically enhance the grain micronutrient content (Fe and Zn) in sorghum (Reddy et al. 2005; Ashok Kumar et al. 2009). Studies at ICRISAT identified promising Fe- and Zn-rich donors in the sorghum core collection for use in developing Fe- and Zn-rich cultivars (Ashok Kumar et al. 2009). Significant positive correlation was observed between grain Fe and Zn contents ($r = 0.75$). Five accessions—IS 5427, IS 5514, IS 55, IS 3760, and IS 3283—with high grain Fe (>50 mg kg^{-1}) and high Zn (>37 mg kg^{-1}) contents can be utilized to increase the diversity and micronutrient density of sorghum hybrid parents in the future (Table 14.8). PVK 801 is a high yielding, grain-mold-tolerant ICRISAT-MAU partnership variety possessing high grain Fe (>50 ppm) and Zn (>35 ppm) contents.

The way forward

Climate change will modify the LGP across the regions of interest, but this can be mitigated by the retargeting and redeployment of existing germplasm. Predicted temperature increases, through their effect on increasing rate of crop development, will have greater negative impact on crop production than the relatively small (+/− 10%) changes in rainfall that are predicted to occur. Yield gap analyses at ICRISAT and elsewhere have shown that the negative impacts of climate change can be largely mitigated through greater adoption of improved crop, soil and water management innovations by farmers, and better targeted crop improvement approaches by farmers, more explicitly focused on adaptation to climate change. The impact of climate change on yields under low input agriculture is likely to be minimal as other factors will continue to provide the overriding constraints to crop growth and yield. The adoption of currently recommended improved crop, soil, water, and pest management practices, even under climate change, will result in substantially higher yields than farmers are currently obtaining under low input systems. Adoption of heat tolerant varieties could result in complete mitigation of climate change effects that result from temperature increases. Owing to the evolutionary advantages, its genetic resources and progress in genetic advancement, sorghum is in a unique position to cope with climate change. Development of medium to long duration cultivars with heat and drought tolerance, resistance to pests and diseases, and higher micronutrient density in high- yielding backgrounds is the key for future sorghum improvement programs. Tapping alternate markets like sweet sorghum for biofuel and fodder, grain for poultry feed and starch and

Table 14.8. Mean performance of selected sorghum germplasm lines evaluated for grain Fe and Zn contents at ICRISAT-Patancheru, during the 2007 and 2008 post rainy seasons.

IS No./ pedigree	Race	Origin	Days to 50% flowering	Plant height (m)	Glume coverage (%)	Grain yield (t ha^{-1})	Grain size (g 100^{-1})	Iron (mg kg^{-1})	Rank	Zinc (mg kg^{-1})
5427	Durra	India	65	2.0	54	2.0	2.75	60.5	1	56.8
5514	Guinea-bicolor	India	68	1.7	71	1.4	2.97	56.2	2	44.6
55	Durra-caudatum	US	71	1.0	75	1.3	2.64	54.1	3	38.3
3760	Caudatum-bicolor	USSR	68	1.9	67	2.2	2.23	52.8	4	37.1
3283	Bicolor	US	66	1.8	71	1.9	2.70	50.2	5	42.0
17580	Caudatum	Nigeria	66	1.9	79	1.6	2.09	49.9	6	40.5
15952	Guinea	Cameroon	81	2.4	38	2.5	3.35	49.3	7	41.3
3813	Durra	India	79	2.2	83	1.4	1.73	49.2	8	38.1
15266	Caudatum	Cameroon	70	1.4	54	2.7	2.65	48.6	9	43.6
2939	Kafir	US	69	2.0	63	3.6	3.94	48.4	10	37.2
4159	Durra	India	65	1.9	50	1.5	3.30	47.6	11	37.6
3929	Kafir-durra	US	75	2.0	79	2.2	2.09	47.6	12	39.5
3443	Guinea-caudatum	Sudan	68	1.7	63	3.3	3.47	47.4	13	39.3
3925	Durra-caudatum	US	78	2.0	67	2.4	1.95	47.2	14	38.5
5460	Durra-bicolor	India	66	1.5	79	1.4	2.68	46.9	15	46.4
12452	Caudatum-bicolor	Sudan	64	1.9	79	3.2	4.34	46.8	16	33.2
2801	Caudatum	Zimbabwe	71	1.8	71	2.3	3.11	45.5	17	45.0
2536	Kafir-caudatum	US	72	1.8	83	2.3	2.36	45.2	18	37.0
5429	Durra	India	66	1.7	79	2.8	2.99	44.4	19	30.0
356	Durra	US	84	1.1	46	2.2	2.71	44.2	20	32.9
2265	Durra-bicolor	Sudan	75	2.2	71	1.8	1.69	44.2	21	40.9
12695	Bicolor	South Africa	68	1.9	100	2.8	2.58	44.1	22	38.9
5538	Durra	India	65	1.4	33	1.7	2.22	43.9	23	36.9
5476	Durra	India	69	1.5	75	2.1	2.69	40.8	24	35.5
16337	Caudatum	Cameroon	80	1.7	38	2.4	3.03	40.5	25	34.0
5853	Guinea-durra	India	65	1.7	29	2.4	5.91	40.5	26	31.5
14318	Bicolor	Swaziland	79	2.1	79	2.2	2.25	39.3	29	38.0
10674	Durra-caudatum	China	65	2.1	46	1.9	4.04	38.5	30	37.6
22215	Durra-bicolor	USSR	80	2.1	71	2.9	2.39	26.3	31	21.4

malting will help farmers in rainfed regions realize greater incomes from sorghum cultivation.

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