Sorghum Management Systems and Production Technology Around the Globe

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Contents

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Abstract

Sorghum (*Sorghum bicolor* (L.) Moench) is one of the most resilient crops grown in the tropical, subtropical, or temperate regions of Africa, Asia, Oceania, and Americas. Globally, the top five worldwide sorghum producers are USA, Nigeria, Sudan, Ethiopia, and India. Sorghum production area is declining and shifting to lower productivity regions or soil types; however, annual productivity gains continue in excess of 8.7 kg/ha due to genetics alone and up to 50 kg/ha when genetics and management combinations are considered. Growers prefer sorghum because of the low risk and reliable production especially in low-input production systems but often switch to cotton, maize, or soybean crops rather than intensify sorghum production. Further management (agronomic practices) and breeding efforts should be dedicated to increasing attainable yield and reduce the yield gap (potential minus actual yields). The latter can be achieved by improving the understanding of the complexity of the genotype (G) by environment (E) by management (M) interaction (G × E × M). A summary presenting best management (e.g., planting date, seeding depth, cultivar-/hybrid-type selection, row spacing, plant density, and crop rotations) of modern sorghum hybrid traits across environments could provide insights for yield improvement. This chapter provides an update on the state of the art on the sorghum management systems and production technology under diverse environments across the globe. We identify that sowing date and maturity group remain the most important management and genetic trait combinations for sorghum systems due to changes in production technologies, climate, and increased production in marginal areas of different continents.

Keywords

Agronomics practices · African sorghum scenario · Argentinian sorghum scenario · Australian sorghum scenario · Crop rotation · Geometry · Indian sorghum scenario · Spatial arrangement

1 Introduction

Sorghum is grown in tropical, subtropical, and temperate regions of Africa, Asia, Oceania, and Americas. Globally (for 2018 year), the top ten sorghum producers are USA (9271 thousand MT), Nigeria (6862 thousand MT), Sudan (4953 thousand MT), Ethiopia (4932 thousand MT), India (4800 thousand MT), Mexico (4531 thousand MT), Brazil (2273 thousand MT), China (2194 thousand MT), Niger (2100 thousand MT), and Burkina Faso (1930 thousand MT) (FAOSTAT 2018). Crop improvement research efforts across different continents have paid the dividend in terms of increased productivity which did help in maintaining the production levels of around 45 million MT, despite area decreasing trends in most regions. Close to 50% of the sorghum is produced in Africa, with 24% in the Americas and and 15% in Oceania and Asia. US sorghum yields are approximately 4 Mg ha^{-1}, well above the levels documented for India and China. Argentinian sorghum production was well above the overall productivity documented in Mexico and Brazil, 3.6 Mg ha^{-1} versus 3.5 and 2.9 Mg ha^{-1}, respectively (Food, Agriculture Organization of the United Nations 2018).

Sorghum is a multipurpose crop well adapted to different weather and cropping systems. It is grown in rotation with legumes, cotton, oilseeds, or vegetables. Developing countries account for approximately 90% of the global crop area and 70% of the total production. However, high-yielding sorghum hybrids are grown in developed countries. Since sorghum is grown in both rainfed and irrigated systems, crop breeding efforts were primarily focused on abiotic stress-related traits and reproductive growth-related traits. Major genetic gains are reported from the USA, which has witnessed a genetic gain at an annual rate of 50 kg ha^{-1}(Unger and Baumhardt 1999).

Among the most important management options, planting date and cultivar-/hybrid-type selection are prioritized to best match the locally prevailing environment in terms of minimum temperature (frost conditions) at higher latitudes while understanding the relevance of crop-growing degree days at lower latitudes. Planting date and sufficient soil moisture availability for uniform crop establishing were critical to attain potential yields in all regions. Tillage and crop rotation are important management aspects for a long-term sustainable crop production. In many areas around the globe, the worst crop preceding sorghum is sorghum itself since biotic pest carryover is a major limitation. Country and season-based fertilizer recommendations have been standardized, but in rainfed areas, the use of inputs depends on the in-crop seasonal distribution of rainfall. Semiarid tropics that are frequented with prolonged dry spells pose a risk, which is mitigated by adoption of intercropping systems.

Planting two differently maturing crops helps in harvesting at least one of the crops when the rainfall is inadequate at critical development phases.

Major advances in sorghum systems research include using of simulation modeling and remote sensing applications to identify the best crop management and trait combinations using historical data across growing seasons. Crop simulation models can predict phenotype expression and yield in response to changes in G × E × M. Nonetheless, the major challenge of sorghum is that the investment in technology and breeding is not comparable to other major crops, and this has negatively impacted sorghum area. There is a need to make sorghum more attractive to farmers, acceptable yield levels, in agreement with a more market options.

In this chapter, we highlight the global sorghum scenario, relevant management systems and production technology, agronomic traits, and progress with the goal of providing more emphasis on improving our understanding of G × E × M interactions for enhanced productivity.

2 US Sorghum Scenario

Major sorghum production takes place in the central and south central region known as the “Great Plains,” with a majority of this production located in the states of Kansas and Texas. States following in importance on production are Oklahoma, South Dakota, Arkansas, Louisiana, and Nebraska (USDA-NASS 2016). Planting date, management practices, and environment exert a complex influence on the US sorghum-producing regions. Irrigated sorghum areas are concentrated in the western part of Texas, Oklahoma, and Kansas with an overall total of less than 50% of the sorghum acreage irrigated (Census of Agriculture 2007).

2.1 Sorghum Improvement and Crop Management

For the USA, sorghum improvement during the last decades has evolved at a slower rate relative to corn (Mason et al. 2008). The rate of genetic gain for the last 50–60 years (Miller and Kebede 1984) was similar over time with an overall annual increase of 50 kg ha^{-1} (Unger and Baumhardt 1999). Crop improvement was primarily focused on progressing resource capture and drought avoidance; however, Assefa and Staggenborg (2011) documented changes in physiological characteristics for new sorghum hybrids under varying water deficit environments. Improved understanding of sorghum response to diverse management practices under varying scenarios of genotype (G), environment (E), and management practices (M) should be pursued to identify traits that help improve crop adaptation and resilience to weather variations.

Crop management practices can greatly influence potential sorghum productivity. The most relevant management practices include hybrid selection, planting date as influenced by crop rotations, seeding depth, row spacing, and plant density. Soil conditions, primarily related to soil temperature and moisture, are the main drivers influencing the optimal planting dates for sorghum in the USA and, more specifically, for the Great Plains region (Central and Southern Great Plains, latitudes 30°N to 40°N). Optimal planting dates for the Great Plains are dependent on the soil temperature conditions, with recommended temperature ranging from 15 to 23 °C. Germination and emergence are impaired with temperatures below 10 °C (Anda and Pinter 1994). Rotation is also another component, playing a primary role in determining the optimum planting date for the US Great Plains region. In the eastern part of this region (longitude 95°W to 80°W), where corn and soybean crops are prevalent, sorghum is frequently planted later.

For the state of Kansas, major US sorghum-producing state, last 5-year period, overall 50% planting date for the state was approximately on early June in 2019. The historical trend portrayed a change to earlier planting dates at a rate of about 0.2 day per year. This change can be attributed to warmer springs, change in agronomic technologies related to machinery, improvements on seed treatment, and genetics. If sorghum is planted too early, delays in emergence can be reflected in poor plant-to-plant uniformity and reductions in the number of plants. Other major US sorghum-producing states such as Texas and Oklahoma have a broader optimal planting date window. For the "Southern Great Plains" (including Texas, Louisiana, New Mexico, and Mississippi), planting date depends on the region of the state, for the panhandle of Texas occurs from mid-April until June. On the other side of the state, recommended planting dates for Texas are from late January to February in the Lower Rio Grande Valley, late February to mid-March in the Coastal Bend and Upper Gulf Coast, and from March to April in Central and North Central Texas (Trostle and Fromme 2011). For Oklahoma, 50% planting date was achieved on early June in the last 5 years.

Planting date will also determine the probability of the sorghum to reach full maturity before a damaging fall freeze event (depending on the planting region), and in consequence, the length of the growing season is estimated by the calculation of the growing degree days (GDDs). Seasonal 30-year GDDs information [base temperature = 10 °C; if (daily_min. <10 °C): daily_min. = 10 °C; if (daily_max. >37.8 °C): daily_max. = 37.8 °C; GDD = {(daily_max. + daily_min. air temp.)/2} − base temp.] was obtained as to estimate the length of the crop season (Fig. 1). For the US sorghum, the growing region was divided into two areas: (1) "Southern Great Plains/Early Sorghum Production" region (including the states of Texas, Louisiana, New Mexico, and Mississippi) and (2) "Northern Great Plains/Late Sorghum Production" region (including the states of Oklahoma, Kansas, Colorado, Arkansas, and Missouri). As expected, cumulative GDD increased from north to south, increasing the length of the growing season for sorghum and presenting differential temperature and precipitation conditions (Fig. 1).

2.2 Planting Date and Cultivar Duration

Selection of planting date for sorghum should be made to avoid exposing the crop to heat and drought conditions during the blooming time. A recent study documented

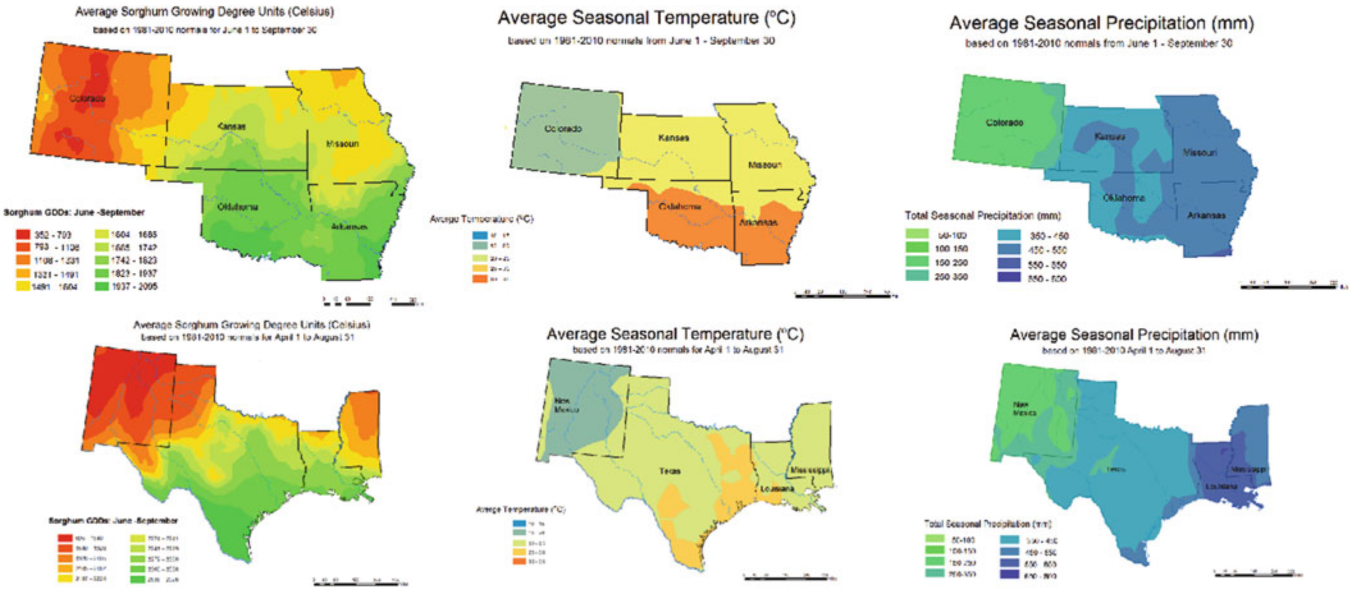

Fig. 1 Cumulative growing degree days, seasonal temperature (°C), and precipitation (mm) from April to August for the "Southern Great Plains/Early Production" region (including Texas, Louisiana, New Mexico, and Mississippi) (upper panels) and from June to September for the "Northern Great Plains/Late Production" region (including Oklahoma, Kansas, Colorado, Arkansas, and Missouri) (lower panels). (Produced by K-State Weather Data Library)

the effect of heat on sorghum (Prasad et al. 2015), portraying that the critical period for yield formation was 10 days before and 5 days after flowering. Therefore, planting date can be utilized as a critical management tool for determining flowering time in sorghum. Planting date also influences the final number of plants attained; thus, final seeding rate should be properly adjusted. Late planting dates are more susceptible to produce less number of tillers compared to normal planting times (lower duration of the growing season), potentially decreasing yields if the final seeding rate is not adequately adjusted (Ciampitti et al. 2019). In addition to seeding rate, hybrid maturity is a factor that should be considered in combination with planting date; for example, for the Texas Panhandle, a mid-maturity hybrid is recommended to be planted until June 30, but a later planting time, July 15, could be explored if an early maturity hybrid is decided to be planted (Barber et al. 2007). For the state of Kansas, a more predictable (a lower yield variation) yield for sorghum was obtained when planting time occurred early June relative to earlier or later to this date (Ciampitti et al. 2019). The latter could be associated with better conditions during flowering (late summer rains), minimizing the impact of stress (e.g., drought and heat) on yield formation. Early planting times will increase biomass and leaf area with a possibility of attaining superior yield but under the risk of experiencing abiotic stress conditions during blooming. On the opposite side, delayed planting times might be beneficial from the "blooming" weather standpoint but detrimental in environments where an early freeze event can limit the duration of the grain filling and, in consequence, produce a large impact on final yields. In Oklahoma, it is generally not recommended to plant sorghum during May, in an effort to avoid anthesis occurring from mid-July to mid-August, which is the hottest period in the state.

2.3 Seeding Depth

Seeding depth is another critical factor for planting sorghum, with optimal seeding rate depending on soil factors such as texture, temperature, and moisture and plant factors related to residue quantity and cover (temperature related). Optimal seeding depth can range from 2.5 to 5 cm; for example, adequate emergence can be found when sorghum is planted at 2.5 cm depth in higher clay soils and 5 cm in sandy soils. Deeper seed placement (>5 cm seeding depth) can reduce emergence, affecting final stand count and/or early season plant-to-plant uniformity. For late planting and under drier soil moisture conditions, sorghum seed can be placed deeper if beneficial soil moisture is present.

2.4 Crop Rotation and Tillage

Crop rotation and tillage are among the many decisions the producers make at the onset of every growing season. Rotation and tillage can produce a beneficial effect in crops within a rotation. Within the tillage systems, the concept of conservation tillage (including reduced-till, mulch-till, strip-till, ridge-till, zero-till, and no-till) refers to minimal mechanical soil disturbance, maintenance of a mulch of carbon-rich organic matter (>30% residue cover after planting), and crop residues. No-tillage (NT) is a system where the soil is left undisturbed from harvest to planting except for strips up to one-third of the row width. In the USA, about 35.5% of cropland allocated for major crops is under NT, leaving the remaining 65.5% under tillage of different frequency (Horowitz et al. 2010). Positive NT impacts for soil environmental health via improvements in carbon sequestration, biological activity, soil structure, and water conservation are commonly reported (Hobbs et al. 2008; Six et al. 2002; Busari et al. 2015). A water saving from NT system in drylands, through reduction of evapotranspiration, increased infiltration, and improvement in soil conditions, was also evident (Bonfil et al. 1999; Peiretti 2006; Williams et al. 2009).

2.4.1 Hybrid Selection with Desirable Traits

Hybrid selection is a critical factor for improving sorghum productivity. Selection should not only consider maturity, resistance to pests (insects and diseases), and stalk strength but also consider head exertion, seedling vigor, and hybrid performance. Hybrid maturity is related to the probability of entering into physiological maturity before the first fall freeze. From a physiology standpoint, a hybrid is fully mature when its black layer is formed (black line at the grain base), coinciding with the cessation of dry matter accumulation. For example, for the state of Kansas, use a shorter-season hybrid when planting occurs late. When planted early, long-season hybrids are recommended for using the full length of the season (greater yield potential). Standability is also a positive trait, and wherever possible, harvest fields presenting stalk strength issues first. Try to plant sorghum so that blooming occurs in favorable conditions, avoiding hot/dry weather, but also consider allowing time for maturity. To diversify risk, plant hybrids with different maturities to minimize the effect of adverse environments. The full-exertion trait is preferred due to improvements in grain set and lower susceptibility to biotic stress (e.g., mold).

Hybrid performance should be considered when planting sorghum. Yield stability is a favorable trait, presenting stable yields from low- to high-yielding environments. Recently, a research study evaluating three contrasting sorghum hybrids (dryland suited, irrigated suited, and well adapted) under full irrigation documented similar yield of >10 Mg ha^{-1}. Hybrid selection under rainfed conditions portrayed a yield difference from 0.5 to 1 Mg ha^{-1}, emphasizing the importance of site-specific information of hybrid performance.

2.5 Row Spacing

Row spacing influences productivity when sorghum yields are greater than 6 Mg ha^{-1}. Under low-yielding environments, conventional (75 cm) row spacing seems to be the best option compared to the narrow (25 cm) row spacing. Narrowing rows can promote fast canopy closure, decrease evaporation (Steiner 1986, 1987; Sanabria et al. 1995), and improve weed control. In a summary of studies conducted across the Great Plains region, Staggenborg et al. (1999) and Maiga (2012) documented superior sorghum yields when the row spacing decreases from 75 to 25 cm under high-yielding environments (Ciampitti et al. 2019). Under nonstress conditions, yield response to narrow rows is strictly associated with improvement in light interception early in the season, which can be translated into greater yields. Nonetheless, for the Coastal Bend region of Texas, Fernandez et al. (2012) reported a lack of response to narrowing rows in sorghum (38 vs. 76 cm) even under favorable growing conditions. In another study from Texas, Fromme et al. (2012) documented that narrow rows (51 cm) slightly improve yields compared to wide rows in lower-yield environment (below 7 Mg ha^{-1}). In overall, even when a more consistent positive yield response was documented for narrow rows and high-yielding environments (>6 Mg ha^{-1}), the main primary benefit on this practice is the implications related to improvement in weed management.

2.6 Plant Density

Yield response to seeding rate is not as consistent in sorghum relative to other crops such as corn. The unique ability of sorghum to compensate for lower than optimal plant density via development of tillers alleviates the effect of seeding rate on sorghum yield. Sorghum hybrids with low tillering capacity may present a consistent yield response to plant density relative to high tillering ones, which can compensate for lower plant density with tillers, resulting in greater fertile panicles per plant. Optimum plant density depends on factors such as the availability of soil (nutrient and water) and environmental resources. Depending on the study, plant density ranged from less than 59,000 plants ha^{-1} (<550 mm), 86,000 plants ha^{-1} (660 mm), and 110,000 plants ha^{-1}(810 mm), presenting a strong relationship between plant density and water supply. A summary of studies from the Great Plains region (Welch et al. 1966; Fernandez et al. 2012; Pidaran 2012; Schnell et al. 2014) reported mixed results of sorghum yield response to seeding rate with positive, neutral, or negative yield responses depending on the hybrid, management practices, and environment evaluated. In several studies, plant densities above 200,000 plants ha^{-1} were more sensitive to above or below normal precipitation and did not present any consistent yield improvement. Superior seeding rates should be used with later planting dates due to fewer productive tillers with warmer temperatures during vegetative stages.

2.7 Geometry and Spatial Arrangement

Plant geometry and spatial arrangement are relevant for sorghum production, primarily under dryland environments with the goal of water conservation (Blum and Naveh 1976). Clump planting (e.g., planted in group of three plants) shows similar or better yield response than uniformly spaced plants with yields below 5–6 Mg ha^{-1}. Above the 5–6 Mg ha^{-1}, the uniform plant arrangement outyields clump planting.

Therefore, clump planting presents great potential for stabilizing or increasing yields in low-yielding environments. The skip-row configurations (e.g., skip one and plant one row) presented lower yield (5.6 Mg ha^{-1}), primarily in high-yielding environments, due to reduced light interception. Concluding, alternative planting geometries such as cluster (with six plants planted but alternating between rows) and clump appear to have fewer disadvantages than the skip-row geometry in dryland conditions (Haag 2013).

3 Indian Sorghum Scenario

3.1 Seasons and Relative Potential

Indian grain sorghum is grown during *kharif* (rainy), *rabi* (post-rainy), and summer (limited irrigations) seasons across different states (Kumar et al. 2010). Sorghum area, production, and productivity in India, as shown in Fig. 2, depict a declining trend in both area and production over the past few years. Sorghum grain productivity (mean of largely rainfed seasons) depicts an increase from 0.76 to 0.93 Mg ha^{-1} over a period of 14 years. The *kharif* (June to Oct) and summer (Jan to May) seasons are typically characterized by longer photoperiod, while it is shorter (<12 h) during *rabi* (Oct to Feb) season. The sowing during *rabi* commences with the annual phenomenon of equinox falling on September 21 (Kumar et al. 2014).

Another distinguishing feature of *rabi* season is the dependence of sorghum growth and development on receding stored soil moisture in the vertisols of Maharashtra and Karnataka (southern) states of India. Despite potentially high yields of *kharif* season cultivars, sorghum area has been witnessing a steady decline across different states in India, not only owing to some specific biotic stresses but also farmer's growing interest in alternative crops like cotton, soybean, and maize. But

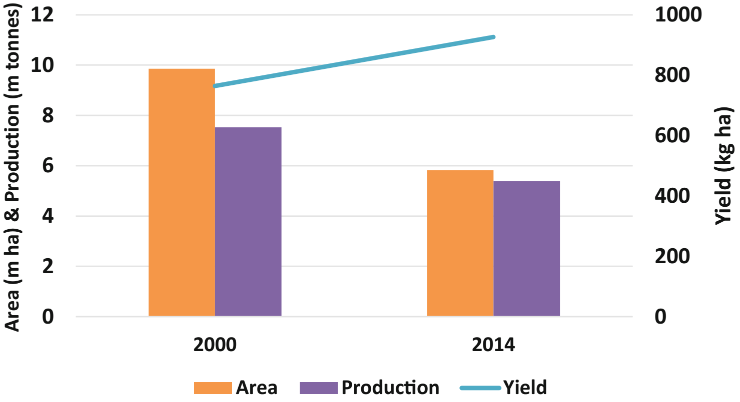

Fig. 2 Area, production, and yield trends of grain sorghum during the past few years. (Source: http://www.fao.org/faostat/en/#data/QC)

fortunately, sorghum *kharif* hybrids in recent times have found a new abode in nontraditional areas of Andhra Pradesh like Guntur and East Godavari districts during winter season in rice fallows, where farmers have been recording high-grain yields in the range of 5–6 Mg ha^{-1} (Mishra et al. 2011). Sorghum is sown in rice fallows under zero tillage after the harvest of the rice crop in December each year and comes to maturity during April in a dry summer weather, facilitating harvest of very clean grain. Maharashtra and Karnataka are the two important states that grow sorghum during both *kharif* and *rabi* seasons. In terms of productivity, Andhra Pradesh has recorded more than 2 Mg ha^{-1} as compared to all other states mainly because of the potential *kharif* hybrid yields in rice fallows.

One of the important environmental influences on sorghum especially at higher latitude, that is, 25°N 85°E (northeastern India), is the minimum temperature. In a multilocation trial during summer in NE India, it was found that the minimum temperature (<15 °C) increased the tiller number when sown early during second fortnight of February. As the minimum temperature increased above 15 °C by first fortnight of March, it had lesser influence on tiller number in sorghum. Planting window in nontraditional areas is narrowed by the minimum temperature at the start especially during summer season while by rainfall (onset of southwest monsoon) at maturity which could deteriorate the grain quality due to fungal mold incidence.

3.2 Cultivar and Relative Potential

Sorghum improvement in India historically commenced with the national release of CSH-1 as the first hybrid and followed with the spread of high-yielding improved seed across the rainfed sorghum-based cropping systems. A number of hybrids and open-pollinated varieties have been released for cultivation till date, specifically to suit different seasons across India both at the national level by the Indian Council of Agricultural Research (ICAR) and at the state level by State Agricultural Universities (SAUs). Indian crop breeding program targeted both yield improvement and biotic stress resistance across both longer (kharif cultivars) and shorter photoperiods (rabi cultivars) so as to attain higher productivity. Some of the prevalent public sector sorghum hybrids/varieties that are adapted to longer photoperiod (kharif and summer seasons) include CSH 14, CSH 16, CSH 25, CSH 30, CSV 20, CSV 23, and CSV 27, while cultivars that are suitable for shorter photoperiod (rabi season) include CSH 15R, CSH 19R, CSV 14R, CSV 216R, CSV 22R, and M 35-1 (Kumar et al. 2017). The only sorghum cultivar that performs in terms of improved productivity across all three seasons is the hybrid CSH 13 (Kumar et al. 2009).

Mishra et al. (2017), in their study during summer season, evaluated the relative performance of both hybrids and varieties of sorghum in eastern India. Sorghum hybrid “CSH 16” recorded significantly higher grain yield followed by “CSH 13” and “CSH 14” (Table 1). Among the varieties, “SPV 462” followed by “CSV 27” were found to be promising in terms of grain yield. On mean yield basis, hybrids

Table 1 Yield and related characters of sorghum hybrids and varieties

Sorghum cultivars	Grain yield (Mg/ha)	Stover yield (Mg/ha)	Plant height (cm)	Harvest index (%)	Panicle length (cm)	Panicle weight (g)	Test weight (g)
CSH 13	4.93	22.66	230.1	17.75	33.9	113	27.5
CSH 14	4.45	18.56	207.8	20.15	30.1	86	25.4
CSH 16	5.51	15.84	193.2	25.83	38.1	108	24.2
CSH 25	4.13	17.17	194.7	19.54	40.8	103	27.8
CSH 30	2.91	12.56	177.1	18.52	38.6	82	23.1
CSV 15	3.57	18.97	198.7	16.75	29.8	82	24.2
CSV 20	3.5	14.69	198.3	18.99	29.8	90	24.5
CSV 23	3.25	27.09	208.8	10.56	30.2	70	25.2
CSV 27	3.82	24.00	185.6	13.75	29.7	107	20.5
SPV 462	3.89	20.79	217.7	16.49	32.7	98	26.2
SEm±	0.17	0.41	2.10	0.68	0.40	6.00	0.09
CD ($P = 0.05$)	0.47	1.17	6.00	1.96	1.60	16.00	2.70

produced 22% higher grain yield over the varieties, while varieties produced 22% higher stover yield as compared to hybrids.

In sorghum, the stover yield is linearly related to plant height ($y = 0.19x - 20.5$; data not shown). Indian crop improvement program consciously bred for taller cultivars (an important selection trait) since sorghum fodder importance in Indian farming system has been well documented. The dual utilization of both clean grain for human consumption and dry fodder (stover) by farm animals has been to its great advantage in sustaining sorghum area especially during rabi season since no other field crop can compete in these rainfed ecosystems of Maharashtra and Karnataka. Grain yield in sorghum is a function of harvest index ($y = 0.14x + 1.6$; data not shown) especially in hybrids where the grain component is more than 20%, while in varieties, the fodder component is higher by 80% and more. In general, the low harvest index in Indian sorghums is due the importance being given by the crop improvement team to both grain and fodder, targeting an integrated (crops, farm animals) farming system. Sorghum breeder's selection for bigger-sized panicles and bolder grain has led to the release of sorghum cultivars in which there is a linear relation between panicle weight and grain yield ($y = 0.05x - 0.35$; data not shown). Introduction of sorghum hybrid technology through the All-India Coordinated Sorghum Improvement project helped gain time and space efficiencies. Tall photosensitive genotypes were replaced by the hybrids that flowered and matured early and thus helped gain time efficiency, while higher harvest index resulted in space efficiency, producing + grain per unit area.

Sorghum *kharif* hybrids in recent times have found a new abode in the nontraditional districts of Guntur and East Godavari in Andhra Pradesh during summer season where the farmers have been recording high grain yields in the range of 5–6 Mg ha^{-1}. With a limited number of irrigations (2–3), the farmer is able to attain high profits with a benefit:cost ratio of 2.4 (Kumar—unpublished).

3.3 Location Specific Management and Relative Potential

National Agricultural Research Project (NARP), which was launched by the Indian Council of Agricultural Research (ICAR), had the mandate for generating location-specific recommendations, and need-based research, targeted for specific agroecological situations. The focus was on designing a program that could solve the major agricultural growth-related issues based on natural resources, major crops, farming systems, production constraints, and socioeconomic conditions prevalent in any given zone. Stress was on generating location-specific technologies across various crops that were grown in these zones. In NARP, the country was divided into 127 agroclimatic zones, and below are the specific zones of major sorghum-growing states of Maharashtra and Karnataka (source: http://www.imdagrimet.gov.in/node/3535).

Kumar et al. (2004), while discussing the Indian monsoonal pattern, emphasized the typical feature of distribution variability (especially rainy days) resulting in early, mid-season, and late drought scenarios during sorghum crop growth period. Crop

Table 2 Tillage influence on sorghum grain yield and related economics

Tillage	Grain yield (Mg/ha)	Cost of cultivation ($\times 10^3$ Rs/ha)	Net returns ($\times 10^3$ Rs/ha)	Total energy requirement ($\times 10^3$ MJ/ha)
Conventional	3.12	27.72	23.51	8.94
Reduced	2.91	23.22	22.92	8.28
Minimum	2.64	22.02	20.46	7.62
SEm±	0.08	1.00	0.95	–
CD ($P = 0.05$)	0.22	2.86	2.78	–

management in such rainfed crop production systems attains greater importance, aiming to attain the full potential of an improved sorghum cultivar, which has the functional hybrid vigor for greater grain partitioning. Conservation tillage practices that help maximize in situ soil water intake, sowing window for optimal stand establishment, and integrated nutrient management are three important aspects investigated across agroclimatic zones of sorghum-growing states of India.

Tillage is an important component of sorghum crop management wherein soil moisture infiltration, weed management, and an ideal seed bed preparation are targeted specifically under rainfed farming. But destruction of soil structure and higher decomposition of organic matter leading to issues related to infiltration and soil health have gained greater importance. Multilocation trials related to conventional, reduced, and minimum tillage influence on sorghum were studied by Mishra et al. (2014). Cost of cultivation and energy requirement could be reduced under reduced and minimum tillage treatments as compared to conventional tillage (Table 2). Reduced tillage (2.91 Mg ha^{-1}) wherein the summer plowing was avoided resulted in on-par grain yield as compared to conventional tillage (3.12 Mg ha^{-1}) and with almost similar net returns. Consequently, reducing the tillage operations, minimizing organic carbon losses, and improving soil structure have been recommended for improved sorghum crop management.

Crop establishment studies across multilocations in India indicate significant effect of sowing time on grain yield during both kharif and rabi seasons. During kharif season, early sowing had improved the grain yield by 10% (Table 3). The results indicate that planting sorghum seed with the onset of southwest monsoon (early) helps to set a greater sink capacity indicating, that is, greater grain number, while significant increase in harvest index substantiates a functional improvement in terms of better partitioning into a more valued end product, that is, grain. But during rabi season, early sowing in September showed a decline by 9% in grain yield (Table 3), and the reason could be the rabi cultivar response to photoperiod (Ravi et al. 2009). Rabi season cultivars when grown during *kharif* season signified by longer photoperiod typically produce a smaller head and taller stalk (increased plant height). Sowing during early October would be ideal during *rabi* season so as to better match the short photoperiod requirements. Delay in sowing makes the crop encounter terminal drought and could result in reduced yield; in this case, the reduction was about 11%.

Table 3 Planting time influence on yield during the kharif (upper) and rabi (below) season

Season	Planting time	Grain yield (t/ha)	Harvest index (%)
Kharif	June first fortnight	3.69	0.31
	June second fortnight	3.35	0.28
	SEm±	0.07	0.003
	CD ($P = 0.05$)	0.20	0.01
Rabi	Sept first fortnight	2.13	0.29
	Oct first fortnight	2.35	0.32
	Oct second fortnight	2.09	0.28
	SEm±	0.05	0.004
	CD ($P = 0.05$)	0.15	0.01

Table 4 Sorghum grain yield (kg/ha) as influenced by farmyard manure (FYM), vermicompost (VER), and inorganic sources of nutrients (IORG)

Sorghum yield (kg/ha)	Locations			
Treatment	Akola	Indore	Parbhani	Mean
100% inorganic (IORG)	3040.83	5083.52	2840.91	3655.08
Recommended dose of nitrogen (RDN)				
50% RDN IORG + 50% FYM	3419.61	4320.99	2041.25	3260.62
75% RDN IORG + 25% FYM	3598.49	4557.01	2577.86	3577.79
50% RDN IORG + 50% VER	3188.13	4411.77	2030.72	3210.21
75% RDN IORG + 25% VER	3556.40	4720.41	2683.08	3653.30
50% RDN IORG + 25% FYM + 25% VER	3293.35	4484.39	2135.94	3304.56
C.D. (5%) Bi-Bj	242.8	487.11	224.93	913.33
C.V. (%)	6.03	8.87	7.58	21.95
F (Prob)	0.0	0.01	0	0.63

Integrated nitrogen management through use of both organic and inorganic sources has been the third aspect that has been researched across multilocations in India. The mean performance across multilocations in terms of sorghum grain yield was not significant, and hence, location-specific recommendations have greater relevance in crop management. At Akola in Maharashtra state, 25% farmyard manure (FYM) helped increased yield, while at Indore in Madhya Pradesh, 25% vermicompost (VER) along with 75% recommended N rate (Table 4).

4 African Sorghum Scenario

4.1 Status of the Crop: Production (Yield) and Acreage

Africa is the second largest producer of sorghum after America. In continental terms, sorghum ranks second after maize in terms of area and production. In 2012, the share of sorghum in the continent's cereal production was estimated at 23,350,064 Mg or

14.37% of total cereal production (Harold and Tabo 2015). By 2016, a total of up to 29.8 million tons of sorghum were produced in Africa. This represents a total harvested area of 30 million hectares with an average yield of about 1 Mg ha^{-1}(FAOSTAT 2018). Western Africa is the main contributor in terms of area harvested, followed by Northern Africa (due to Sudan) and Eastern Africa. In West Africa, Nigeria is the principal producer of sorghum with a sharp decrease in 2005, followed by Niger and, to a smaller extent, Burkina Faso and Mali (having a steady small increase in area harvested). In East Africa, the main provider is Ethiopia followed by United Republic of Tanzania, which experienced a sharp increase of area in mid-70s and seems to stabilize since then. In Central Africa, Cameroun and Chad are the two main producers. In Southern Africa, South Africa was the main producer before the 90s and since then came to the same level as Botswana or Lesotho.

Since the 80s, there was a constant increase of the area harvested in parts of Africa, certainly reflecting the increase of harvested area in Sudan (data to interpret with care) and the relative increase in Niger, Ethiopia, since the 90s and Chad and Cameroun since the mid-90s (Fig. 3). It was also seen that there was a drastic decrease of acreage in South Africa.

In Africa, sorghum-based systems are commonly managed as low-input systems. In traditional cultivation, the yield can reach 0.6–1 Mg ha^{-1}. When sorghum is intensively cultivated, the yield generally ranged from 1 to 3.5 Mg ha^{-1}. Sorghum grain yield in Africa slightly increases in the past 50 years from 0.8 to 1 Mg ha^{-1} (Fig. 4). Limited access of smallholder farmers to inorganic fertilizer or manure amendments is compounded by increased continuous cropping in response to food demand and population growth. Grain yield in Northern Africa in the 2000s reached up to 2 Mg ha^{-1}, mostly due to the doubtful high yield in Algeria (not shown); in FAO stat, grain yield is calculated from the production and the area harvested, so the small area harvested reported in Algeria inducing a rather high yield up to 10 Mg ha^{-1}. In Western Africa, the yield increase is similar to the overall yield increase in Africa, with Burkina Faso that started with a poor 0.4 Mg ha^{-1} in the early 60s to reach 1 Mg ha^{-1} in 2016, catching up with its neighboring countries. Conversely, Niger, one of the main producers, due to its high area harvested, had a decreasing grain yield from 0.7 to less than 0.2 in 1990 to get back to 0.5 Mg ha^{-1} in 2016. In Eastern Africa, sorghum yield goes up and down with a general trend around 1 Mg ha^{-1}. An exception is Ethiopia that experienced a sharp rise of grain yield from 2 to produce up to 2.5 Mg ha^{-1} in 2016. A similar picture as in Eastern Africa is true for Central Africa with only Cameroun having a steady increase in yield since mid-90s to reach a bit more than 1.5 Mg ha^{-1} in 2016.

In Africa, information on the crop production practices for improving yields is known but rarely applied due to other limitations rather than agronomic knowledge. Indeed, although best management practices are well documented, their adaptation to specific context is needed. A few examples, with a specific focus from West Africa, are presented here.

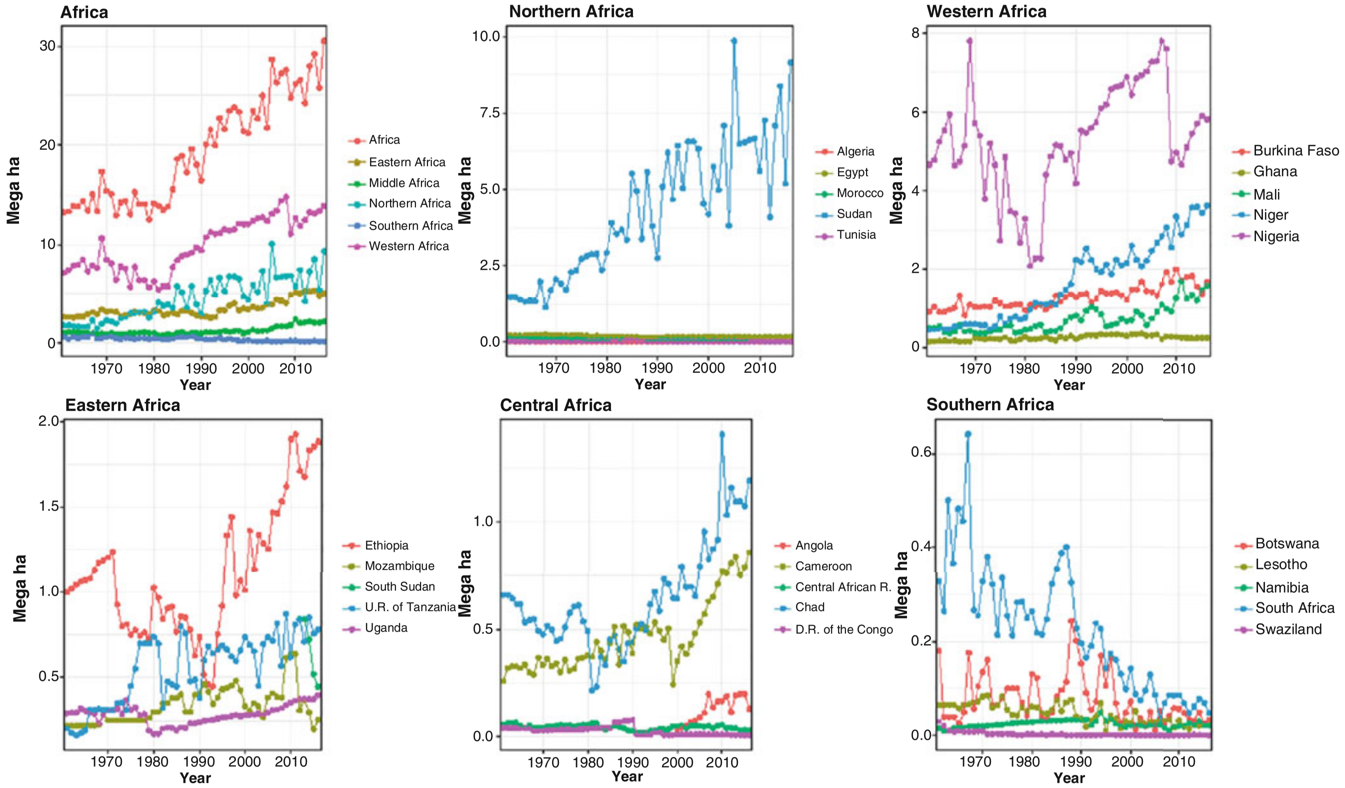

Fig. 3 Area harvested in Africa and per subregion from 1961 to 2016 (FAOSTAT). For each subregion, we represented the five top producers of sorghum (countries classified according to the United Nations geographical regions). Note that the y axis scale is different on every graph to represent clearly the area harvested in each subregion

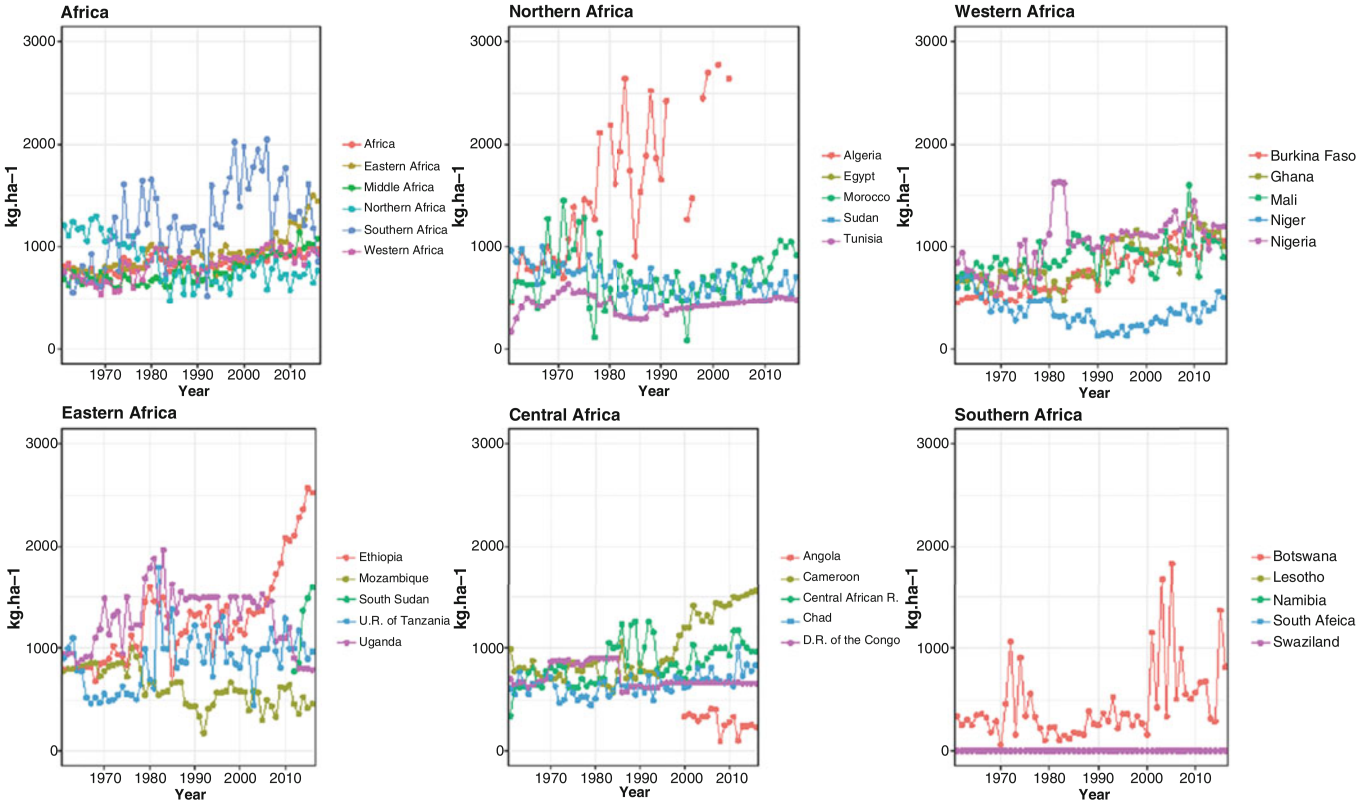

Fig. 4 Sorghum yield in Africa and per subregion from 1961 to 2016 (FAOSTAT). For each subregion, we represented the five top producers of sorghum (countries classified according to the United Nations geographical regions)

4.2 Main Agronomic Practices for Rainfed Sorghum-Based Systems in West Africa

4.2.1 Soil Preparation

For the preparation of the soil, it is necessary to perform an average plowing at the beginning of wintering to have a good seedbed. In thin or fragile soil, the preparation can be done by scarification or spraying. In West Africa, good soil preparation is necessary to allow a good start of the crop and a gain in yield. For a field cultivated the previous year, land preparation consists of clearing the land from the leftover of the crop residues by gathering together and burning them on the field. If it is a new field, a more drastic clearing is needed, removing trees. This land clearing is done at the end of the dry season, about 1 month before sowing. However, the low inherent fertility of tropical soils and degradation, nutrient deficiency, and water stress are key factors that hamper rainfed agriculture in semiarid West Africa. Hence, alternative solutions as minimum or zero tillage and maintenance of soil cover are currently tested in the region as technologies to reduce soil degradation, mitigate the effect of droughts, and increase crop productivity while reducing production costs (Lahmar and Yacouba 2012). For instance, *Guiera senegalensis* and *Piliostigma reticulatum* are managed by farmers to provide localized mulching. These twigs attract the termites that will consume them, open galleries in the soil crust, and bury organic matters likely to be returned gradually to crops. This litter also reduces runoff, improves and stabilizes infiltration, traps wind and water sediments, and provides a lot of carbon and nutrients to the soil (Lahmar et al. 2012).

Also, studies have been carried out on the effect of soil type and previous crop on sorghum yield (Falconnier et al. 2016). They showed that there was significant ($P < 0.01$) variation among farmer-defined soil types in grain yield of sorghum with greater yields on black soils than on sandy and gravelly soils. In addition, the best previous crops for sorghum are the same as for all cereals in general, that is, legumes (e.g., peanuts, cowpeas, soybeans) and cotton. To a lesser degree, millet and short fallow may be suitable. The worst crop precedence for sorghum is sorghum itself.

4.2.2 Sowing Methods

Seeds must first be treated with a fungicide and/or insecticide (thiram, organomercuric, aldrin, heptachlor, and carbofuran.) They must be healthy and free from impurities. Sorghum should be sown in reasonably moist soil after sufficient rainfall of about 20 mm is received. It is not recommended to sow it in dry weather or on dry soil. The recommended sowing period is from late May to late July (for short-cycle cultivar), with a peak around mid-June to mid-July according to the location. Planting time is advised so that plants reach flowering about 20–30 days before the end of the rainy season. Hence, the peak of sowing date, in regions with around 600–700 mm annual rain like in the Sanmatenga province in Burkina Faso, tends to be mid-June to early July, while in regions with an average annual rainfall over 800 mm like in Koutiala or Kati in Mali, the peak of sowing is a bit later around mid-July. Seeding is done in 4- to 5-seeded pits at a depth of 2–3 cm. Thus, the seed

Table 5 Fertilization recommendation for sorghum in four West African countries (adapted from Chantereau et al. 2013)

Country	Organic manure	Mineral fertilization
Burkina Faso	2.5 Mg ha^{-1}	Burkina phosphate 400 kg ha^{-1} every 3 years 100 kg ha^{-1} of NPK at sowing or first weeding 50 kg ha^{-1} of urea at boosting
Mali		100 kg ha^{-1} of DAP (phosphate diammonium) at first weeding 50 kg ha^{-1} of urea at boosting
Niger	3–5 Mg ha^{-1}	6 g $hill^{-1}$ of NPK and 2 g $hill^{-1}$ of DAP at first weeding 50 kg ha^{-1} of urea at tillering 50 kg ha^{-1} of urea at boosting
Senegal		150 kg ha^{-1} of NPK at sowing or first weeding 50 kg ha^{-1} of urea at tillering 50 kg ha^{-1} of urea at boosting

dose per hectare is 6–12 kg for spacing of 80 cm × 40 cm, 60 cm × 60 cm, and 80 cm × 15 cm. Thinning or resprouting and/or transplanting after 2–3 weeks is done to achieve an optimal stand density of 62,500 plants per hectare.

4.2.3 Fertilization and Weed Control

Declining soil fertility and limited farmer access to inorganic fertilizer frequently cause suboptimal grain yields throughout sub-Saharan Africa. However, it is estimated that a 5 Mg of well-decomposed manure per hectare every two (2) years will maintain the soil fertility level while favoring increases in yield of cereal crops. Blanchard et al. (2014) specified that according to the quality of the manure and the soil type, this rule should be adjusted as follows: 2.4–5.1 Mg ha^{-1} on sandy soils and 2.1–4.4 Mg ha^{-1} on clay soils. For mineral fertilization, it is recommended to apply 100 kg ha^{-1} of NPK or 100 kg ha^{-1} of NPKSB at sowing or first weeding (15 JAS) and 50 kg of urea ha^{-1} 35–40 days after sowing (at boosting stage of the crop) in Burkina Faso, but this recommendation varies slightly according to the country (Table 5). However, after cotton cultivation, the amount of NPK could be reduced by half given the residual fertilizer effect.

Further, Tonitto and Ricker-Gilbert (2016) published a recent review on nutrient management on sorghum-based systems in Africa. They confirmed that sorghum yield can improve in average by 66% if there is a nutrient input, no matter the form (mineral, organic, legumes). Weeding can be reduced by post-sowing herbicide (i.e., Titan) at 2–3 L/ha. In intensive cultivation, the first weeding occurs about 15 days after emergence. The second sarclo-hoeing must follow between 15 days and 3 weeks maximum after the first weeding. Weeding is done manually, mechanically, or chemically. The use of herbicides followed by ridging at 3 or 4 weeks may allow any subsequent interventions to be suppressed.

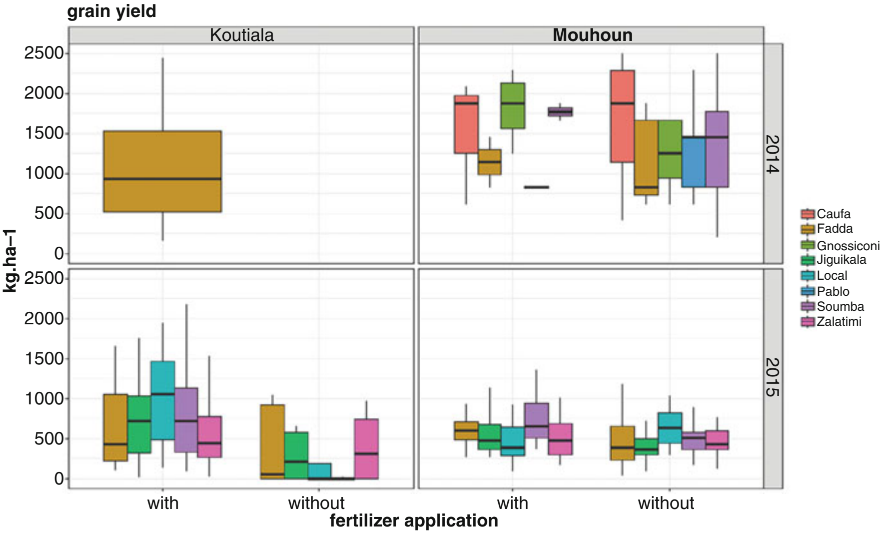

Fig. 5 Sorghum grain yield in farmers' fields in Koutiala, Mali, and Mouhoun province, Burkina Faso (2014–2015) with or without fertilizer for different sorghum varieties (Adam, unpublished data). This figure presents results from on-farm experiments that compare different varieties performances with and without fertilizer applications. Overall, we observed a slight increase in grain yield from an average of 600 kg ha^{-1} without fertilizers up to an average of 880 kg ha^{-1} with fertilizers. However, this result has to be analyzed according to the context. For instance, we notice in Fig. 5 that in a rather drier year (2015), yield increase will be more significant, going from 400 to 650 kg ha^{-1}, than in good year (from 1650 to 1900 kg ha^{-1}, 2014). Also, the yield increase varies according to the variety (from 30% up to 70%) and from one region to another (+100% for Koutiala, Mali, while only 10% in Mouhoun, Burkina Faso)

4.2.4 Intercropping Systems

Most often, the plant intercropped with sorghum is a legume (cowpea, groundnuts, or soya) or a cereal (corn or millet) to a lesser extent. On the Mossi Plateau in Burkina Faso, farmers often grow sorghum in association with cowpeas or peanuts. In the intercropped system, sorghum is the dominant plant because it is the species best able to use the resources of the environment for which the competition is exercised (Chantereau et al. 2013). Zougmore et al. (2000) demonstrated that sorghum-cowpea intercropping is beneficial in agricultural production terms since the grain yield of the intercropped plots was double than obtained with sorghum or cowpea monocultures. In addition, our preliminary results demonstrate that use of soya seems more beneficial than peanut or cowpea.

Intercropped sorghum with cowpea is an ancestral practice in West Africa. It is a mixed farming system that consists of planting two or more crops simultaneously on the same plot during the same season. Given the short duration of the rainy season in Sahel, cycles are juxtaposed and crop coverage is either total or partial during growth cycles. The spatial arrangement of the associated species is highly variable, and

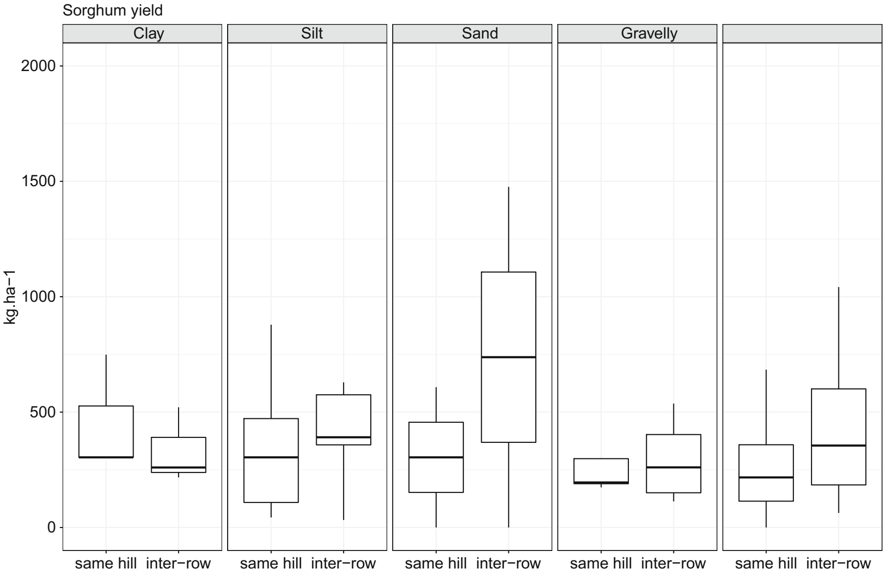

Fig. 6 Sorghum grain yield in farmers' fields Sanmatenga province, Burkina Faso (2016), comparing intercropping with seeds of cowpea in the same hill or in alternating rows (Adam, unpublished data)

according to Traoré (2009), intercrops are arranged in alternating lines, sometimes bands, or sown in mixture in the traditional mixed cultures. Indeed, to promote agroecological intensification, alternative intercropped cropping systems are tested with farmers. In Burkina Faso, first results from on-farm experiments show that use of interrow spatial arrangement gives a better grain yield than if cowpea and sorghum are at the same hill in farmers' fields especially on sandy soils (Fig. 6).

All smallholders appreciate the advantages of the different intercropping patterns and value the ease of work of the interrow intercropping systems compared to the farmers' practices combining cowpea and sorghum in the same hill. However, adoption is low, and farmers also clearly mentioned that the traditional way of intercropping should deserve more consideration from the research side. As a result, we initiated a project on improving the sorghum-cowpea systems in the same hill (Adam et al. unpublished).

4.2.5 Other Systems

In West Africa, other traditional systems are commonly seen in the field. These techniques consist of structures that mostly help to prevent erosion through either the setup of rows of rock, digging of a basin, or installing bunds. These practices are fragile and time-consuming but can reduce runoff by up to 40% and facilitate the accumulation of a bit of organic matter (Roose et al. 2017). The "zaï" is another technique fairly common in the Sahelian regions of Burkina Faso (and Niger). The zaï, mostly practiced on degraded land, consists of digging a hole of 20–40 cm of

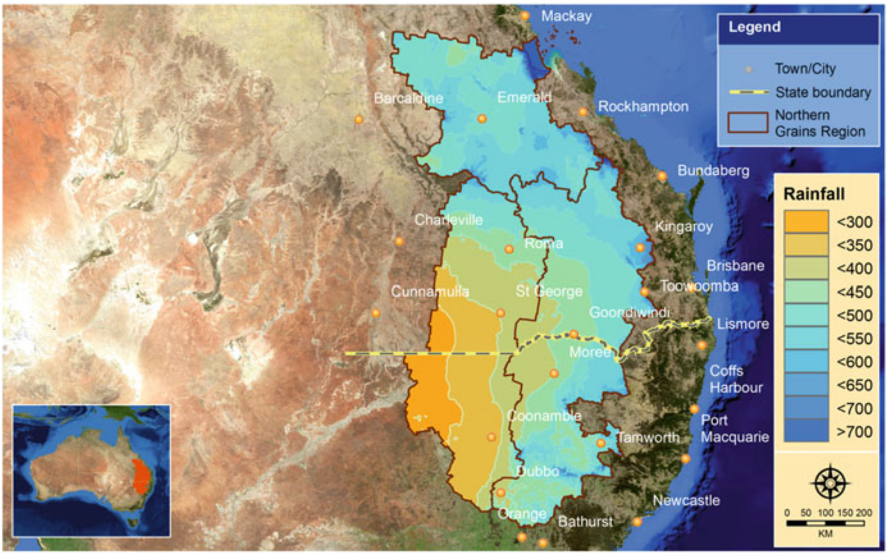

Fig. 7 Mean October to April rainfall (mm) for the northeastern Australian sorghum region

diameter and 10–20 cm deep, every 80–120 cm in staggered rows. During the dry season, these "holes" capture sand, silt, and organic matter, and before the rain, farmers will add to it a handful of organic matter from manure of different origins. After a storm, about a dozen seeds of sorghum will be sown, and 3–4 weeks later, thinning will occur, leaving three to four plants per hole. If possible, the farmers will add more manure in the coming weeks and will harvest 3–4 months after sowing. This technique enables to increase grain yield from 0.5 to 1.6 Mg ha^{-1} the first year (Kaboré 1995, Zougmore et al. 2008). Many variants of this technique exist, and a more detailed description can be found in Roose et al. (2017).

5 Australian Sorghum Scenario

5.1 Status of the Crop

Sorghum is the dominant summer grain for northeastern Australia and is primarily grown from northern New South Wales and southern through to central Queensland, between 21 and 32°S latitude. Sorghum is preferred to alternative summer grains because of its production reliability even when the crop is frequently water stressed during grain filling. Mean summer rainfall is typically between 450 and 700 mm across a west to east transect of the cropping region (Fig. 7) with high-season rainfall variability (Pratley 2003). The crop is typically grown on heavy clay soils after fallow periods of 9 months or more where up to 300 mm of plant available water are

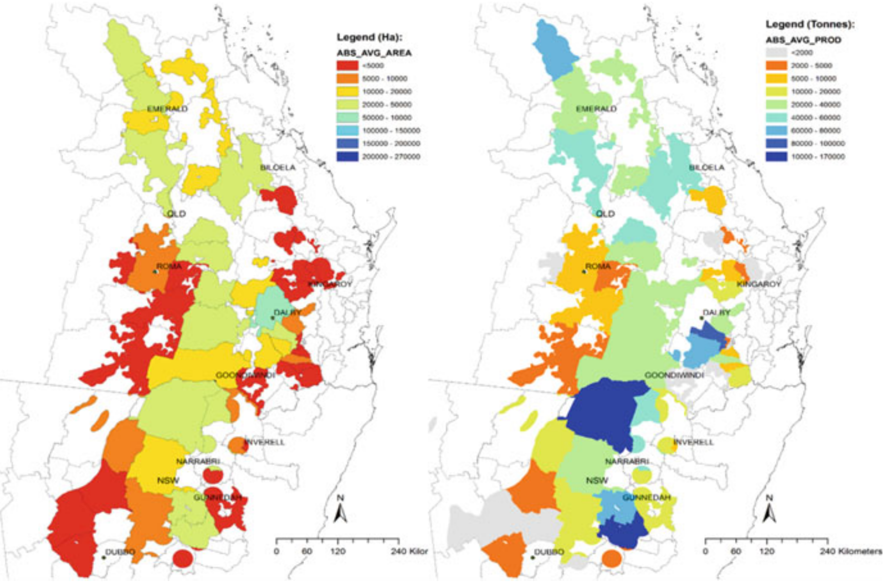

Fig. 8 Sown area (LHS) and production (RHS) for sorghum by Australian Statistical Local Area averaged for harvest years 1983–2001, 2006, and 2011 (Australian Bureau of Statistics; census data)

stored in the soil to support yield without in-crop rainfall. Australia has well-established markets, and most of the grain is used domestically for stock feed. From 1977 to 2016, an average of 39% of the crop was exported, but market varies from 1 to 116% of annual production (ABARES 2017).

The total sorghum area of 622,119 ha produces 1,416,027 Mg per year averaged across all growing regions from 2000 to 2011 (Fig. 8). Sorghum cropping area varies up to threefold seasonally, most notably in the major production area of Moree (Fig. 9). Yields also fluctuate seasonally, but an annual increase of 2.1% (44 kg ha^{-1} year^{-1}) was estimated between 1983 and 2011 when seasonal climate variability was accounted for using a shire scale crop stress model (Potgieter et al. 2016).

5.2 Main Agronomic Practices with Focus on the G × E × M

5.2.1 Planting Date

Sorghum is sown from September to February across the Australian cropping region to target flowering between mid-October and mid-March (Table 6). Earliest sowings occur after the frost risk has past and 9:00 soil temperatures at seeding depth (50 mm) are 16 °C and rising. The high evaporative demand during this period means that rain is required to moisten the topsoil before sowing even when surface

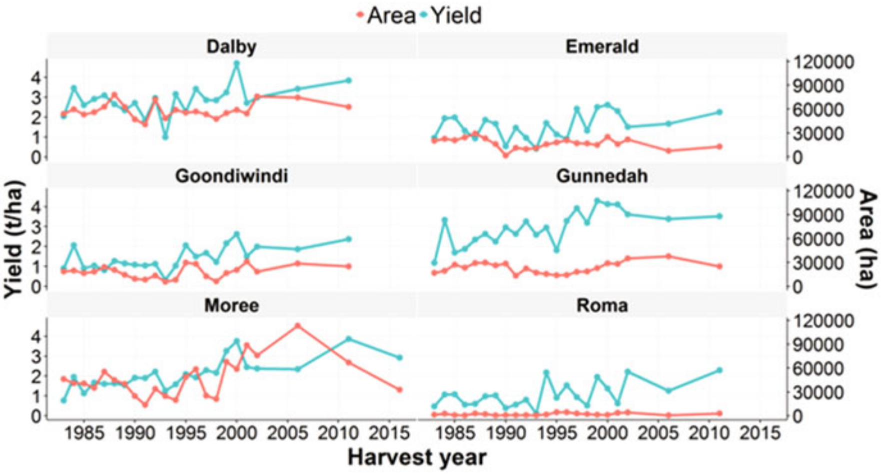

Fig. 9 Changes in sorghum production area and yield for six Australian Statistical Local Areas from 1983 to 2016 (Australian Bureau of Statistics)

residues are retained. In the most northern regions, sowing is not recommended due to heat stress for 1–2 months before end of December (Singh et al. 2017). However, genetic differences in heat tolerance of pollen were identified, potentially broadening the sowing window (Singh et al. 2016). The latest plantings occur before the risk of chilling temperatures (minimum daily temperatures <13 °C) during flowering and ergot reduce seed set.

Simulation analysis of sorghum sowing identified a high risk of crop failure when sown in August and September at Goondiwindi and Dalby due to frost-induced leaf area loss or water stress driven by tillering effects on LAI (Muchow et al. 1994). However, leaf area was not reduced in recent sorghum field trials that were frosted (−2 °C) before floral initiation, avoided heat stress at flowering, and were high yielding (unpublished results). Sorghum sowing practice in Moree shire which borders Goondiwindi to the south is from August to October despite recommendations of late September to early October. This remote-sensed time for the start of season or greening up for all summer crops is clipped to the cropping region. Summer active lay pasture and forage crops will also contribute to the start of sowing but are only small areas evident as regions of dryland summer cropping intensity approaching 1 crop per year. Cotton crops cover 29 to 92% of the summer cropping area and therefore contribute to start of season observations from mid-October to November. Early sowing recommendations require reevaluation in a cropping systems context and with climate change projections.

5.2.2 Plant Density, Row Configuration, and Spacing

Australian sorghum farmers match plant density, along with row configuration and spacing, to plant available soil moisture expected over the crop cycle. Narrow rows (≤0.75 m) and high plant density (≥100,000 pl ha^{-1}) may be used under full

Table 6 Recommended and industry practice sorghum sowing times across northeastern Australian cropping areas

		Sowing window; ✓ =recommended, *=actual industry practice																													
		JUL				AUG				SEP				OCT				NOV				DEC				JAN				FEB	
Growing region		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2
Queensland																															
Central	Kilcummin					*	*	*	*																	✓	✓	✓	✓	✓	✓
Queensland	Central & southern Highlands					*	*	*	*															✓	✓	✓	✓	✓	✓	✓	
	Callide & Dawson						*	*	*	*												✓	✓	✓	✓	✓	✓	✓	✓		
Southern	Darling Downs									*	*	*	*	*	✓	✓	✓	✓	✓	✓	*	*	*	*	✓	✓	✓	*	*		
Queensland	Western Downs								*	*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	*	*	*	*	✓	✓	✓	*	*		
	Boarder Rivers													*	✓	✓	✓	✓	✓	✓	✓	*	*	✓	✓	✓	*	*			
New South Wales																															
North	Northern plains										*	✓	✓	✓	✓	✓	✓	*	*	*	*	*	*	✓	✓	✓	✓	*			
	Liverpool Plains, North west													*	✓	✓	✓	✓	✓	*	*	*	✓	✓	✓	✓	*				
Central	Central west															*	✓	✓	✓	✓	*										

irrigation, and yields >8 Mg ha^{-1} would be expected (GRDC 2017; Wylie 2008). Across much of the production region, where the yield target is >3 Mg ha^{-1}, row widths of 0.75–1 m and plant densities of 30,000–80,000 pl ha^{-1} are used (Wade and Douglas 1990; Hammer et al. 2014). As conditions become increasingly marginal, wide, single, and double skip rows are used with low plant densities (<50,000 pl ha^{-1}), which limits the yield potential (<3 Mg ha^{-1}) and reduces risk of crop failure (GRDC 2017; Whish et al. 2005a, b). These plant densities are low by world standards, and consequently, tillers are a ubiquitous source of biomass and grain production, particularly with a high photothermal quotient and adequate resources during the crop establishment phase (Alam et al. 2017). Simulations suggest that the effect of hybrid and agronomy interactions on yield is minor relative to the effect of the environment but strongest when water stress at flowering is moderate and terminal water stress is severe (Clarke, unpublished). Recommended practices include zero or minimum tillage, stubble retention, preemergent residual herbicide and seed-safener use, controlled traffic, and late-grain fill spray-out (GRDC 2017).

5.2.3 Relevant Agronomic Traits and Progress

Crop improvement in Australia is underpin by public sector investment in the Queensland Department of Agriculture and Fisheries sorghum breeding program (Henzell and Jordan 2009). This operates as a germplasm enhancement program that develops lines and populations for particular traits. This germplasm is licensed to the private sector, who also develops parental lines and conduct broadscale testing (Chapman et al. 2000). The major achievements of the program have been increased midge resistance, drought resistance (stay-green), and grain yield. This program operates in conjunction with an advanced understanding of sorghum physiology, a locally developed and calibrated crop simulation model, and genomic resources to form an integrated crop improvement program (Hammer and Jordan 2007).

Grain weight and head size (grains/head) are two of many descriptors Australian seed companies use to describe the performance of their hybrids. Across multi-environment trials (2014–2016) yielding between 3 and 12 Mg ha^{-1}, the mean grain weight of commercial hybrids and prerelease hybrids ranged between approximately 22.5 and 32.5 mg/grain (Clarke unpublished). These same crops had between approximately 2000 and 3000 grains/head. Across these trials, the effect of environment (estimated using check hybrid yield) was not significant on grain weight for any hybrid. However, trials showed significant genotype effects on mean grain weight that were produced by hybrids with grains outside the typical range of 25–30 mg/grain. The effect of genotype on grain weight was offset by the tendency of hybrids with small grains to have more numerous grains/head.

The parameter $\varkappa$, used in APSIM to parameterize the sensitivity of grain number to dry matter accumulation over the period from floral initiation to the start of grain fill, is 0.00083 g/grain for the hybrid MR-Buster, which was released in the 1990s (Hammer et al. 2010). Among commercial hybrids and prerelease hybrids tested in 2014–2016, this value is the highest, with the range extending as low as 0.00045 g/grain (McLean et al. unpublished). This suggests that under identical conditions, contemporary germplasm available to Australian farmers has the capacity to set a relatively large number of grains. Such a trait is desirable because yield is often sink-limited in annual crops such as sorghum (Fischer and Wilson 1975a, b; Gambín and Borrás 2007; Muchow and Wilson 1976).

Grains/head may be an important determinant of G × E interactions among Australian commercial hybrids. Genotype × environment interactions readily complicate the task of matching hybrid to site and seasonal conditions. That is, the best performing (highest-yield, lowest-risk) hybrid in one environment may be superseded by another hybrid in a contrasting environment. "Yield stability" is a proxy for hybrid performance across environments. According to this concept, hybrids that are "stable" have yields that are relatively insensitive to changes in the productivity of the environment, known as the environmental index (EI). Such hybrids may be well suited to maintaining yield in stressful environments: a low-tillering- and/or early maturity-type hybrid whose relatively small canopy conserves soil moisture. Less stable hybrids respond strongly to changes in EI. Niche hybrids well adapted to high inputs or favorable seasons would be an example of the latter.

Analysis of the commercial hybrids most frequently represented across the multi-environmental trials referred to above identified important contrasts in yield stability. This analysis used the yield of MR-Buster to represent EI. A close negative correlation was observed between yield stability and relative yield across trials, which were characterized by low to moderate water stress (water stress environment types 1–3; Hammer et al. 2014). When simulations were used to extend the observations into environments terminating in severe water stress (environment types 4 and 5), the low stability (highly responsive) hybrids continued to show a yield advantage over stable hybrids. One of the most important traits determining yield stability appears to be grains per head. Hybrids that showed a weak or negative increase in grains/head with increasing EI were more stable, whereas the trend for less stable yet higher yielding hybrids was strongly positive. Among sorghum culms, the panicle of the main stem has been observed to have the largest number of grains, with secondary maxima occurring on tillers emerging from main stem nodes 2–3 (Lafarge et al. 2002). The UQ-QAAFI trials show hybrids that consistently productive tillers are most responsive to changes in EI at recommended plant densities and may be relatively high yielding across a wide range of environments, especially when yields are high (>6 Mg ha^{-1}).

Despite substantial pre-breeding genetic advances, Australian farmers have access to very similar broadly adapted commercial hybrids. For example, time of sowing trials at Warwick (2014–2015, $n = 12$) and Warra (2017–2018, $n = 9$), representing maturity groups ranging from quick to late and from medium-quick to medium-long, respectively, showed a range in flowering dates of 10 days or less despite a range in sowing dates of approximately 90 days or more. Despite the similarity, there are important contrasts among commercial hybrids influencing yield distribution, but there is also scope for breeding programs to diversify the range of potential phenotypes available on the market and for research to inform the agronomy and environments to which they are matched/adaptable.

6 Argentinian Sorghum Scenario

6.1 Sorghum Area and Productivity

Argentina is an historic sorghum producer, alternating the second place in exports with Australia in recent years (SSMA 2016). The area sown with sorghum in Argentina is relatively constant when compared to other crops like soybean or maize. During the last 25 years, around one million hectares are sown with sorghum each year, being the fifth crop after soybean, maize, wheat, and sunflower. Historically, sorghum area used to be higher, exceeding two million hectares around 1970–1980. Soybean and maize crops rapid development and improvement have contributed to sorghum area reductions. During the 2016/2017 growing season, the area sown with sorghum was close to 800,000 ha (PAS 2018). National sorghum grain production during 2016/2017 in Argentina was 3.2 million ton (PAS 2018). At the country level, sorghum yield showed a general positive trend when historical data is analyzed, albeit it showed episodes where yield remained stable. One of these periods was during 1980s, coincident with the introduction and rapid adoption of soybean crops. Another period started in 2000, possibly associated with the development of new technologies in maize and soybean, particularly genetically modified crops, and an increasing use of fertilizers (Satorre 2011). All these events indirectly affected sorghum national yield through the displacement of the crop into marginal and less productive areas. When considering the entire period, national sorghum yield was 1.5 Mg ha^{-1} in 1960 and is currently 4.5 Mg ha^{-1}. This gain is the result of improvement in both genetic and management (Gizzi and Gambín 2016). The yield progress was around 70 kg ha^{-1} $year^{-1}$. This rate can be considered high when compared to other important producers such as USA, Africa, and India (FAOSTAT 2018).

Agricultural production environments in Argentina cover an extensive area of around 65 million hectares, from latitude 24 to 40°S, involving the Llanura Pampeana or central region and the Llanura Chaco Pampeana or NEA (Alvarez and Lavado 1998). Main soil taxonomy orders are mollisols in Llanura Pampeana, alfisols in Chaco, and entisols and aridisols in the western area of both regions, showing important variation in soil depth and clay content (Alvarez and Lavado 1998). Annual average temperature ranges from 14 °C in the south to 23 °C in the north, and annual precipitation varies from 200 mm in the west to 1200 mm in the east. This diversity in climate and soils determines an important variation in sorghum yield across the entire region, ranging from more than 10 Mg ha^{-1} in the more productive areas to less than 3 Mg ha^{-1} in the southwest of the central region (Ministerio de Agroindustria 2018).

Sorghum crops are still highly valued to farmers because it has relatively low production costs and a particular ability to resist different types of abiotic stress including water deficit or excess when compared to other cereals (Doggett 1988). For these reasons, sorghum is usually grown in poor soils (i.e., soils with low organic matter, shallow soils, salinity soils). As stated previously, this was intensified during the last decades with the advancement of more profitability crops like maize and soybean. This was very clear during the last 7 years with the rapid adoption around the entire region of late sown maize, obtaining high and stable yields in a wide range of productive environments (Gambín et al. 2016). Late sown maize has become a valid alternative for maize producers to reduce risk in poor soils. In agreement to this, sorghum area is decreasing, being this area progressively less productive.

6.2 Exploring G × E × M for High Yields

A clear understanding of the target populations of sorghum environments is currently lacking in Argentina. For this reason, there is not clear definition of which genotypic traits or management practices are relevant to different growing environments. Sorghum production environments in Argentina are variable in soil type, soil depth, and water retention. This, combined with seasonal and annual variation in rainfall and temperature, determines different patterns of water stress during the crop cycle. It is well known that the timing, intensity, and duration of a water stress cause different effects on crops growth and development (Passioura 1983), and we are lacking a measure of the frequency of occurrence of different types of stress.

The same applies with temperature stresses, which are predicted to be more frequent in the near future (Lobell and Field 2007). The impact of high temperatures on sorghum flower development and grain set has been demonstrated (Prasad et al. 2008, 2015), but it is not clear how frequent these extreme temperatures are in our region. On the other hand, cold temperature restrains crop establishment in some areas, but this has not been characterized either.

Simulation models are a valuable tool to simulate crop growth and development (Passioura 1996). They play a fundamental role in crop breeding when used (1) for an environmental characterization, in order to identify the nature and frequency of stress events in the target population of environments, and (2) for predicting the phenotype of genotype × management combinations in target environments (Hammer and Jordan 2007). There are relevant evidences of the use of simulation models for these purposes in several species, including sorghum, and different regions (Chapman et al. 2000; Chenu et al. 2011; Sadras et al. 2012; Hammer et al. 2014; Seyoum et al. 2017; Singh et al. 2017). APSIM sorghum is a simulation model designed to exhibit reliable predictive skills at the crop level while also introducing sufficient physiological rigor for complex phenotypic responses (McCown et al. 1995; Hammer et al. 2010). The model is being used to simulate water stress index for ca. 300 growing seasons around the central region using soil and weather information for more than 40 years per location. This information will be used to determine the most common patterns of water stress and their frequency (Chapman et al. 2000). Preliminary information suggested that water stress around flowering is highly frequent for the sowing date most used in the central region (end of October–November) (Fig. 10). This is coincident with the critical period of yield definition in this species (ca. 15 days pre- to 10 days post-anthesis; Pepper and Prine 1972; van Oosterom and Hammer 2008), having negative consequences on yield. The

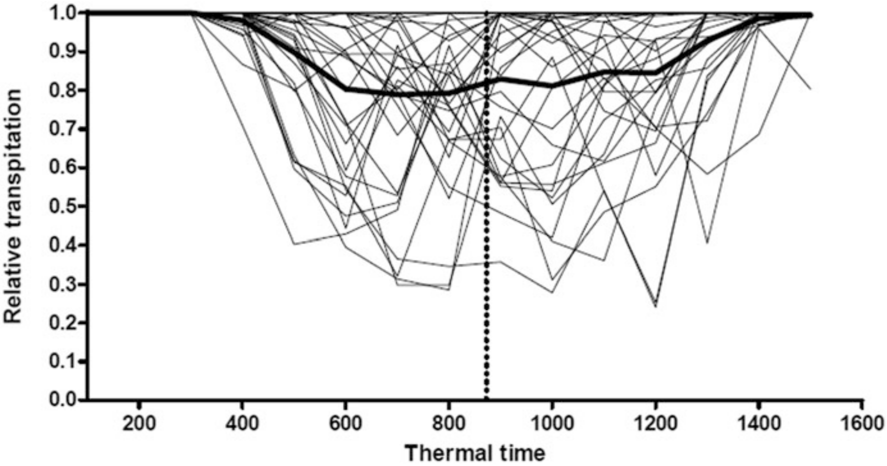

Fig. 10 Water stress patterns for each season as measured by relative transpiration index. Flowering occurred at about 900°Cd as indicated by the dotted vertical line. The bold line is the weekly water SD averaged over all seasons (39 years at Zavalla, Argentina)

information will be valuable to determine management options and genotypic traits relevant for particular scenarios.

For example, sowing date and maturity could be combined to avoid coincidence of the critical period for yield with a high probability of water stress (or temperature stress). The frost-free period around the central region ranges from 190 days in the south to 250 days in the north, and there is large genotypic variability in maturity among commercial sorghum genotypes (60–90 days to anthesis). This suggests there are many options of sowing date × maturity that could be explored. Stand density and row spacing are other interesting practices for modifying water consumption. Under water-limited conditions, increasing row spacing has been a successful practice in other regions (Whish et al. 2005a, b) and could be an option in the southern or western drier areas. The contrary applies under more productive environments (Giorda and Ortiz 2011).

Commercial sorghum genotypes show large variation in several attributes including biomass growth and partitioning (Gizzi and Gambín 2016), tillering capacity (Kim et al. 2010), root attributes (Singh et al. 2011), phenology plasticity (Ludlow and Muchow 1990; Donatelli et al. 1992; Craufurd et al. 1993), and transpiration efficiency (Mortlock and Hammer 1999; Xin et al. 2009) that could be explored as valuable traits under different growing scenarios.

6.3 Relevant Agronomic Traits and Progress

A recent retrospective analysis determined the genetic gain for grain yield in sorghum hybrids released in Argentina during the last 30 years was positive, averaging 8.7 kg ha^{-1} $year^{-1}$ (Gizzi and Gambín 2016) (Fig. 11). The genetic gain for grain yield was similar across environments, ranging from a rainfed-low-N environment (8.1 Mg ha^{-1}) to an irrigated-high-N environment (10.8 Mg ha^{-1}). A similar sorghum genetic gain was reported in Nebraska from 1956 to 2000 (13 kg ha^{-1} $year^{-1}$; Mason et al. 2008). When compared to other crops in Argentina, sorghum genetic gain was similar to sunflower (12 kg ha^{-1} $year^{-1}$; de la Vega et al. 2007) but lower than maize (132 kg ha^{-1} $year^{-1}$; Luque et al. 2006). The genetic gain was 0.1%, expressed in relative terms. This value is low when compared to others crops (Duvick and Cassman 1999; Fischer et al. 2014), possibly reflecting differences in plant breeding research investment (Mason et al. 2008).

Genetic grain yield gain was not the result of a single improved trait. Among all measured canopy traits, the genetic gain for grain yield was associated with an improvement in grain set efficiency per unit of accumulated panicle biomass at anthesis, stay-green, and post-anthesis source/sink ratio. Results indicated that breeding improved several grain-filling attributes (Gizzi and Gambín 2016). When analyzing what traits high-yielding hybrids showed irrespectively of their market release date, particular characteristics were evident: high grain number, low grain

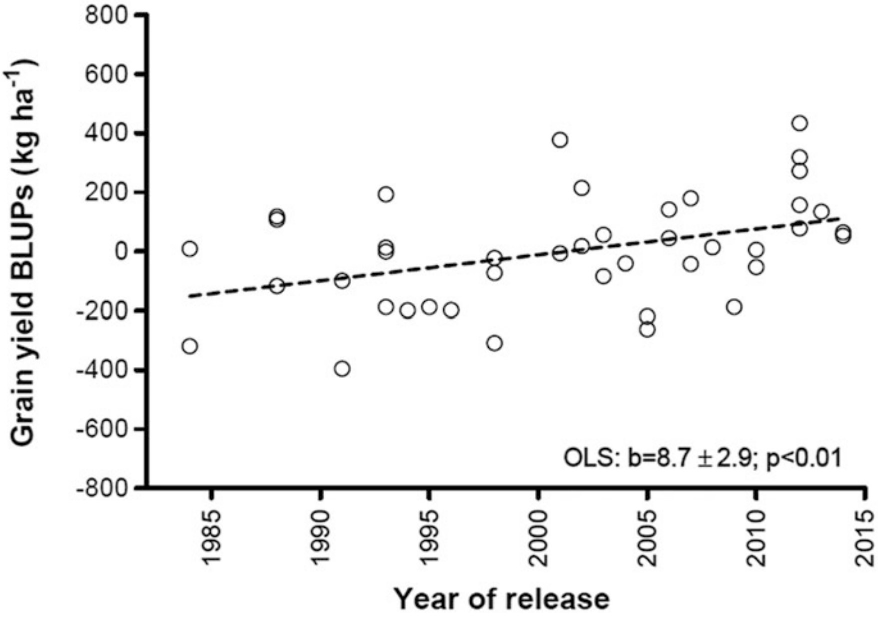

Fig. 11 Best linear unbiased predictors (BLUPs) for grain yield for a total of 43 hybrids against year of hybrid commercial release from 1984 to 2014. BLUPs were estimated from three different growing environments. Extracted from Gizzi and Gambín (2016)

size, medium-late maturity, intermediate height, and stay-green trait. This suggested that potential improvement could be exploited through specific adaptation and trait pyramidization.

Recent evidences indicated important G × E interactions for yield in the central region (Carcedo et al. 2017). Phenology differences among genotypes explained a large portion of this G × E interaction through its influence on grain weight (Carcedo et al. 2017). Very late flowering genotypes performed poorly in terms of grain weight and yield. Longer grain filling contributed to grain weight and yield at environments with low water stress levels, particularly when combined with intermediate or short maturity. Early materials contributed to grain weight and yield at environments with pre-flowering water stress. The information is useful to sorghum breeders at temperate environments, describing secondary traits that could assist selection at particular environments (Carcedo et al. 2017).

In summary, the genetic of sorghum has improved, but sorghum breeding programs in Argentina are being continuously discontinued or reduced by most seed companies, affecting the breeding process. Breeding programs are also focused on quality traits (tannin concentration, lignin content), which has limited yield genetic gain. Although this, yield potential for some materials is comparable to other C4 cereals like maize (close to 15 Mg ha^{-1}). The need of investment in research, breeding, and extension of sorghum is evident.

6.4 Main Agronomic Practices

Genotype selection (i.e., maturity) and other main agronomic decisions differ between the two main regions (central region and northeast region). In the central region, a high proportion of sorghum fields are sown after soybean as a predecessor crop and under no-tillage. The typical sowing window starts from the end of October to mid-November when soil temperature and moisture favor crop establishment. Genotype selection is mainly based on yield and relative maturity, being intermediate (ca. 75 days from emergence to anthesis) or intermediate-late (ca. 80 days from emergence to anthesis) the usual maturities in the region.

In the NEA region, a high proportion of sorghum fields are sown as a second crop after sunflower, and 82% of this area is under no-tillage in this region (Brihet 2017). The rest 18% is cultivated under conventional tillage. The sowing window is later than the central region and starts at the end of December, immediately after sunflower harvest, and extends during January. The particular sowing date is determined by soil water availability. Genotype maturity used is intermediate-late during December and early-mid January sowings, shifting to early maturity (less than 70 days from emergence to anthesis) when sowing dates are close to the end of January.

As sorghum crops are usually cultivated in poor soils, applied technology around the entire region is low, especially when compared to other crops (Brihet 2017). The proportion of farmers applying low technology to their sorghum fields has increased in the last decade (Brihet and Gayo 2016). Recommended stand density is usually

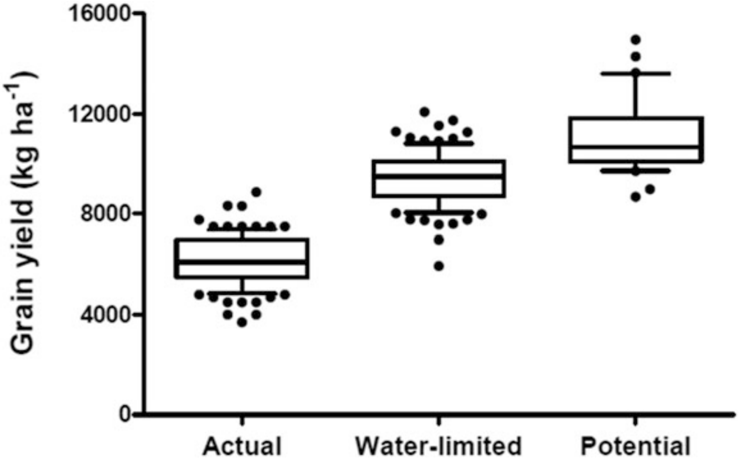

Fig. 12 Boxplot and whiskers (representing percentile 10 and 90) representing actual yield (*n*: 103), water-limited yield (*n*: 95), and potential yield (*n*: 33) in the central region of Argentina (south of Santa Fe province). Actual yields are based on county data from the Ministerio de Agroindustria during 2005–2016 (https://datos.agroindustria.gob.ar/dataset/estimaciones-agricolas)

high (around 18–20 pl m^{-2}) to compete with weeds, a major local problem. The recommendation is to reduce the stand density (15–18 pl m^{-2}) in more limited environments or increase it (higher than 20 pl m^{-2}) in the more favorable ones (Trucillo and Ortiz 2011). Row spacing is usually 0.70 or 0.52 m. Local experiences indicated positive yield gains when reducing row spacing from 0.70 to 0.52 m (Trucillo and Ortiz 2011) and that further reductions might result in yield advantages under some situations (low stand density; short maturity genotypes; Gambín et al. 2013).

Fertilization is not a common practice in Argentinean sorghum production, and, when done, applied N rates are quite low (25 kg N ha^{-1}; Brihet 2017). This is mainly related to the fact that most sorghum fields came from soybean as a predecessor crop, with the expected relative higher levels of soil N at sowing. Although this, soil samples as a diagnostic tool for fertilizer decisions are not common.

In summary, agronomic practices used by current sorghum farmers are not based on a clear understanding of G × E × M, which is in accordance to the current estimated yield gap (i.e., difference between potential yield or water-limited yields and actual yields; van Ittersum et al. 2013). Sorghum yield gap under rainfed conditions in the central region is ca. 3.5 Mg ha^{-1} (Fig. 12). This gap increases to ca. 4.7 Mg ha^{-1} under potential conditions. In relative terms, yield gap is around 37% to the water-limited yield, which is higher to values reported for main crops like maize and soybean in the same region (Merlos et al. 2015).

Water-limited yields are based on rainfed field experiments at Zavalla, Santa Fe province, during 3 years (2013, 2014, and 2015) under recommended sowing date (November), stand density (17–24 pl m^{-2}), and additional N (totalizing

120–160 kg N ha^{-1} soil plus fertilizer). Potential yields are based on similar experiments but under irrigated conditions and with additional N totalizing 220 kg N ha^{-1}.

6.5 Argentina Sorghum Future Perspective

Based on some of the evidences described above, the present of sorghum in the country is complex. The investment in technology and breeding has not been comparable to other major crops like maize and soybean, and this has negatively impacted in sorghum area and yield gains during the last decades. Although this, Argentina is still within the main sorghum exporters, and this needs to be seen as a real opportunity. Globally, sorghum demand is increasing, together with an array of crop uses, particularly human consumption and ethanol production (SSMA 2016). Argentina needs to find more opportunities for sorghum.

Here, we described two working areas that are relevant for increasing sorghum yield per area at the farmer level and for providing tools to farmers when deciding the inclusion of sorghum in their farming systems.

7 Sorghum Versus Maize: A Comparative Analysis

It is not clear as to in which environments sorghum is more competitive in terms of yield when compared to maize. Currently, both crops are destined to different environments, and at similar sites, the applied technology to each crop is quite different. This leads to a permanent sub-estimation of sorghum yield by farmers. It is not clear how both crops perform under same environments, and some evidences imply sorghum is competitive in specific environments.

Agriculture expansion and intensification have contributed to climatic change, and in this context, sorghum is attractive. Several studies agree that the agricultural production will be riskier. Simulation analysis indicate that maize production is more sensitive to rainfall and temperature compared to other cereals like sorghum (Fischer et al. 2005; Lobell et al. 2008), and sorghum is proposed to substitute maize in some regions in the future (Lobell et al. 2008). In other regions like Southern Africa, comparative field experiments are important to complement and support simulation analysis concerning adaptation of crops to climatic change (Rurinda et al. 2014).

In Argentina, it is estimated that temperature will increase 0.5–1 °C during the next two decades, being this increment >1 °C at the end of twenty-first century (Barros et al. 2014). In the north and west of the country, temperature could raise from 2 to 2.5 °C. Regarding rainfall, projections indicate that will increase in some areas (north and central areas of the country) and reduce in others (western areas and Patagonia) (Barros et al. 2014). There are ecophysiological studies comparing both crops (Gambín et al. 2008), but very few have empiric evidence of crop comparisons to define environments and managements for sorghum as a more competitive option.

It is well known that maize performs better than sorghum under low water and N limitations (Muchow 1988; Farré and Faci 2006; Ferraris et al. 2013), and evidences suggest sorghum yield performs better than maize under water-limited conditions (Stone et al. 1996; Ferraris et al. 2013). There are not clear evidences of comparative performance under water excess. Studies in other regions indicated a threshold of 200–500 mm of available water below which yield of sorghum exceeds maize (Stone et al. 1996; Farré and Faci 2006). Local evidence indicated that the sorghum yield can be 3000 kg ha^{-1} higher than maize under water-limited conditions (Ferraris et al. 2013). Under these situations, sorghum even responded to applied N while this was not observed in maize.

Food security has become an important topic in recent studies associated with human population increases (Chen et al. 2011). Together with food security, there is an increasing need for a more sustainable agriculture (Chen et al. 2011; Foley et al. 2011). Expansion and intensification of agriculture have a strong impact on biodiversity, C reservoir, and soil properties. Agriculture had a relevant impact on ecosystems, being pollution and soil degradation the main problems (Oesterheld 2008). This is mainly associated to deficient management and poor crop rotations. Remaining biomass after harvest is essential for maintaining soil fertility, soil C levels, and physical properties (Huggins et al. 1998; Novelli et al. 2017), and in this context, sorghum crops are of particular interest. Future studies should focus on the amount and quality of remaining biomass (Amaducci et al. 2000), where this species can make a significant difference.

8 Future Perspective

Several common points of action have been identified:

- Environmental characterization using modern tools and demarcating/aligning regions based on agroclimatic uniformity and recommending practices that are location specific.
- Relevant and actionable data to support rainfed farming systems selection of G × M combinations for expected seasonal conditions incorporating climate forecasts.
- Integrating G × E × M knowledge to develop cultivars suitable for targeted regions.
- Further parameterizing simulation models with new sorghum trait and technology advanced for predicting yield distributions.
- Integrating multidisciplinary and multiregional projects through international funding.
- Identifying new models that have greater impact and help in bridging the yield gaps.

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