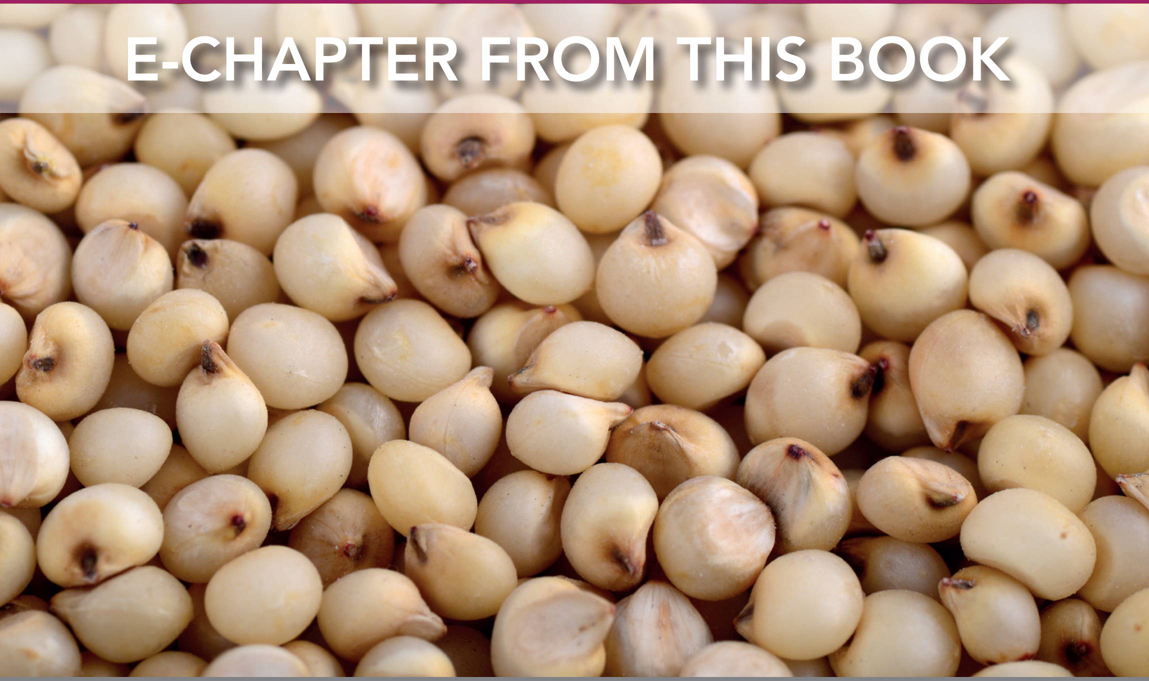
BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Achieving sustainable cultivation of sorghum

Volume 2: Sorghum utilization around the world

Edited by Professor William Rooney
Texas A&M University, USA



burleigh dodds
SCIENCE PUBLISHING

Sorghum cultivation and improvement in West and Central Africa

E. Weltzien and H. F. W. Rattunde, University of Wisconsin-Madison, USA, formerly International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Mali; T. A. van Mourik, International Potato Center, Ghana; and H. A. Ajeigbe, International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), Nigeria

1 Introduction

The diversity of sorghum cultivated in Africa attests to the African origin of this crop. Ten to 25 or more varieties of sorghum may be cultivated as distinct pure stands in a single village in Mali (Siart, 2008) or Burkina Faso (Barro-Kondombo et al., 2010). In Northern Cameroon, varietal mixtures are cultivated, with each mixture containing 12 varieties on average (Barnaud et al., 2006). Farmers have developed strategies for using varietal diversity to minimize risk and maximize productivity in the context of complex and diverse adaptive challenges, strategies developed over several thousand years of cultivating sorghum. The diversity of sorghum types cultivated reflects the wide and contrasting ecosystems in which it is cultivated and the range of ways it is used (Rooney, 2004).

Sorghum in West and Central Africa (WCA) is primarily produced between the 500- and 1200-mm rainfall isohyets. These rainfall isohyets, following an east-west orientation parallel to the southern edge of the Sahara (Fig. 1), as well as biotic constraints and soil

http://dx.doi.org/10.19103/AS.2017.0015.29

Chapter taken from: Rooney, W. (ed.), *Achieving sustainable cultivation of sorghum Volume 2: Sorghum utilization around the world,* Burleigh Dodds Science Publishing, Cambridge, UK, 2018, (ISBN: ISBN: 978 1 78676 124 8; www.bdspublishing.com)

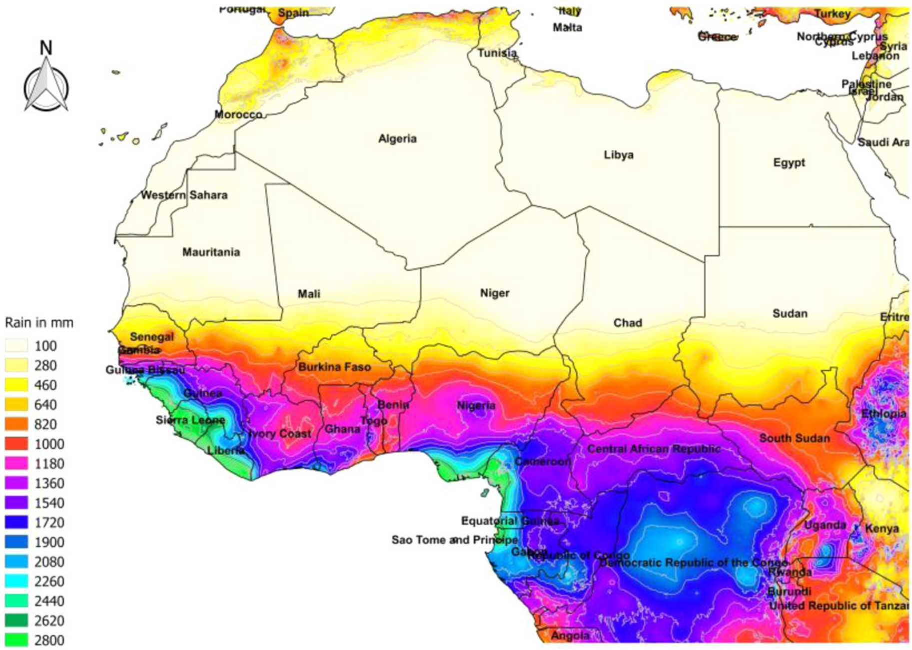


Figure 1 Rainfall isohyets of West and Central Africa (Source: www.esri.noaa.gov).

typology, determine the major varietal adaptation zones. Sorghum continues to be a basic staple food for large portions of the population in this region. The total sorghum production is larger and increasing in West Africa (1980, 5.5 m tons vs 2010, 12.9 m tons) as compared to East Africa (1980, 3.3 m tons vs 2010, 6.4 m tons) and Southern Africa (1980, 0.8 m tons vs 2010, 0.3 m tons) (FAOSTAT, 2017). This chapter aims to provide insights and entry points for understanding sorghum cultivation in the WCA region. Chapter sections describe the major sorghum production systems, options for intensification and sustainable production, genetic diversity and opportunities to breed for enhancing sorghum crop value, and progress in strengthening seed systems.

2 Overview of sorghum production systems in West and Central Africa

Sorghum is grown first and foremost for food throughout most of WCA. This crop therefore is not just a commodity but has been a determinant of survival and an integral part of life and culture of this region over millennia. For example, sorghum in WCA is typically considered a 'men's' crop (Weltzien et al., 2006), with men being responsible for sustaining the families by providing the basic staple cereals used to cook the main meals. As such it was traditionally taboo for men to sell sorghum grain and put the survival of their family in jeopardy. Thus sorghum certainly was a subsistence crop, grown for home consumption as tô (thick porridge), degué (thin porridge), couscous or other preparations, including beer in some locations. Yet, farmers are ever more integrated into a cash economy, and sorghum is increasingly grown not only for food but also for cash income and fodder, with strong demand for sorghum grain from both rural and the fast-growing urban populations and processing companies. Women often cultivate sorghum as well, but typically in smaller areas. The grain they produce is often for special needs, such as for children's meals outside of the main family meals, during hunger times when the men's grain stores are exhausted, or for sale to meet household expenses. The use of sorghum grain for malting in artisanal and/or industrial brewing can be locally very important, such as in parts of Burkina Faso, Ghana and Nigeria. And finally, the sorghum residue, the stover, can be important for feeding livestock, particularly for dry season survival in lower rainfall zones and areas with more intense land use.

2.1 Sahelian region

The Sahel zone, on the edge of the Sahara, is a zone with annual rainfall between 100 and 600 mm (Nicholson, 2013), and agricultural production between 300 and 600 mm. The rainfall occurs in a single rainy season, primarily between July and September. The Sahel is known for its high inter-annual variability and unpredictable rainfall, leading to frequent droughts and even famine. The predominant soils in this zone are aridisols with sand content often 80% or higher. This zone spans sub-Saharan Africa from Senegal in the west to Sudan in the east (Fig. 1).

Pearl millet is the dominant staple crop in this zone, with sorghum cultivated in areas where there are heavier soils such as in the Gedaref of Sudan or in lower lying areas where water accumulates or stagnates. However, sorghum is the dominant cereal in certain sandy soil areas where pests or diseases prevent pearl millet cultivation. One such area is the north-west region of Mali, where blister beetles feeding on the pollen and anthers of pearl millet frequently cause poor seed set. Sorghum is also intercropped with pearl millet, especially in deep sandy soils where water reserves at lower depths can be reached by late-flowering sorghums. In Niger this type of 'dune sorghum' also benefits from dew during November and December to complete its growth cycle. Sorghum may be cultivated in rotation with pearl millet to interrupt the multiplication of the parasitic weed *Striga hermonthica* in areas where this parasite is specific to pearl millet.

A sorghum cropping system that uses receding water following the end of the rainy season in Sahelian areas is identified by region-specific names; 'Decrue' in Mali and Mauritania, 'Fadama' in Northern Nigeria or 'Marwari' in Chad and Cameroon (Comas and Gomez MacPherson, 2002). Bird damage and stemborer attacks are strong biotic constraints in this production system. Sorghum may also be irrigated in these areas, especially where there is a high demand for animal fodder as in Mauritania (Mohamed et al., 2016).

Animal husbandry is the basis for livelihoods and resilience in the drought-prone Sahelian zone (Mohamed et al., 2016). Sorghum and pearl millet stover therefore are highly valued, with nearly all stover being consumed by livestock grazing or managed feeding during the dry season.

2.2 Savannah region

The Savannah region encompasses a broad swath of land with annual precipitation ranging from 600 to 1300 mm, with rainfall declining as one heads northwards towards the Sahel. Subzones are identified within this region based on rainfall levels; the Sahel Sudan Savannah or Northern Sudanian zone (approximately 600 to 800 mm), the Sudanian-Savannah or Southern Sudanian zone (800 to 1100 mm), and the Northern Guinea-Savannah zone (1100 to 1300 mm). These agroecological zones stretch across WCA immediately south of the Sahel zone, extending from Senegal and Ghana to Chad and parts of South Sudan (Fig. 1). The sowing period for sorghum depends on the onset and length of the rainy season, with sowing in the wetter Northern Guinea zone spanning the period from May to early August, whereas in the Sudanian zone it occurs in the months of June and July, with typically later onset in the Northern Sudanian relative to the Southern Sudanian zone.

Sorghum is the dominant traditional staple crop in the Savannah region. It is often grown in rotation or intercropped with cotton, maize, millet, groundnuts, cowpeas or soybean in varying proportions and intercrop arrangements. Sorghum typically follows cotton or maize in these rotations and benefits from residual fertility, receiving little direct application of inorganic fertilizer. Sorghum's ability to more reliably produce under poorer soil fertility conditions contributes to its important role in these farming systems and its importance for food security. Pearl millet, rice and diverse minor millets, roots and tubers and other legumes are also grown in this region for food security and sale in local markets.

Research and development interventions for intensifying sorghum production have greatest potential for positive and rapid outcomes in the Savannah region, especially in the context of higher grain prices. Recently sorghum demand in the malting and confectionery industries has increased significantly, especially in Nigeria (Office of the Honorable Minister of Agriculture, 2012) and Ghana, with sorghum being substituted for other cereals in the production of malt and composite flours. The opportunities are greatest in the Southern Sudanian zone, where the largest population and sorghum production areas are found, and in the Northern Guinea Savannah, where historically relatively less research and development efforts have been made. There are some indications of intensification (Sanogo et al., 2010), but it depends on the individual farm unit and location (Falconnier et al., 2015; Ollenburger et al., 2016).

Labour shortage, resulting from limited mechanization and low population densities, especially in higher rainfall areas, is one of the main constraints to sorghum production and intensification in these zones (Kenga et al., 2003). Weed control is a primary constraint, although the use of herbicide is rapidly increasing. Women sometimes lead in adopting herbicide use to cope with the higher weed pressures resulting from later allocation and ploughing of their fields relative to men's fields. Low soil fertility is another serious constraint to sorghum productivity in this region (Buerkert et al., 2001; Leiser et al., 2012), with sorghum typically cultivated in fields deemed to be too poor for maize production. Furthermore, what little inorganic fertilizer is applied has relatively low efficacy (Buerkert and Hiernaux, 1998) due to labour limitations and near absence of mechanization for optimal application methods (Leiser et al., 2012). Thus the value and sustainability of new sorghum production technologies will be determined to a considerable extent by their labour requirements and their contributions under specific soil fertility and weed management contexts.

The integration of livestock and crop production is progressing where land use is intensifying and where improved control of the Tsetse fly reduces the risk of Trypanosomiasis for ruminants. Intensified agroforestry and horticulture are also important emerging options. Maize has become an important staple in the higher rainfall areas, complementing or even replacing sorghum in these zones. Maize can produce higher yields with sufficient fertilization, and due to its shorter growth cycle, spreads the work load and provides food during the 'hungry period' prior to the end of the rainy season, although with serious risks of aflatoxin contamination.

Sorghum, unlike maize, normally matures after the rains end which, together with a lax panicle form, minimizes grain mould infestations of the openly exposed grains (Haussmann et al., 2012). Photoperiod sensitivity enables sorghum to flower at a relatively fixed calendar date and to mature after the rains end, despite highly variable sowing dates. This ability not only helps to minimize grain mould and aflatoxin contamination but also reduces the potentially devastating damage by bird and livestock grazing, by facilitating synchronous, optimally timed, maturation relative to the end of the rains. It also reduces risks of poor grain filling encountered by late-maturing plants that run out of water. Photoperiod sensitivity is thus a key mechanism for yield stability and grain quality in these zones (Clerget et al., 2008; Haussmann et al., 2012). Although photoperiod-insensitive varieties can be grown in niche environments, photoperiod-sensitive varieties are best for the predominant, full-season, production environments, and hybrids with photoperiod sensitivities similar to those of local varieties have recently been bred (Rattunde et al., 2013; Kante et al., 2017). Photosensitive varieties typically have adaptation ranges in east-west bands of only about 100 km width, corresponding to the narrow east-west rainfall isohyets of WCA (Fig. 1).

3 Intensification and sustainability of sorghum production systems in WCA

3.1 Soil fertility management and varietal options for farmers

WCA has some of the most geologically ancient soil parent materials and a preponderance of highly weathered soils with low soil organic matter content and low fertility (Breman, 1998). The low plant-available phosphorus (P) in these soils is a major limiting factor to sorghum production (Doumbia et al., 1998; Buerkert et al., 2002; Ouédraogo et al., 2005; Kihara et al., 2016). Whereas the critical P threshold required for sorghum growth is 11.6 ppm Bray1 P (Doumbia et al., 1993), sorghum production fields in Mali averaged only 8.3 ppm Bray1 P in the more intensified cotton-growing Dioila region and 4.5 ppm Bray1 P in the Mande region where little or no cotton is grown (unpublished data). Soil organic matter was also low (0.6% organic C) in both zones.

Sorghum's ability to reliably produce harvestable grain under low soil fertility conditions without mineral fertilization is one reason why it remains an important staple cereal in WCA. Approximately 90% of sorghum in the region is produced without inorganic fertilization, primarily due to farmers' financial constraints. The crop relies to a great extent on residual fertilizer effects from previous crops and limited applications of organic amendments. The low fertility conditions under which sorghum is grown is a major contributor to the generally low (approximately 1 ton/ha) grain yields obtained by farmers in the region (Buerkert et al., 2001; vom Brocke et al., 2010).

Agronomic studies already in the 1960s showed that sorghum yield responses to nitrogen (N) and phosphorus (P) applications were attainable, although there was no response to N without P applications in Northern Nigeria (Kaduna to Zaria) (Goldsworthy, 1967). A recent meta-analysis of sorghum response to soil fertility options in Africa reported 47–98% yield increases with N and P chemical fertilizers and 43–87% yield increases with use of organic nutrients across 29 studies in Africa (Tonitto and Ricker-Gilbert, 2016). This study estimated that net returns from N+P applications were higher than those from N alone, but the net returns with both mineral fertilizer treatments were considerably lower than those with sorghum–cowpea (*Vigna unguiculata*) rotations in Burkina Faso where in-depth economic analyses were done. Intercropping sorghum and cowpea, however, gave net returns that were considerably lower than those obtained with rotations and slightly lower than those obtained with mineral fertilizer treatments.

Organic soil amendments are vital for intensification of WCA farming systems (de Ridder and van Keulen, 1990). The integration of livestock with crop production offers important opportunities for enhancing sorghum producers' access to animal manure (McIntire et al., 1993).

The method of fertilizer application is a major determinant of fertilizer efficiency for sorghum. Broadcasting fertilizer without incorporation is expected to result in losses through run-off, N volatilization and poor plant uptake (Leiser et al., 2014). Also, farmers' practice of applying fertilizer only after the first weeding, three to five weeks after sowing, is expected to deliver P too late to benefit the current crop. Placement of small quantities of fertilizer [4 kg NPK ha^{-1} (Buerkert and Hiernaux, 1998), 3 g per planting hole (Aune et al., 2007)] near the seed at or shortly after sowing were found to increase yields at least 30% and give a threefold increase of P use efficiency relative to traditional practices (Buerkert and Hiernaux, 1998). Microdosing just 0.6 g NPK per planting hole was able to increase grain yield on a poor heavy clay soil (Abdalla et al., 2015). The development of appropriately scaled implements for mechanized application of fertilizer could greatly enhance fertilizer efficiency and yields by enabling farmers to incorporate fertilizer in a timely and effective manner despite their labour constraints.

The complexity of WCA farming systems, with trade-offs between income generation, soil conservation and community agreements, calls for focus on farm and farming system and not just individual fields for targeting technologies (Giller et al., 2011). Although context-specific information on fertilization would be useful to sorghum farmers seeking to optimize fertilization rates and profitability, such information is extremely rare. For example, information on rate of returns to fertilizer use by soil type and fertility level, rainfall zone and preceding cropping history would help farmers make informed decisions.

Sorghum fertilization and varietal options were jointly examined for their effects on productivity and profitability in a series of 81 on-farm variety trials conducted in Mali by the Institut d'Economie Rurale, ICRISAT and farmer organizations from 2009 to 2012. Three different types of varieties (farmers' local, pure-line bred and Guinea-race hybrids) and two fertilization options [without and with fertilization (100 kg di-ammonium phosphate and 50 kg urea/ha)] were tested. The trials were conducted by equal numbers of women and men farmers in the Dioila, Koutiala and Mande zones of Mali. Fertilization improved grain yields on average by 55% to 70% depending of the type of variety (Table 1). The net returns, estimated by subtracting the expenses for fertilizer, seed and seed treatment and field labour from the value of the grain produced, were higher with fertilization than without for all types of varieties. The research-bred pure-line and hybrid varieties, however, showed approximately double the returns to fertilizer use relative to the farmers' local variety. The use of these improved sorghum varieties, with considerably lower cost for seed relative to that of fertilizer, appears to offer farmers a type of insurance for obtaining returns on their investment in fertilizer purchase.

Table 1 Mean yields and net returns under unfertilized and fertilized conditions of farmers' local varieties, research-bred pure-line and hybrid varieties over 81 on-farm trials in Mali, 2009–12

	Unfertilized control		Fertilized		Gain fertilized over control	
Variety type	Yield (kg/ha)	Net return (Fcfa*)	Yield (kg/ha)	Net return (Fcfa)	Yield (%)	Net return (%)
Local	685	117 436	1062	146 164	55	24
Bred pure-line	785	134 083	1332	192 083	70	43
Hybrid	893	150 843	1516	222 360	70	47

*Monetary unit in West Africa with fixed exchange rate to the Euro (656 Fcfa:1 Euro).

3.2 Soil and water conservation

An array of techniques have been developed for soil and water conservation (SWC) that are pertinent for the predominant sorghum production areas of WCA where water run-off can cause serious soil, nutrient and water losses (Zougmoré et al., 2009).

Contour bunds, stone or earthen mounds with permanent grass cover installed on the contour are the most widely followed and economically important practices. Contour earthen bunds are inexpensive and profitable (Gigou et al., 2006). The installation of contour bunds with oxen-drawn plough requires external help for determining the contour lines. A local Malian NGO has assisted with installation of contour bunds, and farmers' demand has exceeded the NGO's capacity (Gigou et al., 2006). Grass strips with *Andropogon gayanus* is another option (Zougmoré et al., 2009).

Contour bunds have substantially reduced losses of organic carbon, N and P by reducing soil losses by 84% with stone lines and 71% with grass strips (Zougmoré et al., 2009). Application of compost even without installation of barriers was also found to substantially reduce soil loss (Zougmoré et al., 2009).

The installation of erosion barriers alone is not necessarily sufficient for obtaining good sorghum performance on nutrient-deficient soils without application of soil fertility measures (Zougmoré et al., 2003; Fatondji et al., 2009). Further, by combining water conservation and soil fertility measures, even greater reductions of run-off can be obtained. Whereas SWC measures alone reduced run-off by 59%, these measures plus application of mineral N or organic N reduced run-off by 67% and 84%, respectively (Zougmoré et al., 2010). This synergy of soil fertility and SWC measures was also observed with compost application with SWC barriers reducing soil loss by 79%, whereas compost alone gave only a 52% reduction (Zougmoré et al., 2010).

The Zai technique offers possibilities for enhancing sorghum yields on degraded, highly crusted soils as found in parts of Burkina Faso. This technique involves digging planting holes that not only break hard surface layers but enable capture of windblown sediment and effective placement of scarce organic amendments (Fatondji et al., 2009). The half-moon basin technique, introduced in Northern Burkina Faso (Zougmoré et al., 2003), also offers the possibility of point applications of soil amendments and water capture in highly crusting degraded soils.

The management of excess water is also critical for successful sorghum production as waterlogging can severely impede early vegetative growth. Farmers often sow sorghum on ridges, typically made with animal traction, to favour good crop growth despite the presence of standing water.

3.3 Pest, disease and weed management

Sorghum productivity in WCA can be constrained by a wide range of insect pests, diseases and competition from weeds. Each agroecology and dominant production system has specific complexes of biological threats to both yield and quality of grain for food and stover for ruminant fodder. Options for pest, disease and weed management for WCA sorghum production are presented below, considered by stage of growth.

4 Biological constraints encountered in specific growth phases

4.1 Seed storage and seed vigour

Most sorghum farmers in WCA store their own seed. Panicles harvested for seed are typically tied together by braiding the peduncles, and are thus identifiable as seed and kept separate from grain. These bundles are dried more carefully than grain and often stored in specific places, such as near the smoke of cooking fires, to minimize insect attacks. Some farmers and seed cooperatives have successfully started to use triple layered bags for storage of seed. The germination percentage and seedling vigour of farmer-produced sorghum seed was found to be excellent, equal to or better than researcher-produced seeds in Mali (M. Diallo, 2009, unpublished PhD thesis).

Important varietal differences in storability of grain and seeds exist in sorghum. Softer endosperm grain types, common among Durra and Caudatum-race varieties, are more susceptible to storage weevils than harder endosperm, Guinea-race, grain types.

4.2 Crop establishment and early growth

Bird feeding on sown grain or young seedlings can lead to huge losses during sorghum establishment. Sorghum emergence is rapid, occurring in three to five days, and bird scaring during the brief period of establishment is feasible and often practised. Some forms of seed treatment and fertilizer placement in or next to planting holes can enhance seedling growth through this critical period. Seed priming can also reduce the time taken from sowing to emergence and enhance early vigour (Harris, 2006), minimizing the time the sorghum crop is exposed to bird damage or damping off diseases.

Sorghum shoot fly (*Atherigona soccata*) and spittle bugs [*Poophilus costalis* (Walker)] although relatively rare, can be problematic where sowing dates differ widely and pest population buildups on early sown fields can devastate those that are sown later. Timely placement of fertilizer, and particularly P (Leiser et al., 2014), can help sorghum crops grow out of this susceptible stage more quickly. Stemborers in Northern Nigeria, with *Busseola fusca* (Fuller) being the most important species (Ajayi, 1989), can cause serious damage to sorghum starting in the establishment phase and continuing throughout the growth duration.

Weed control is a major concern for sorghum producers in the early growth stages. Farmers prepare land for sowing sorghum by removing weeds, bushes and residues of previous crops. Some farmers sow sorghum with the very first rains, possibly into zai holes, without any further land preparation so as to get a head start over weed growth and benefit from the early season nitrogen flush. The use of pre-emergent herbicide, particularly for later sown sorghums, has been more frequently observed in recent years.

4.3 Vegetative growth phase

Anthracnose (*Colletotrichum sublineolum*) is the most economically important disease (Cuevas et al., 2016), with host resistance specific for stem, rachis and grain (Hess et al., 2002). This pathogen is genetically variable and goes through several cycles of sexual reproduction per season (Gale, 2003). Thus, certain sorghum varieties that were resistant to Anthracnose have shown susceptibility after multiple years of cultivation on the same research station fields. Crop rotation therefore offers farmers a good control option. Removal of sorghum residues from the field can also reduce inoculum levels, but the economic value of the practice needs to be examined. As the microclimate in a sorghum canopy may be altered by plant architecture (e.g. stem internode lengths, leaf size and angle), plant spacing and density, these factors may influence incidence and development of Anthracnose and other diseases.

A wide range of foliar diseases, mostly fungal but also bacterial and viral, occur as well. Although these diseases rarely cause significant grain yield losses, they can cause serious reductions in green leaf area and reduce the fodder quality of stover. Monitoring and incorporating foliar disease resistance are therefore important for dual-purpose grain/fodder varieties.

Various insect infestations can occur but are typically local in their distribution, with high inter-annual variation (Chantereau and Fliedel, 2013). Stemborers (*Busseola fusca, Chilo partellus* and *Sesamia spp*.) may cause serious damage in areas with continuous cultivation of sorghum in some systems such as in Northern Nigeria Savannah region or in residual moisture areas. *Busseola fusca* is the most damaging species (Muturi et al., 2012). Many species of aphids occur but rarely justify chemical treatment, which can disturb natural regulation of insect populations (Chantereau and Fliedel, 2013).

4.4 Reproductive phase

Sorghum midge (*Stenodiplosis sorghicola*) lay eggs in sorghum flower spikelets, and the larvae devour the ovary. The incidence can be severe in certain hotspots (Dakouo et al., 2005; Chantereau and Fliedel, 2013), resulting in panicles devoid of grain. Infestations are often severe where farmers cultivate varieties of contrasting flowering dates as in Northern Ghana, where early maturing-introduced varieties resulted in sorghum midge population buildups that decimated later flowering local varieties, and in eastern Burkina Faso, where midge build up on early flowering red sorghum types that can devastate later flowering susceptible white sorghums.

Head bugs lay eggs and feed on developing caryopsis, causing direct loss and, by providing entry points for fungal pathogens, contribute to grain mould in what can be called a head bug–grain mould complex. *Eurystylus oldi* Poppins is the dominant head bug species in WCA (Ratnadass et al., 2003). Particularly severe damage occurs on compact-panicle varieties bred with introduced germplasm (Ratnadass et al., 2003) and on panicles with poor exertion. The local varieties, with their lax panicles, typically suffer less damage as insects are more exposed to predation and desiccation.

Grain mould is caused by a complex of fungi (Marley et al., 2003; Rooney, 2004). Grain mould may severely discolour grain, reducing yield of usable grain, and may lead to mycotoxins (Marley et al., 2003) that could affect human and animal health. Grain mould also causes significant reduction of seed viability. Anthracnose also infests grains but is independent of head bug feeding.

Bird feeding can cause severe yield losses. Traditional lax panicles and tall plant height may be of some benefit as the swaying panicle is less favourable for birds to perch and feed. Grazing by cattle is also a frequent concern, with plant heights greater than 2.0 m desired to minimize damage to panicles by transhumant cattle.

4.5 Striga: overarching all growth phases

The parasitic weed *Striga* (*Striga hermonthica*) is present throughout WCA, and farmers need to monitor and control this potentially devastating pest. The biology and genetics of the parasite and the host–parasite interactions are now understood in more detail (Ejeta, 2007). Based on these insights, a wide array of crop management alternatives has been tested with farmers for control of *Striga* (Table 2) (Van Mourik, 2007). Farmers' experiences with integration of control techniques indicate the need to combine at least three or more control options. Approaches that contribute to *Striga* control include: (1) enhancement of sorghum growth, e.g. fertilization with optimum timing and placement; (2) reduction of the number of *Striga* seeds in the soil by a) cultivating a false host (trap crop) that induces suicidal *Striga* germination, b) applying compost that increases soil microbial activity which in turn reduces the viability of *Striga* seeds and c) cultivating a resistant variety; (3) suppression of *Striga* growth by practices such as sowing a spreading cowpea that smothers the *Striga* plants and (4) reduction of *Striga* seed production and dispersal by late weeding and particularly by hand-pulling of *Striga* plants. Early sowing of the sorghum crop may also help reduce *Striga* parasitism as *Striga* seeds require two to three weeks of moist 'conditioning' before they can germinate (Ejeta, 2007) and attach to sorghum roots.

Soil fertility and water are closely interlinked factors determining sorghum as well as *Striga* growth and reproduction. The level of soil fertility, particularly plant-available P, contributes to two important, mutually reinforcing dynamics: a) the amount of sorghum growth and extent of shading that limits *Striga* growth and b) the extent of sorghum root exudates that mobilize P as well as stimulate *Striga* germination (Jamil et al., 2013). Thus nutrient-deficient soil conditions contribute to both more *Striga* germination and enhanced *Striga* growth and seed production with reduced shading by poorly developed sorghum canopy. Compost applications showed advantages over inorganic fertilizer for integrated soil fertility and *Striga* management for both sorghum growth and reduction of *Striga* seed viability in on-farm experimentation (Van Mourik, 2007).

Farmers' understanding of *Striga* biology and its interactions with sorghum is essential for them to choose and adopt control practices that fit their specific labour and economic conditions. The fact that *Striga* multiplies by seed is a critical revelation, since the seeds are so small and barely visible that farmers often conclude that magic, rather than seed, is the source of *Striga* infestations. Videos have been produced and made available online for informing farmers (Agro-Insight et al. 2012). Farmers' adoption of *Striga* control practices also depends on obtaining some benefits in the first year of application, even if benefits accrue over many years, since sorghum growers operate under severe resource constraints. The use of spreading cowpea is an example of a particularly attractive practice, as it impedes *Striga* growth and produces valuable hay.

Table 2 Overview of *Striga* control techniques and their effects on sorghum growth, *Striga* growth and development, and *Striga* seed bank in the soil (adapted from van Mourik, 2007)

Control technique/tool	Effect on sorghum growth	Effect on *Striga* growth and development	Effect on *Striga* seed bank
Striga-tolerant sorghum variety	Good growth, yield is generally maintained	No hindrance to growth	Increased risk of post-harvest seed production
Resistant sorghum variety	Good growth, yield is maintained	Reduced growth and development	*Striga* seed production may be reduced
Sowing sorghum early	Good growth using early nitrogen flush	Crop shading reduces *Striga* growth	Risk of post-harvest seed production
Herbicide-coated seeds of a herbicide-resistant variety	Good early growth especially with metalaxyl	Death of early attaching *Striga*	Risk of post-harvest seed production
Intercrop sorghum with high-density cowpea	Possible competition from cowpea	*Striga* growth suppressed by shading	Usually reduced. Risk of post-harvest seed production
Rotation with trap crop, e.g. cotton or soybean	Sorghum benefits from fertilizer applied to cotton	*Striga* germinates but does not develop on trap crop	*Striga* seed bank can be reduced
Rotation with pearl millet	Possible negative preceding crop effect	Sorghum-specific *Striga* populations do not grow on pearl millet	May reduce seed bank due to suicidal germination and poor growth of surviving *Striga*
Rotation with maize	Sorghum benefits from residual fertilizer effects	Sorghum-specific *Striga* populations do not grow on maize	Minimal seed production
Application of fertilizer with placement in or near planting hole	Sorghum establishment and initial development stronger	More *Striga* may germinate but develops poorly due to shading	Risk of post-harvest *Striga* seed production if moisture available
Application of compost before sowing	Sorghum development is favoured	Good germination but growth is reduced by shading	Reduced by the greater microbial activity. Risk of post-harvest seed production
Late weeding, third weeding of sorghum	Limited benefit if previous weedings were effective	*Striga* growth and development is reduced significantly	Reduced addition to *Striga* seed bank
Pulling up *Striga* before they set seed	No direct benefit	Interruption of the growth cycle	Seed bank reduced

5 Genetic diversity and genetic enhancement of sorghum in WCA

5.1 Sorghum diversity and its uses in WCA

Guinea-race sorghums, with flattened, corneous grains, twisting relative to open glumes, are the dominant race in the western Savannah zone from Senegal across Mali and Burkina Faso, but also in Chad and South Sudan (Harlan and de Wet, 1972; Touré and Scheuring, 1982; Barro-Kondombo et al., 2010). The hard corneous grain, pendulous panicles and wide glume opening contribute to good weathering resistance under wet conditions (Harlan and de Wet, 1972; Haussmann et al., 2012). All three Guinea sub-races are cultivated in WCA: guineense, medium-sized grain and most widespread; conspicuum, with larger grain size, is cultivated in North West Nigeria, Cameroon; and margaretiferum, with very small grains, which is genetically and evolutionarily distinct from other Guinea sorghums (Folkertsma et al., 2005; Deu et al., 2006), and is the dominant type cultivated in highest rainfall environments of Sierra Leone and Guinea, but it is also grown in drier environments across WCA, primarily by women, frequently as intercrop in their groundnut fields. The margaretiferum sub-race of sorghum has very hard grains that can be prepared like rice.

Durra-race sorghums, with rounded grain apex and tapering to a wedge-shaped base, are well adapted to sandy soils found across the Sahel from Senegal to Chad and beyond. Sorghums grown on residual moisture as well as the late-flowering Dune-sorghums found in the Sahel are nearly all of the Durra race. They tend to have very specific adaptations of their crop cycle to the prevailing water availability and pest situations, and appear to harbour specific adaptations to high water vapour pressure deficits, that could be useful for future breeding targeting drought resistance (Vadez et al., 2011).

Caudatum-race sorghums are also cultivated in WCA, but are of relatively less importance traditionally than other races. Tall, photoperiod-sensitive and long-duration Caudatum landraces exist, as well as early maturing, photoperiod-insensitive landraces, primarily in the Sahelian zone. Caudatum-race materials, highly represented in sorghum breeding programmes in the United States and India (Harlan and de Wet, 1972), have been introduced and used in WCA sorghum breeding programmes. The direct contribution of these materials has been primarily limited to more niche environments. Serious adaptation difficulties occurred in the Savannah zone with direct use per se as pure-line varieties that risk yield reductions or total loss due to the short crop duration and the compact panicle form exposing crops to bird damage and to the head bug–grain mould complex. However, introgression of Caudatum materials at an appropriate dose into adapted, longer duration materials, has contributed valuable diversity.

Bicolor race sorghums are primarily represented by sweet sorghums (Nebie et al., 2013) which are grown in small areas in most villages, often by children, for their juicy sweet stems. They are genetically distinct from other groups of sorghum.

Intermediate races are of tremendous importance. For example the Kaura (classified as Durra-Caudatum) and the Fara-Fara sorghums (Guinea-Caudatum) are two major types of sorghums cultivated in Nigeria, the largest sorghum-producing country in WCA. In Chad six of the ten possible racial intermediates are cultivated, with Guinea-Caudatum, Durra-Caudatum and Guinea-Bicolor being the most frequent (Yagoua, 1997).

5.2 Breeding for improved sorghum productivity, yield stability and quality

Experience over the past four decades has shown the necessity for WCA sorghum breeding programmes to emphasize the use of germplasm from, and adapted to, the target production ecosystem. Parental material that provides the basic array of adaptive traits and grain qualities is required to breed for yield, stability and value. Therefore, the germplasm bases for breeding in Nigeria, where Kaura and Fara-Fara sorghums predominate, and in Burkina Faso and Mali, with mostly Guinea-race sorghums, are distinct and emphasize farmer-demanded traits. Even within country, distinct breeding streams are required to serve zones where earlier- or later-maturing varieties are demanded.

This approach, however, does not preclude enhancing genetic diversity by introgressing introduced germplasm. The creation of a random-mating Guinea-race population by intermating Guinea landrace varieties from across West Africa is one example (Rattunde et al., 1997). Introduction of novel diversity from unadapted introduced germplasm can also be valuable if it is done at an appropriate dose to retain required grain and adaptation traits at sufficient levels for agronomic utility and acceptability.

5.2.1 Breeding methods

Diverse methods for establishing breeding objectives through collaborative researcher–farmer priority setting have been developed based on experiences in WCA and elsewhere (Christinck et al., 2005). Conventional pedigree breeding, recurrent selection in broad based populations, including subsequent pedigree selection of derived lines, and backcross designs are methods applied in WCA sorghum breeding. The application of molecular tools in applied sorghum breeding has been rare to date, and mostly limited to individual projects. The development of markers for culling early generation progenies with unacceptable grain or glume traits before entering yield testing holds promise for enhancing the efficacy of applied breeding programmes, and research is ongoing to this end (personal communication, Chiaka Diallo, 25 May 2017). Farmer participatory breeding methods have long been employed in the region (Weltzien et al., 2008a), and their use includes on-farm testing of experimental lines (Rattunde et al., 2016) and determination of selection criteria (vom Brocke et al., 2010).

Variety development efforts have primarily targeted pure-line open-pollinated varieties over the past 40 years, although hybrid breeding has recently gained considerable momentum in the region. Both population improvement (discussed below) and bi-parental pedigree breeding methods are being used for pure-line and hybrid parent development in WCA.

Recurrent selection in random-mating populations is conducted to concentrate favourable genes through rapid cycles of selection so as to increase the frequency of progenies with superior performance for the targeted trait(s), while retaining variation for these selected as well as non-selected agronomic traits. This approach offers advantages for sorghum improvement in WCA for a) addressing the large number of plant, panicle and grain traits required for acceptability and adaptation and b) sharing improved germplasm with other breeders or farmers interested to further select for adaptive or quality traits required for their particular production system and maturity zone. The diversity retained for maturity, grain type or plant height, for example, has enabled diverging selection paths to address new target traits or plant types. For instance out of a tall (over 3m plant height)

Guinea population, based on West African Guinea landrace varieties (Rattunde et al., 1997) but containing dwarfing genes at low frequencies, a new population with shorter height was created that provides valuable source material for breeding novel dual-purpose grain/fodder varieties that combine Guinea-race panicle and grain traits with superior stover quality. The variety 'Lata' derived from this population is now both cultivated by Malian farmers as a variety per se and used as the male-parent for successful hybrids (Rattunde et al., 2013; Kante et al., 2017).

A modified backcross approach with only one or at most two backcrosses to an elite donor parent followed by inbreeding of a wide panel of F2-derived backcross lines has proven ideal for enhancing genetic diversity of sorghum in WCA. This approach involves introgression of unadapted germplasm, even of contrasting races, that may offer useful genetic variation for particular traits, combined with selection within backcross F2 families for segregants conforming to the required adaptation/quality norms. This approach is proving most useful in Mali for combining powerful genetic analysis with a progressive, stepwise long-term introgression programme as described by Jordan et al. (2011).

Hybrid breeding with West African sorghum germplasm has shown potential for increasing grain yields (Andrews, 1975; Touré and Scheuring, 1982). However, hybrids based on Caudatum seed parents and Guinea landrace varieties used as male parents lacked adaptation and grain quality traits required for production in the Guinea-race zone, indicating the need to develop both female and male parents that combine well for these traits (Touré and Scheuring, 1982). The first hybrids based entirely on West African Guinea-race germplasm are now available. These hybrids give 30% yield advantages over local varieties in farmers' fields (Rattunde et al., 2013; Kante et al., 2017) and adoption is starting (Smale et al., 2014). As these yield gains were obtained with only a limited number of parental lines and low selection intensity, even greater yield advantages should be attainable by implementing a full-scale hybrid breeding programme that uses the broad genetic diversity of West African sorghums. High levels of heterosis were shown to be achievable by crossing between distinct sub-pools of Guinea-race germplasm (e.g. guinense from Mali and Burkina Faso and conspicuum from Nigeria and Cameroon) (Dagnoko, 2008).

5.2.2 Collaborative multi-location and multi-environment testing

Achieving genetic gains for grain yield requires testing in multiple environments that represent the targeted cropping systems. Such large-scale yield testing, however, is challenging for sorghum breeding programmes in WCA due to resource and technical limitations. Whereas breeders' experimental station fields are typically managed at higher input levels and are few in number, farmers' field conditions and agronomic practices are highly diverse, even within a target production system, and are mostly at suboptimal fertility levels.

Farmer–breeder collaboration for on-farm yield testing provides one approach for increasing genetic gain for grain yield (Weltzien et al., 2008b; Rattunde et al., 2016). One breeding line identified via multi-environment on-farm testing showed a stable 11% yield superiority over the adapted local checks across the full range of production conditions. This line showed both superior phosphorus use efficiency and total P uptake (Leiser et al., 2014), a remarkable combination which may have contributed to its superior yielding ability in farmers' fields. Another approach for increasing gains for grain yield is breeders' collaboration for joint testing of breeding materials across more environments than can be managed by individual breeding programmes.

Large-scale testing of early generation materials would help increase genetic gains for yield by exploiting the high genetic diversity available in early generations and by enabling higher selection intensities than are feasible in later generations. Heritabilities for grain yield in large-scale on-farm testing systems can be sufficient for discriminating among progenies using various experimental designs (Rattunde et al., 2016). Furthermore, farmer collaboration with breeders can help focus efforts on materials that combine yield with farmer-preferred traits, and so improve breeding efficiency for the development of successful varieties.

5.2.3 Improving and combining grain- and stalk-quality

Discussing grain yield with farmers in WCA revealed that they often define yield in terms of food produced rather than weight of grain per area. One major determinant of food yield is the decortication yield, the yield of grits and flour from a given weight of grain after removing the seed coat. Decortication yields of farmer landrace and some bred varieties are typically about 80%, whereas they may be as low as 60% for varieties bred with introduced germplasm. Decortication yields therefore need to be routinely monitored. Farmers also observe varietal differences for the weight of grain needed to feed their family. Free threshing of grain is also an important determinant of food yield, as grain with clasping glumes would be discarded. Varieties that maintain open glumes and are free threshing even under stress conditions are therefore valued for giving more yield stability and food security.

The nutritional value of sorghum is also vital since sorghum, together with pearl millet, form the basis of rural diets in the zone with approximately 800 mm rainfall or less. In this zone the diets of children below five years of age are so highly based on these cereals that they provide approximately half of the iron and zinc intake (Tuinsma, 2006). The widespread and exceedingly high micronutrient deficiencies, especially among children and women of reproductive age, results in weakened immune systems and poor cognitive development, making the micronutrient content of sorghum grains a priority issue. WCA sorghums have significant genetic variability for micronutrient contents and breeding for improved nutritional value is ongoing. Monitoring for acceptable decortication yields will also help maintain micronutrient levels, since approximately half of iron and zinc content is lost by removing the bran (Hama et al., 2011). Various options for improved food preparation can also contribute to nutritional yield. For example, soaking, surface drying and grinding whole grain, where mechanical mills are available, help retain most of the iron zinc, and fibre, and reduce loss of the oil and protein-rich germ. Also, preparation of foods using fermentation or addition of fruit juices containing vitamin C can enhance the bioavailability of iron for improved nutrition.

The development of novel multi-use grain and fodder, or grain-, fodder- and sweet-sorghum types offers options for increasing total yield and crop value. The stems of the tall, highly lignified, landrace sorghum varieties of WCA are of low nutritional quality for ruminant livestock. Newly developed short (less than 2.5 m) sorghum varieties have stems with less lignification, higher digestibility and stover quality far superior to traditional varieties. Selecting in the opposite sense, for high stem lignification, might be taken up in areas where cooking fuel is not easily available or stemborers cause significant damage. The newly bred sweet sorghum varieties and lines combine quality grain with sweet juicy stems that can produce food, fodder and sweet sorghum syrup for human consumption or biofuel. Thus, these dual- or multipurpose sorghums can provide farmers with new cropping options for increasing total value and diversifying production, and thereby contribute to improved resilience.

6 Sorghum and seed system development

Local varieties of sorghum are widely used by farmers in the WCA region. These, mostly smallholder, farmers maintain and manage sorghum seed in a traditional manner on an individual or social network basis. Sorghum, as an indigenous staple crop, plays an important role in the culture for farmers of this region similar to maize in Mexico or wheat in the Middle East. This implies that sorghum seed in WCA is more than a commodity or an agricultural input, as it is associated with traditions and obligations of solidarity and risk sharing within communities.

Effective seed dissemination is vital for ensuring that farmers can access and use new varieties for enhancing value and productivity. The dissemination of newly bred varieties, however, has been problematic in many sorghum-growing countries of WCA, with both cultural aspects and varietal adaptation or quality requirements at play. Therefore all seed system actors, including sorghum breeders, need to understand farmers' seed management practices and culture such that variety development and dissemination efforts address farmers' priority needs and objectives.

6.1 Seed system analysis

Recognizing that the sorghum seed system in WCA, and elsewhere in Africa, is a 'human activity system' means that the first step in developing a seed dissemination approach is to understand the existing seed system and its main actors. This may include grain markets, traditional and commercial dissemination channels and farmers' practices and cultural norms for seed production and seed security in the target production zones. Comprehensive guidelines for seed security assessments have been developed (Sperling, 2008) and conducting such an analysis in non-emergency situations provides valuable information on the system's functioning for the targeted farmers (McGuire and Sperling, 2016).

Important pieces of information include under which circumstances farmers may acquire seed from outside their own farm and by which criteria they choose the variety, the supplier and the seed, as well as the preferred way for reimbursing the supplier of the seed. Understanding the variety and seed requirements for different types of farmers (i.e. gender, family and farm size, role and type of livestock) in a given area is another critical element.

Such a detailed analysis gives critical insights into the type of varieties that farmers seek, in terms of not only agronomic and adaptive traits but also quality traits for use and processing, and degree of uniformity or intra-varietal diversity that is accepted or has intrinsic value. This analysis can thus help guide both the organization of seed production, information exchange and seed dissemination in an effective and socially acceptable manner, and enable sorghum breeders to better orient their work and partnerships for increased impact (Christinck et al., 2005; Weltzien and Christinck, 2008).

Some findings from the Sudan Savannah in Mali illustrate the cultural issues related to seed that bear on efforts to develop effective seed dissemination options:

- 'A good farmer produces his own seed'. Most farmers choose good fields in which they select the best panicles of each variety they intend to sow the following year. The seed panicles are stored in a manner that everyone knows that they are for seed and will not be touched for food. The farmers' own seed is trusted to be adapted to their conditions and needs, and taking seed 'from outside', from a field they have not seen or from 'someone else', may be seen as putting their family at risk (Siart, 2008). However, farmers who see a desirable variety grown by someone they know may 'place an order' to receive a quantity of seed for the following season.

- 'If someone asks me for seed during the sowing period, I am obliged to give it'. The person requesting seed may pay for the seed by exchanging an equal volume of grain either immediately, or if lacking grain, after the subsequent harvest. Taking money for seed is not practised (Siart, 2008).

Farmers in Mali are thus often reluctant to talk about their seed or new varieties: the more people ask for seed the more seed the farmer may have to give away with little or no compensation. Traditionally therefore seed has no commercial value and it is not culturally acceptable for an individual farmer to develop a seed enterprise and profit from others' needs. A group-based seed enterprise, where activities and benefits are shared in a transparent manner, is acceptable, however. A contrasting situation occurs in the Sudan Savanna of Kano and Katsina states in Nigeria where sorghum farmers with appreciable quantities of clean healthy seed or grain at planting time are highly respected in the society and they commonly share some with family and friends as well as sell or exchange with grain in a grain-to-seed ratio of 3:2.

6.2 Sorghum seed dissemination models

The first attempts of producing and disseminating newly bred sorghum and other crop varieties in WCA were directed through state agencies such as agricultural extension- and national seed-services. Although these efforts attained some success, especially with crops such as cotton, this approach was largely abandoned in the 1990s during economic adjustment programmes.

Considerable donor investment in WCA has gone into seed system development that could be called a linear supply chain model. This model operates primarily on the concept that there is a direct flow of creativity and production, initiating with the breeder, which is followed by seed producers and seed sellers, with input from control services, to arrive at the product to be purchased by the farmer. Donor support has primarily targeted public breeding programmes and private companies involved in seed processing and sale, and less so to seed producers, extension services or local retailers. The long-term success of this model for sorghum in WCA will hinge on its ability to add value and options for smallholder farmers that complement their varieties and traditional seed provisioning, establish farmers' trust and provide convenient and timely access to seed through local retailers.

The profitability of sorghum seed marketing enterprises appears to be better in Nigeria, where bakeries and malting or brewing enterprises provide farmers with seed. Sorghum processing industries that need to procure grain of uniform and specified qualities are now contracting growers for the production of specified varieties. These industries may support the dissemination of varieties, provide farmers with credit for seed and other inputs, as well as ensure the market for the product. This model is also being developed for sorghum in Ghana and Sierra Leone and has contributed to the dissemination of sorghum varieties.

A more decentralized seed system model is emerging with farmer cooperatives and associations conducting many seed system functions for sorghum and other staple cereals in Mali, Burkina Faso and Benin. Certified sorghum seed in Mali is now mostly produced by farmer cooperatives, and a great portion of the seed purchased directly by farmers is bought from nearby cooperatives. One factor contributing to this is that the cooperative model is a good fit to the sociocultural values and ecological context. This is particularly true for smallholder farmers for whom food security as well as market considerations are priorities. Critical elements are farmers' knowledge and trust, both of the people involved and of the varieties on offer.

The decentralized, cooperative seed production and dissemination model is a good match for public breeding programmes interested in collaborative large-scale variety testing with organized farmer groups. Such collaboration is ongoing. The long-term collaboration between researchers, development organizations and farmer seed cooperatives can and is helping these farmer groups strengthen their cooperative governance and finance and asset management as their seed production, processing and marketing activities grow.

Decentralized seed enterprises based on farmer groups are not new. They played a role in founding the modern seed systems of Europe (Harwood, 2012) and the United States, with certain seed companies today tracing back to farmer cooperatives and public sector–farmer collaboration. Investing in farmer seed cooperatives to advance sustainable seed system development for smallholder farmers of WCA, however, is currently rare. This will hopefully change when development donors gain awareness of the advantages that this approach can provide. While farmers, and particularly cooperative members, are very aware of the difficulties associated with cooperative management, they highly appreciate local farmer-managed seed supply and dissemination that responds to their variety and seed quality preferences and provides income for them and their communities.

7 Conclusion

Sorghum is the staple food for millions of people in WCA and, until recently, was mostly consumed by the farmers who produce it. Urbanization, however, is accelerating and the opportunities, and the necessity, for farmers to sell sorghum and other grains are increasing. This chapter presents a wide range of entry points for improving the productivity and sustainable intensification of sorghum production systems in WCA. These opportunities, identified through long-term engagement in the region, are tremendous for this resilient and resource-efficient cereal crop. The Savannah zone, where sorghum is predominant, would be the region of highest priority. The need for research to drive these developments is equally great and diverse, from biological and agronomical issues, to institutional arrangements for seed production dissemination and product marketing. Collaboration of a wide range of stakeholders, including farmers, focused on responding to the priorities and needs of farmers and their partners, is critical for sustainably improving livelihoods in sorghum-based agroecologies of WCA.

8 Where to look for further information

Two general tracks for guiding future research to understand and enhance the diverse sorghum production systems in WCA can be suggested: a) focus on options for creating greater value for farmers and their partners, and b) focus on the sorghum systems per se, with attention to actor relationships, communication flows and opportunities for collaboration.

Attention to environmental and social context and individual skills and differential user needs is vital for both tracks in the WCA region, and thus leads to nearly limitless possibilities for research and development. Yet, certain major themes such as the following can be identified for the 'creating-value track': 1) enhancement of food yield and nutritional value, including grain quality for storability, home food preparations and micronutrient content and bioavailability; 2) development of novel multipurpose varieties that combine specific grain and stover qualities for food and feed uses; 3) soil-fertility (especially P) and weed management options that are feasible and profitable for smallholder farmers; 4) hybrid development for the various regions with distinct agroecological conditions and grain quality requirements; and 5) the improvement and joint employment of agronomic practices and varietal resistances for limiting losses due to stem borers, sorghum midge and *Striga*.

Recognizing sorghum production and seed systems as human activity systems makes it necessary to look closely at the actors and their goals, activities and relationships (Long, 2001). Gatzweiler and von Braun (2016) suggested distinct innovation strategies for different groups of smallholder farmers along a gradient of human capability and agroecological potential, and noted that sustainable intensification by smallholder farmers is not just a technical optimization problem, but a 'task of creating value through innovations in the institutional, organizational and technological systems of societies'. Practical approaches for researcher–farmer collaboration in priority setting for breeding and seed system interventions are detailed in a handbook based on sorghum improvement work in WCA (Christinck et al., 2005). And a framework for seed system analysis, proposed by McGuire and Sperling (2016), can help guide organization of seed production, information exchange and seed dissemination in an effective and socially acceptable manner.

A community of collaborating research institutions and farmer organizations is central to the past and ongoing research on sorghum improvement in WCA. National institutes engaged in this research include l'Institute d'Economie Rurale (IER, Mali), Institut de l'Environnement et Recherches Agricoles (INERA, Burkina Faso), Institute of Agricultural Research of the Ahmadu Bello University, Zaria, Nigeria, Institut National de la Recherche Agronomique du Niger (INRAN, Niger), Savanna Agricultural Research Institute (SARI, Ghana), Institut Sénégalais de Recherches Agricoles (ISRA, Senegal), and Institut Tchadien de Recherche Agronomique pour la Développement (ITRAD, Chad). International research organizations include the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and CIRAD (French Agricultural Research Centre for International Development). Universities, both within and outside of the region, contribute particularly through student research activities. Farmer organizations collaborating in sorghum research activities include the Union Locale des Producteurs de Cereales (ULPC) and the Association des Organisations des Producteurs Professionnelles (AOPP) in Mali, Union des Groupements pour la Commercialisation de Produits Agricoles de la Boucle du Mouhoun (UGCPA/BM) and l'Association Minim Song Panga (AMSP) in Burkina Faso and FUMA Gaskiya and Mooriben in Niger.

Several foundations and government agencies have provided important support for the sorghum improvement work in WCA, including the McKnight Foundation's Collaborative Crop Research Program for WCA, the Bill and Melinda Gates Foundation, the United States Agency for International Development and the German Federal Ministry for Economic Cooperation and Development.

9 Acknowledgements

We are most appreciative to all who have contributed to the joint learning that we attempt to synthesize from the sharing of farmers, collaborating in countless trials and discussions, the input of research partners and colleagues, as well as the challenges to address adoption, scaling and different types of impact raised by development partners and donor agencies. We also thank the reviewers, Benoit Clerget and anonymous, for their thoughtful and constructive suggestions and Willmar Leiser for preparation of Fig. 1.

10 References

Abdalla, E., A. Osman, M. Maki, F. Nur, S. Ali, and J. Aune. 2015. The response of sorghum, groundnut, sesame, and cowpea to seed priming and fertilizer micro-dosing in South Kordofan state, Sudan. *Agronomy* 5: 476–90. doi:10.3390/agronomy5040476.

Agro-Insight, ICRISAT, and UACT. 2012 Available at: https://www.accessagriculture.org/integrated-approach-against-striga (verified 24 May 2017).

Ajayi, O. 1989. Stem borers of sorghum in West Africa with emphasis on Nigeria. In *International Workshop on Sorghum Stem Borers*. ICRISAT, Patancheru, India, pp. 27–31.

Andrews, D. J. 1975. Sorghum grain hybrids in Nigeria. *Experimental Agriculture* 11: 119–27.

Aune, J. B., M. Doumbia and A. Berthe. 2007. Microfertilizing sorghum and pearl millet in Mali – agronomic, economic and social feasibility. *Outlook Agric* 36: 199–203.

Barnaud, A., M. Deu, E. Garine, D. McKey and H. I. Joly. 2006. Local genetic diversity of sorghum in a village in Northern Cameroon: structure and dynamics of landraces. *Theoretical and Applied Genetics*. 114: 237–48. doi:10.1007/s00122-006-0426-8.

Barro-Kondombo, C., F. Sagnard, J. Chantereau, M. Deu, K. vom Brocke, P. Durand, E. Gozé and J. D. Zongo. 2010. Genetic structure among sorghum landraces as revealed by morphological variation and microsatellite markers in three agroclimatic regions of Burkina Faso. *Theoretical and Applied Genetics* 120: 1511–23. doi:10.1007/s00122-010-1272-2.

Breman, H. 1998. Amerlioration de la fertilité des sols en Afrique de l'Ouest: Contraintes et perspectives. In *Soil Fertility Management in West African Land Use Systems*. Margraf Verlag, Niamey, Niger, pp. 7–20.

Buerkert, A., A. Bationo and H.-P. Piepho. 2001. Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. *Field Crops Research* 72: 1–15. doi:10.1016/S0378-4290(01)00166-6.

Buerkert, A. and P. Hiernaux. 1998. Nutrients in the West African Sudano-Sahelian zone: Losses, transfers and role of external inputs. *Z. Pflanzenernaehrung Bodenkunde* 161: 365–83.

Buerkert, A., H.-P. Piepho and A. Bationo. 2002. Multi-site time-trend analysis of soil fertility management effects on crop production in Sub-Saharan West Africa. *Experimental Agriculture* 38. doi:10.1017/S0014479702000236.

Chantereau, J. and G. Fliedel. 2013. Le sorgho. Quae; CTA; Presses agronomiques de Gembloux, Versailles; Wageningen; Gembloux.

Christinck, A., E. Weltzien and V. Hoffmann. 2005. *Setting Breeding Objectives and Developing Seed Systems with Farmers. A Handbook for Practical Use in Participatory Plant Breeding Projects*. Magraf Publishers and CTA, Weikersheim, Germany and Wageningen, The Netherlands.

Clerget, B., M. Dingkuhn, E. Goze, H. F. W. Rattunde and B. Ney. 2008. Variability of Phyllochron, Plastochron and Rate of Increase in Height in Photoperiod-sensitive Sorghum Varieties. *Annals of Botany* 101: 579–94. doi:10.1093/aob/mcm327.

Comas, J. and H. Gomez MacPherson. 2002. La culture du sorgho de décrue en Afrique de l'Ouest et du Centre. Situation actuelle et définition d'un Plan d'Action Régional. In *La culture du sorgho* *de décrue en Afrique de l'Ouest et du Centre*. Situation actuelle et définition d'un Plan d'Action Régional. Nouakschott, Mauretania.

Cuevas, H. E., L. K. Prom, T. Isakeit and G. Radwan. 2016. Assessment of sorghum germplasm from Burkina Faso and South Africa to identify new sources of resistance to grain mold and anthracnose. *Crop Protection* 79: 43–50. doi:10.1016/j.cropro.2015.10.007.

Dagnoko, S. 2008. Dissecting heterosis in Guinea race sorghum: Simultaneous analysis by conventional breeding and molecular marker approaches.

Dakouo, D., G. Trouche, N. B. Malick, A. Neya and K. B. Kaboré. 2005. Lutte génétique contre la cécidomyie du sorgho, Stenodiplosis sorghicola : une contrainte majeure à la production du sorgho au Burkina Faso. *Cahiers d'Agriculture* 14: 201–8.

de Ridder, N. and H. van Keulen. 1990. Some aspects of the role of organic-matter in sustainable intensified arable farming systems in the West-African Semi-Arid-Tropics (sat). *Fertility Research* 26: 299–310.

Deu, M., F. Rattunde and J. Chantereau. 2006. A global view of genetic diversity in cultivated sorghums using a core collection. *Genome* 49: 168–80.

Doumbia, M. D., L. R. Hossner and A. B. Onken. 1993. Variable sorghum growth in acid soils of subhumid West Africa. *Arid Soil Research and Rehabilitation* 7: 335–46. doi:10.1080/15324989309381366.

Doumbia, M. D., L. R. Hossner and A. B. Onken. 1998. Sorghum growth in acid soils of West Africa: Variations in soil chemical properties. *Arid Land Research and Management* 12: 179–90. doi:10.1080/15324989809381507.

Ejeta, G. 2007. Breeding for resistance in sorghum: exploitation of an intricate host–parasite biology. *Crop Science* 47: S-216–S-227. doi:10.2135/cropsci2007.04.0011IPBS.

Falconnier, G. N., K. Descheemaeker, T. A. Van Mourik, O. M. Sanogo and K. E. Giller. 2015. Understanding farm trajectories and development pathways: Two decades of change in southern Mali. *Agricultural Systems* 139: 210–22. doi:10.1016/j.agsy.2015.07.005.

FAOSTAT. 2017. Available at: http://faostat.fao.org (verified 24 May 2017).

Fatondji, D., C. Martius, R. Zougmore, P. L. G. Vlek, C. L. Bielders and S. Koala. 2009. Decomposition of organic amendment and nutrient release under the zai technique in the Sahel. *Nutrient Cycling in Agroecosystems* 85: 225–39. doi:10.1007/s10705-009-9261-z.

Folkertsma, R. T., H. F. W. Rattunde, S. Chandra, G. S. Raju and C. T. Hash. 2005. The pattern of genetic diversity of Guinea-race *Sorghum bicolor* (L.) Moench landraces as revealed with SSR markers. *Theoretical and Applied Genetics* 111: 399–409. doi:10.1007/s00122-005-1949-0.

Gale, L.R. 2003. A population genetic approach to variation in colletotrichum graminicola, the causal agent of sorghum anthracnose. In Leslie, J. F. (ed.), *Sorghum and Millets Diseases*. Iowa State Press, Ames, Iowa, USA, pp. 191–9.

Gigou, J., K. Traore, F. Giraudy, H. Coulibaly and B. Sogoba. 2006. Farmer-led contour ridging can reduce water runoff in African savannahs. *Cahiers Agricultures* 15: 116–22.

Giller, K. E., P. Tittonell, M. C. Rufino, M. T. van Wijk, S. Zingore, P. Mapfumo, S. Adjei-Nsiah, M. Herrero, R. Chikowo, M. Corbeels, E.C. Rowe, F. Baijukya, A. Mwijage, J. Smith, E. Yeboah, W. J. van der Burg, O. M. Sanogo, M. Misiko, N. de Ridder, S. Karanja, C. Kaizzi, J. K'ungu, M. Mwale, D. Nwaga, C. Pacini and B. Vanlauwe. 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems* 104: 191–203. doi:10.1016/j.agsy.2010.07.002.

Goldsworthy, P. R. 1967. Responses of cereals to fertilizers in Northern Nigeria. I. Sorghum. *Experimental Agriculture* 3: 29. doi:10.1017/S0014479700004087.

Hama, F., C. Icard-Vernière, J.-P. Guyot, C. Picq, B. Diawara and C. Mouquet-Rivier. 2011. Changes in micro- and macronutrient composition of pearl millet and white sorghum during in field versus laboratory decortication. *Journal of Cereal Science* 54: 425–33. doi:10.1016/j.jcs.2011.08.007.

Harlan, J. R. and J. M. J. de Wet. 1972. A simplified classification of cultivated sorghum. *Crop Science* 12: 172–6. doi:10.2135/cropsci1972.0011183X001200020005x.

Harris, D. 2006. Development and testing of 'On-farm' seed priming. *Advances in Agronomy* 90: 129–78. doi:10.1016/S0065-2113(06)90004-2.

Harwood, J. 2012. *Europe's Green Revolution and Its Successors: The Rise and Fall of Peasant-friendly Plant Breeding*. Routledge. Available at: https://books-google-com.ezproxy.library.wisc.edu/books?hl=en&lr=&id=shnXQjmkaVoC&oi=fnd&pg=PP2&dq=The+European+Green+Revolution+and+Others+Since+Then&ots=VIzbeWlGnH&sig=kj2jrnBAPtC20oWQASMz1KStAXs (verified 9 November 2016).

Haussmann, B. I. G., H. Fred Rattunde, E. Weltzien-Rattunde, P. S. C. Traoré, K. vom Brocke and H. K. Parzies. 2012. Breeding Strategies for Adaptation of Pearl Millet and Sorghum to Climate Variability and Change in West Africa (F. Asch, Ed.). *Journal of Agronomy and Crop Science* 198: 327–39. doi:10.1111/j.1439-037X.2012.00526.x.

Hess, D. E., R. Bandyopadhyay and I. Sissoko. 2002. Pattern analysis of sorghum genotype x environment interaction for leaaf, panicle, and grain Anthracnose in Mali. *Plant Disease* 86: 1374–82.

Jamil, M., T. A. Van Mourik, T. Charnikhova and H. J. Bouwmeester. 2013. Effect of diammonium phosphate application on strigolactone production and *Striga hermonthica* infection in three sorghum cultivars: Diammonium phosphate application on *Striga hermonthica*. *Weed Research* 53: 121–30. doi:10.1111/wre.12003.

Jordan, D. R., E. S. Mace, A. W. Cruickshank, C. H. Hunt and R. G. Henzell. 2011. Exploring and Exploiting Genetic Variation from Unadapted Sorghum Germplasm in a Breeding Program. *Crop Science* 51: 1444. doi:10.2135/cropsci2010.06.0326.

Kante, M., H. F. W. Rattunde, W. L. Leiser, B. Nebié, B. Diallo, A. Diallo, A. O. Touré, E. Weltzien and B. I. G. Haussmann. 2017. Can tall guinea-race sorghum hybrids deliver yield advantage to smallholder farmers in West and Central Africa? *Crop Science* 57: 833. doi:10.2135/cropsci2016.09.0765.

Kenga, R., M. M'Biandoun, A. Njoya, M. Havard and E. Vall. 2003. Analysis of constraints to agricultural production in the Sudan-Sahelian zone of Cameroon using a diagnostic survey. In *Actes du Colloque*. CIRAD, Montpellier, Garoua, Cameroon.

Kihara, J., G. Nziguheba, S. Zingore, A. Coulibaly, A. Esilaba, V. Kabambe, S. Njoroge, C. Palm and J. Huising. 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 229: 1–12. doi:10.1016/j.agee.2016.05.012.

Leiser, W. L., H. F. W. Rattunde, H.-P. Piepho, E. Weltzien, A. Diallo, A. E. Melchinger, H. K. Parzies and B. I. G. Haussmann. 2012. Selection strategy for sorghum targeting phosphorus-limited environments in West Africa: analysis of multi-environment experiments. *Crop Science* 52: 2517–27. doi:10.2135/cropsci2012.02.0139.

Leiser, W. L., H. F. W. Rattunde, E. Weltzien and B. I. G. Haussmann. 2014. Phosphorus uptake and use efficiency of diverse West and Central African sorghum genotypes under field conditions in Mali. *Plant and Soil* 377: 383–94. doi:10.1007/s11104-013-1978-4.

Marley, P. S., M. Diourt, A. Neya, S. K. Nutsugah, P. Srm, S. O. Katil, D. E. Hess, D. F. Mbaye and Z. Ngoko. 2003. Sorghum and pearl millet diseases in West and Central Africa. In Leslie, J. F. (ed.), *Sorghum and Millets Diseases*. Iowa State Press, Ames, Iowa, USA, pp. 419–25.

McIntire, J., J. Powell, S. Fernandez-Rivera and T. Williams. 1993. African semi-arid tropical agriculture cannot grow without external inputs. In Addis Ababa, Ethiopia.

McGuire, S. and L. Sperling. 2016. Seed systems smallholder farmers use. *Food Security* 8: 179–95. doi:10.1007/s12571-015-0528-8.

Mohamed, E. M. I., C. Jordi, C. David, M. Luciano and G. oacute mez, M. Helena. 2016. Irrigated sorghum and cowpea after wet-season rice as a pathway out of subsistence agriculture in the Senegal River Valley in Mauritania. *African Journal of Agricultural Research*. 11: 1824–35. doi:10.5897/AJAR2016.10876.

Muturi, P. W., P. Rubaihayo, M. Mgonja, S. Kyamanywa, H. C. Sharma and C. T. Hash. 2012. Novel source of sorghum tolerance to the African stem borer, Busseola fusca. *African Journal of Plant Science* 6 doi:10.5897/AJPS12.051.

Nebie, B., R. Nanema, P. Bationo-Kando, E. Traore, V. Labeyrie, N. Sawadogo, M. Sawodogo and J. Zongo. 2013. Variation de caractères agromorphologiques et du Brix d'une collection de sorghos à tige sucrée du Burkina Faso. *International Journal of Biological and Chemical Sciences* 7: 1919–28. doi:10.4314/ijbcs.v7i5.12.

Nicholson, S. E. 2013. The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *International Scholarly Research Notices* 2013: e453521. doi:10.1155/2013/453521.

Office of the Honorable Minister of Agriculture. 2012. Agricultural transformation action plan, sorghum transformation value chain, Abjuja, NIgeria.

Ollenburger, M. H., K. Descheemaeker, T. A. Crane, O. M. Sanogo and K. E. Giller. 2016. Waking the sleeping Giant: Agricultural intensification, extensification or stagnation in Mali's Guinea Savannah. *Agricultural Systems* 148: 58–70. doi:10.1016/j.agsy.2016.07.003.

Ouédraogo, E., L. Brussaard, A. Mando and L. Stroosnijder. 2005. Organic resources and earthworms affect phosphorus availability to sorghum after phosphate rock addition in semi-arid West Africa. *Biology and Fertility of Soils* 41: 458–65. doi:10.1007/s00374-005-0840-0.

Ratnadass, A., P. Marley, M. Hamada, O. Ajayi, B. Cissé, F. Assamoi, I. D. Atokple, J. Beyo, O. Cisse, D. Dakouo, M. Diakite, S. Dossou-Yovo, B. Le Diambo, M. Vopeyande, I. Sissoko and A. Tenkouano. 2003. Sorghum head-bugs and grain molds in West and Central Africa: I. Host plant resistance and bug–mold interactions on sorghum grains. *Crop Protection* 22: 837–51. doi:10.1016/S0261-2194(03)00066-8.

Rattunde, H. F. W., S. Michel, W. L. Leiser, H. P. Piepho, C. Diallo, K. vom Brocke, B. I. G. Haussmann and E. Weltzien. 2016. Farmer participatory early-generation yield testing of sorghum in West Africa: Possibilities to optimize genetic gains for yield in farmers' fields. *Crop Science* 56: 1–13. doi:10.2135/cropsci2015.12.0758.

Rattunde, H. F. W., E. Weltzien, P. J. Bramel-Cox, K. Kofoid, C. T. Hash, W. Schipprack, J. W. Stenhouse and T. Presterl. 1997. Population improvement of pearl millet and sorghum: Current research, impact and issues for implementation. In *Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet*. Lubbock, Texas USA, pp. 188–212.

Rattunde, H. F. W., E. Weltzien, B. Diallo, A. G. Diallo, M. Sidibe, A. O. Touré, A. Rathore, R. R. Das, W. L. Leiser and A. Touré. 2013. Yield of photoperiod-sensitive sorghum hybrids based on guinea-race germplasm under farmers' field conditions in Mali. *Crop Science* 53: 2454. doi:10.2135/cropsci2013.03.0182.

Rooney, W. 2004. Sorghum improvement – integrating traditional and new technology to produce improved genotypes. In *Advances in Agronomy*. Elsevier, pp. 37–109.

Sanogo, O. M., N. de Ridder and H. van Keulen. 2010. Diversity and dynamics of mixed crop-livestock agricultural households in Southern Mali. *Cahiers Agricultures* 19: 185–93. doi:10.1684/agr.2010.0401.

Siart, S. 2008. Strengthening local seed systems: Options for enhancing diffusion of varietal diversity of sorghum in Southern Mali, In H. Boland, V. Hoffmann and U. J. Nagel (Eds.), *Kummunikation und Begratung, Sozialwissenschaftliche Schriften zur Landnutzung und Ländlichen Entwicklung (series # 85)*, Magraf Publishers GmbH, Weikersheim, Germany, 185p. ISBN 978-3-8236-1525-5; ISSN 0947-0352.

Smale, M., Alpha Kernga, Amidou Assima, Eva Weltzien and Fred Rattunde. 2014. An overview and economic assessment of sorghum improvement in mali. *Michigan State University International Development Working Paper*. Working Paper 137: 40.

Sperling, L. 2008. When disaster strikes: a guide for assessing seed security. Centro International de Agricultura Tropical (CIAT), Cali, Colombia. Available at: https://cgspace.cgiar.org/handle/10568/69690 (verified 24 June 2017).

Tonitto, C. and J. E. Ricker-Gilbert. 2016. Nutrient management in African sorghum cropping systems: Applying meta-analysis to assess yield and profitability. *Agronomy for Sustainable Development*. 36. doi:10.1007/s13593-015-0336-8.

Touré, A. B. and J. F. Scheuring. 1982. Presence de genes mainteneurs de l'androsterilité cytoplsamique parmi les varietiés locales de sorgho au Mali. *Agronomie Tropicale* 37: 362–5.

Tuinsma, M. 2006. La consommation et la contribution au régime alimentaire du mil et du sorgho au Mali, Niger et Burkina Faso: L'apport en (micro) nutriments, International Crops Research Institute for the Semi-Arid Tropics, Bamako, Mali, 43p .

Vadez, V., L. Krishnamurthy, C. T. Hash, H. D. Upadhyaya and A. K. Borrell. 2011. Yield, transpiration efficiency, and water-use variations and their interrelationships in the sorghum reference collection. *Crop and Pasture Science* 62: 645–55. doi:10.1071/CP11007.

van Mourik , T. A. 2007. Striga hermonthica seed bank dynamics: process quantification and modelling, Wageningen University, Wageningen, The Netherlands, 123p. ISBN 978-90-8504-692-9.

vom Brocke, K., G. Trouche, E. Weltzien, C. P. Barro-Kondombo, E. Gozé and J. Chantereau. 2010. Participatory variety development for sorghum in Burkina Faso: Farmers' selection and farmers' criteria. *Field Crops Research* 119: 183–94. doi:10.1016/j.fcr.2010.07.005.

Weltzien, E., K. vom Brocke, A. Touré, F. Rattunde and J. Chantereau. 2008a. Revue et tendances pour la recherche en sélection paticipative en Afrique de l'Ouest. *Cahiers Agricultures* 17: 165–71.

Weltzien, E. and A. Christinck. 2008. Participatory plant breeding: Developing improved and relevant crop varieties with farmers. In *Agricultural Systems: Agroecology and Rural Innovation for Development*. Academic Press, Burlingont, MA, USA and London UK, pp. 211–51.

Weltzien, E., A. Christinck, A. Touré, F. Rattunde, M. Diarra, A. Sangare and M. Coulibaly. 2006. Enhancing farmers' access to sorghum varieties through scaling-up participatory plant breeding in Mali, West Africa. In Almekinders, C. and Hardon, J. (eds), *Bringing Farmers Back into Breeding. Experiences with Participatory Plant Breding and Challenges for Institutionalisation*. Agromisa Foundation, Wageningen, Netherlands, pp. 58–69.

Weltzien, E., M. Kanouté, A. Toure, F. Rattunde, B. Diallo, I. Sissoko, A. Sangaré and S. Siart. 2008b. Sélection participative des variétés de sorgho à l'aide d'essais multilocaux dans deux zones cibles. *Cahiers Agricultures* 17: 134–9.

Yagoua, N. D. 1997. Caracterisation du sorgho pluvial, (Sorghum bicolor (L.) Moench.), de la zone soudanienne du Tchad. In Actes du Colloque 'Gestion des Ressources Génétiques des plantes en Afrique des Savanes'. Brochage Imprimerie Chirat, St-Just-La Pendue, France, Bamako, Mali, pp. 111–20.

Zougmoré, R., A. Mando and L. Stroosnijder. 2009. Soil nutrient and sediment loss as affected by erosion barriers and nutrient source in semi-Arid Burkina Faso. *Arid Land Research and Management* 23: 85–101. doi:10.1080/15324980802599142.

Zougmoré, R., A. Mando and L. Stroosnijder. 2010. Benefits of integrated soil fertility and water management in semi-arid West Africa: An example study in Burkina Faso. *Nutrient Cycling in Agroecosystems* 88: 17–27. doi:10.1007/s10705-008-9191-1.

Zougmoré, R., Z. Zida and N. F. Kambou. 2003. Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. *Soil and Tillage Research* 71: 143–9. doi:10.1016/S0167-1987(03)00050-3.