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Agriculture-Environment Series – Sorghum/Millet Systems At-A-Glance

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Table 1: Environmental Interactions in Sorghum & Millet Production Systems in Sub-Saharan Africa (SSA) and South Asia (SA).

	Pre-Production	*Production*		*Post-Production*
Environmental Constraints	**LAND CONSTRAINTS:** Sorghum and pearl millet are the 5th and 6th most important cereal crops in the world. In some regions the area planted may increase with climate change.	**WATER:** Sorghum and millets are grown with as little as 400-500 mm of rainfall per year. Though drought-tolerant, both sorghum and millet have greatly reduced yields in drought conditions.	**SOIL AND NUTRIENTS:** Sorghum and millets are often phosphorus-limited. Acid soils and wind damage (blown sand) also hinder crop yields. **CROP PESTS:** Weeds (*Striga*) and insect pests also cause serious losses. Downy mildew is the largest biotic constraint to pearl millet.	**POST-HARVEST LOSSES:** Post-harvest losses in sorghum and millet vary; can be 12% of harvests. **CROP RESIDUES:** Removal of crop residues for fuel is common in SSA. In SA residues are sold as fodder.
Rank Importance	4	1	2	3
Adaptation Strategies	**EXPANSION:** Sorghum and millet area in Africa has increased dramatically since 1980. **INTENSIFICATION:** Crop area in South Asia has decreased since 1980, but production is still rising.	**IRRIGATION:** Growing sorghum or millet is often an adaptation to water constraints where other crops might fail. Sorghum grows best with early water access through irrigation. Millet performs best with water access throughout the season.	**VARIETIES/HYBRIDS:** In India 82% of pearl millet and 75% of sorghum are improved varieties or hybrids. Diverse traditional varieties remain widespread in SSA. **AGROCHEMICAL INPUT USE:** In Asia sorghum is increasingly chemical-intensive (fertilizers and pesticides). In SSA subsistence cropping is the norm.	**TRADITIONAL STORAGE:** With proper drying, traditional storage can be effective; storage chemicals are sometimes used.
Environmental Impacts	**LAND DEGRADATION:** Owing to their resilience to abiotic stresses, sorghum and millet may encourage expansion onto previously uncultivated slopes and marginal lands; lands often more fragile and thus more vulnerable to environmental damage from crops.	**WATER DEPLETION:** Increasing water scarcity threatens the productivity of irrigated crops worldwide. Owing to lower yields for a given amount of water, sorghum is generally not economical under irrigation. But in SA it is often irrigated in rotation with other crops, thus exacerbating nutrient and water depletion.	**DISEASES:** Breeding for early maturation exposes flowers to moisture, allowing mildews to thrive. Downy mildew is a continuing threat to pearl millet due to changing races of the disease; this disease evolution may hasten with widespread fungicide use. **FERTILIZERS:** The marginal soils and environments where sorghum/millet are most often grown are frequently not responsive to fertilizer use.	**WASTED EFFORT:** Post-harvest losses represent wasted effort and environmental resources. **SOIL DEGRADATION:** Where residues are removed and sold for livestock fodder, fuel and construction, soil degradation and nutrient deficiencies are exacerbated.
Best Practices	**USE OF IMPROVED VARIETIES AND EXISITNG GENETIC DIVERSITY:** Improved varieties exist; sorghum/millet genetic diversity provides opportunities for adaptation to marginal sites. Managing soils can also raise productivity.	**WATER CONSERVATION & SPECIES SELECTION:** Judicious water and soil management raises water use efficiency. Drought-tolerant (traditional & improved) crops also increase yields. Agrobiodiversity is a key strategy for climate adaptation.	**BALANCED NUTRIENT MANAGEMENT:** Phosphorus fertilization has improved pearl millet yield by 52%, but is most effective when combined with improved soil management. Planting on ridges (to conserve soil and water), combined with phosphorus fertilizer has been shown to improve grain yield by nearly 135%.	**PROPER DRYING:** With low moisture content post-harvest losses can be minimized. **UTILIZE RESIDUES:** Incorporating residues into soils can reduce GHGs and raise fertility; fodder alternatives may be needed.

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Agriculture-Environment Series:
Sorghum/Millet and Environment in South Asia & Sub-Saharan Africa

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Introduction

This review is one in a series that examines crop-environment interactions drawing on both the academic literature and the field expertise of crop scientists. In this brief we examine the environmental constraints to, and impacts of, smallholder sorghum and millet production systems in Sub-Saharan Africa (SSA) and South Asia (SA). Millet in this paper primarily refers to pearl millet (*Pennisetum glaucum)*, although a number of other millets of significance to smallholder production and food security are also discussed.

The review highlights crop-environment interactions at three stages of the sorghum/millet value chain: pre-production (e.g., land preparation), production (e.g., soil, water, and input use), and post-production (e.g., crop storage and crop residues). At each stage we emphasize environmental constraints on smallholder farming (e.g., poor soil fertility, water scarcity, crop pests, etc.) and also environmental impacts of poor farming practices (e.g., soil erosion, water depletion, chemical contamination, etc.). We then highlight best practices for overcoming environmental constraints and minimizing negative environmental impacts in smallholder sorghum/millet production systems.

Table 1 summarizes the key environmental constraints and environmental impacts associated with sorghum and millet in SSA and in SA. Sorghum and millet are most commonly grown on low fertility soils and sloped terrain, and in drought-prone climates - in part because they are more tolerant of poor natural conditions than other cereal crops (Garí, 2002; U.S. National Research Council, 1996). In Africa, both sorghum and millet are regularly planted by smallholder farmers as a hedge against drought that might reduce yields of other crops (Clay, 2004).

Notably, sorghum and millet exhibit relatively few of the environmental impacts commonly associated with more intensively cultivated crops such as fertilizer runoff, pesticide contamination, or water depletion, since both of these crops are overwhelmingly grown by smallholder farmers with few, if any, chemical or irrigation inputs. Nevertheless, the tendency to grow sorghum and millet on marginal and heavily sloped lands does pose some environmental risks – including soil degradation and erosion – that can be mitigated through the adoption of best practices as described below.

Sorghum and Millet Production Systems

In 2011 sorghum and millet together accounted for 42% of cereal area harvested and 25% of cereal production in Sub-SSA, compared to 13% of cereal area harvested and 5% of cereal production in SA (FAOSTAT, 2012).

Sorghum: Sorghum (*Sorghum bicolor* is the predominant species cultivated) is the fifth most important cereal crop in the world and is grown primarily in rainfed conditions in both developed and developing countries, including the countries of SSA and SA (Clay, 2004). Sorghum is moderately drought tolerant, and 80% of sorghum worldwide is produced in dryland systems (Assefa *et al.*, 2010). Sorghum is grown commercially in both developed and developing countries (FAOSTAT, 2012). Intensive sorghum systems are highly mechanized, use hybrid seed and fertilizers, and either no-till with herbicide or mechanized tillage. Sorghum yields range from 3 to 5 metric tons per ha under intensive cultivation, as compared to more extensive smallholder systems which average 0.5 to 1.0 metric tons per ha (Clay, 2004).

Smallholder farmers in developing countries primarily grow sorghum for local markets or subsistence consumption. Where possible the crop is grown as a dry season crop in rotation or intercropped with pulses or other cereals. Waddington *et al.* (2010) describe sorghum production in six different systems in SSA and SA:

1. SSA- Highland Temperate Mixed
2. SSA- Cereal-Root Crop Mixed
3. SSA- Maize Mixed
4. SSA- Agro-Pastoral Millet/Sorghum
5. SA- Rainfed Mixed
6. SA- Dry Rainfed

Sorghum is typically grown on marginal land with unreliable rainfall and few inputs, which contributes to low yields (Waddington *et al.,* 2010). The yield of the average smallholder sorghum farmer in SSA and SA is only 44% of the highest estimated attainable yields for smallholder farmers worldwide (Waddington *et al.*, 2010). But the crop remains of enormous – and increasing – importance for some of the poorest smallholder farmers: in least developed countries, sorghum production increased by 74% between 1980 and 2011 (FAOSTAT, 2012).

Millet: Millets (which are not a single species but rather a diverse group of small-grained annual cereal grasses) make up 10% of area harvested for all crops in SSA, and 4% in SA (FAOSTAT, 2012). Millets are particularly important for smallholder farmers on drought-prone marginal lands. So-called "major millets" like pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*) are medium-yielding, fairly drought tolerant and sometimes grown commercially in both developing and developed countries.[1] Pearl millet is the sixth most important cereal crop worldwide and is a staple in parts of both Africa and Asia (US National Research Council, 1996). Minor millets such as Kodo millet (*Paspalum scrobiculatum*) and Fonio (*Digitaria exilis*) are grassier plants with shorter stalks and smaller grains, producing lower yields but exhibiting a remarkable ability to survive severe drought (Palaniappan, 2009; Bala Ravi, 2004). Other hardy grasses like tef (*Eragrostis tef)*, the most widely grown and important staple in Ethiopia, are also classified as millets.

[1] Sorghum itself is sometimes also classified as a "major millet."

Millets are even more drought resistant than sorghum and are often planted in place of sorghum when drought conditions are expected (Clay, 2004). Most millet is produced in Asia and Africa in temperate, subtropical, and tropical areas. It is primarily produced for subsistence consumption, but is also important for livestock fodder. South and East Asia produce about 60% of the world's millet crop, followed by Eurasia/Central Asia (14%) and Africa (16%). India is the leading producer worldwide, generating roughly 38-42% of global millet production (FAOSTAT, 2012; Bala Ravi, 2004). With the exception of some commercialized farming in India, millet cropping systems in SSA and SA are extensive and use few inputs or improved technologies. Mainly because millet is grown under unfavorable conditions, its yields are lower than other cereals – though less variable in the event of severe drought (FAO, 1996). Some millets, such as tef, also have short growing seasons and can be well fitted into multiple cropping systems or very short growing seasons. Millets are frequently intercropped with legumes or less commonly, with sorghum or maize.

Millet varieties planted by subsistence farmers in SSA are typically low yielding (~500 kg/ha) due to genetic as well as environmental factors, have low rates of fertilizer response, and are locally adapted (US National Research Council, 1996). Pearl millet makes up 90% of the millet grown in Central and West Africa (FAOSTAT, 2012). Various other millet varieties are grown throughout Africa, with pearl millet concentrated in West Africa and Sudan, and finger millet more prevalent in Southern and Eastern Africa (FAO, 1996). Tef is almost exclusively grown in Ethiopia.

In South Asia pearl millet is typically grown for both grain food and fodder as a non-irrigated crop, though in some places it is irrigated for fodder (Basavaraj *et al.,* 2010). It is frequently grown with other crops such as pulses and oilseeds. Smallholders in southern India grow sorghum and four types of millet (pearl millet, finger millet, little millet, and foxtail millet) in diverse combinations depending on local preferences and ecologies. Similarly, of sorghum and millet crops grown in SSA, sorghum is the most widely grown, followed by pearl millet, finger millet, tef, and fonio.

Pre-production of Sorghum and Millet

Land Constraints

Because sorghum and millets are drought-tolerant and require relatively few inputs, they are often grown on agriculturally marginal land that is also ecologically fragile (Clay, 2004).

Sorghum: Sorghum area harvested in SSA increased by 76% from 10,986,931 ha in 1980 to 19,381,554 ha in 2010, with the former Sudan and Nigeria making up much of the new harvested area (FAOSTAT, 2012). A 1996 FAO publication reported that increased sorghum area harvested in Africa during the 1980s was largely due to land expansion into drier production zones as a result of population growth. Area under sorghum production in SA meanwhile has *decreased* steeply - in India area harvested declined from 15,809,400 ha in 1980 to 7,381,700 ha in 2011 (FAOSTAT, 2012). The area of sorghum harvested in South Asia overall decreased by 53% from 16,204,761 ha in 1980 to 7,595,433 ha in 2011. Production quantity also declined from 10,662,302 metric tons in 1980 to 7,140,516 metric tons in 2011 (FAOSTAT, 2012). A 2009 IFPRI study attributed decreased sorghum cultivation in India to changing preferences among consumers, which has led many sorghum growers to shift production to other cereal or cash crops (Pray & Nagarajan, 2009).

Millet: Worldwide millet area harvested followed a similar pattern to that of sorghum, overall declining from 38,372,337 ha in 1980 to 34,790,620 ha in 2010, while the least developed countries (defined by the FAO) more than doubled area harvested from 1980 to 2010 (FAOSTAT, 2012). SSA's millet area harvested increased from 12,139,937 ha in 1980 to 21,118,993 ha in 2010 (FAOSTAT, 2012). In SA, India remains the largest producer of pearl millet, and indeed is the largest producer of the grain in the world, but area under millet production in India has declined since 1966 (Millet Network of India, n.d.; FAOSTAT, 2012), particularly in Gujarat (Basavaraj *et al.*, 2010).

<u>Adaptations to Land Constraints</u>

Adaptations to land constraints for sorghum and millet production have differed drastically across continents: in SSA, population growth has forced farmers to shorten fallow periods and to expand sorghum and millet cultivation to land previously deemed unsuitable for agriculture (Fisher, 2009). At the same time, widespread soil degradation has led farmers to plant sorghum and millet on existing cropland that is no longer suitable for growing higher-yielding grains, such as maize.

In contrast, in SA the dominant strategy to increase sorghum and millet production has been intensification (Pray & Nagarajan, 2009). Notably, even while the area of sorghum and millet harvested in India declined steeply, average crop yields have remained steady or increased over time. In fact, overall millet production in SA has *increased* since the 1980s, in spite of decreasing area harvested, reflecting the use of improved varieties and adoption of more intensive cultivation methods (Basavaraj *et al.,* 2010).

An additional key adaptation to land and climate constraints in both SSA and SA has been to take advantage of sorghum's and especially millet's natural genetic diversity, planting different varieties suited to different regions' land and climate conditions. For example, the minor millet fonio *(Digitaria exilis)* is especially important in West Africa where it is highly adapted to drought and low-fertility soils. It is characterized by a short production time, about 10 weeks for the earliest maturing cultivars, which mitigates the influence of drought, offering a fast source of food in a critical food insecure period (when other crops, including other millets, are not yet matured).

Environmental Impacts of Land Use

In SSA, continued expansion of sorghum and millet production on the extensive margin is likely to exacerbate environmental problems such as wind and water erosion that already affect marginal lands (Scherr & Yadav, 2001). Shortened fallows and expansion onto marginal lands has already resulted in declining soil fertility on sorghum/millet plots, which in part explains the pattern in SSA where millet area has increased but yields have declined (FAO, 1996).

In SA the environmental impacts of intensification of sorghum and millet production are less clear – on the one hand, it is possible that providing farmers with training and agricultural inputs to intensify millet and sorghum production can lower pressures on marginal lands. This outcome assumes that farmers choose to focus their efforts on relatively higher quality land and that marginal/sloped land currently planted to sorghum/millet will be left uncultivated. On the other hand, if sorghum and millet production becomes more intensive, negative environmental impacts common in other crops such as nutrient runoff and agrochemical leaching may become more significant (Scherr & Yadav, 2001).

Best Practices for Land Management

With any crop planted on marginal lands, a strategy to minimize expansion is to aggressively apply comprehensive yield-enhancing technologies in the current production areas. Best practices for land management in sorghum and millet production thus broadly include:

- *Intensification*: Improving the land productivity of millet and sorghum through higher yielding varieties and improved management practices can reduce the pressure to expand the area cultivated. Early sorghum hybrids exhibited a 40% yield advantage over open pollinated varieties (Duvick, 1999), and research is underway to shorten growing periods and heighten drought tolerance in pearl millet (ISAAA, 2012).

In SA to some extent this intensification has already occurred - in India 82% of pearl millet and 75% of sorghum is already of high yielding varieties (Pray & Nagarajan, 2009). But despite the increasing global awareness of plant genetic resources and links to food security, sorghum and millets are relatively neglected in scientific research, agricultural programs, and policies (Burke *et al.*, 2009; GCDT, 2007; Garí, 2002). Recent molecular research emphasizes extraordinary crop diversity in pearl millet (one of many millet species) within Niger alone (one of many regions where millets are grown) (Mariac *et al.*, 2011). Burke *et al.* (2009) suggest that such agro-biodiversity is likely to be a critical component of adaptation strategies to continue agricultural production on increasingly marginal lands in the face of climate change.

Production of Sorghum and Millet

Sorghum and millets are grown with as little as 400-500 mm of rainfall per year, and usually without applying fertilizers or other inputs (Nagarajan *et al.*, 2005). Nevertheless there are several prominent environmental constraints on production including drought, poor soil fertility, crop pests and diseases, and weed competition. Environmental impacts of sorghum and millet production, meanwhile, though less severe than other grain crops, include soil degradation and sediment and agrochemical runoff (where applied), particularly as systems intensify as in SA.

Water Constraints

Farmers grow sorghum in areas too hot and dry for maize and grow millet in areas too hot and dry for sorghum (Burke *et al.*, 2009). Although both sorghum and pearl millet are relatively drought tolerant, drought does lead to a decrease in yield, particularly when plants are water stressed during reproductive stages (Waddington *et al.*, 2010, Mutava *et al.*, 2011). At the same time, since rainfall is frequently short and intense in sorghum and millet growing regions, waterlogging, runoff and erosion represent other significant constraints to sorghum and millet yields (Murty *et al.*, 2007; Witcombe & Beckerman, 1986).

Sorghum: In SA sorghum is grown either as a *kharif* (rainy season) crop or as a *rabi* (post-rainy season) crop. The highest sorghum yields are achieved with the *kharif* crop (around 1 ton/ha) due in large part to abundant water access - sorghum will also tolerate poorly drained soils and can survive temporary waterlogging during the rainy season (Fageria, 2011). Drought still poses a threat to *kharif* sorghum, however, particularly in years of mid-season drought. The *rabi* crop is even more drought-constrained as the crop is dependent upon post-rainy season stored soil moisture (Murty *et al.*, 2007).

In addition to direct impacts on the plant, drought can lead to reduced nutrient uptake and make sorghum more susceptible to pests (Assefa *et al.*, 2010), both of which are discussed further below.

Millet: Millet is often planted on the most marginal lands where maize and even sorghum fail (Mohammed *et al.*, 2002). Pearl millet is more drought tolerant than sorghum and can grow with as little as 12.5 cm of water, though it requires 50 cm or more when grown for animal forage (FAO, 2010). Unlike sorghum, pearl millet requires an even water distribution throughout the growing cycle – pearl millet does not become dormant during drought, and it also cannot tolerate waterlogging (US National Research Council, 1996).

Adaptations to Water Constraints

Often the cultivation of sorghum or millet is itself an adaptation to water scarcity. Indeed, in SSA and SA farmers often plant both crops (sorghum and one or more millet species) to hedge against uncertain rainfall (Ahmed *et al.,* 2000). Sorghum roots can extend to a depth of 2.5 meters, making water at deeper depths available for consumption (Assefa *et al.,* 2010). Sorghum also has high osmotic adjustment, a high ratio of secondary to primary roots, and water-efficient leaf characteristics that make it less susceptible to yield loss from water stress than other cereals (Assefa *et al.,* 2010). Some lower-yielding "minor millets" have deep root systems with efficient soil moisture extraction ability enabling them to grow under severe moisture stress conditions where most other cereal crops (including sorghum and pearl millet) may not survive or produce grain (Bala Ravi, 2004).

Efforts to overcome water constraints on sorghum and millet production in smallholder systems focus on improved water management, planting timing, and using diverse and drought resistant varieties.

- *Irrigation and water harvesting*: Access to irrigation and high quality seed can increase both sorghum green crops (for forage) and the yield of seeds (for grain). In India expanded irrigation and hybrid seeds have increased average *rabi* sorghum crop yields from 460 kg/ha to 640 kg/ha since the 1970s (Singh *et al.,* 2009). Murty *et al.* (2007) note the adoption of water conservation and management practices such as on-farm water harvesting to utilize rainfall can improve both *kharif* and *rabi* sorghum yields without irrigation.

- *Early planting*: In both SA and SSA, optimizing planting dates for sorghum to prevent water stress during water sensitive growth periods is another key strategy to mitigate sorghum yield reductions (Assefa *et al.,* 2010). Singh *et al.* (2009) identify late sowing and low water-holding capacity of shallow soils as the key impediments to expanded *rabi* sorghum productivity in India. Depending on the local situation, making maximum efforts to prepare land early and plant the crop as early as possible with the first rains can boost crop production. In some instances, even dry planting is possible anticipating the early arrival of the rains.

- *Use of local varieties*: Local landrace varieties of millet are often better adapted to drought conditions than improved commercial varieties. However local varieties are lower yielding and typically do not perform as well under optimal growing conditions (Yadav, 2010).

- *Use of improved varieties*: Sorghum research has focused on plant breeding for drought tolerance and for early maturation (Assefa *et al.,* 2010). Traditional sorghum cultivars are photoperiod sensitive, flowering just as or after the rains cease, so that their grains fill and mature during dry weather. Improved cultivars have been developed which flower and mature earlier in the season, when soil moisture levels are generally more favorable for grain filling, allowing for higher yields in low-rainfall years. Improved varieties of drought tolerant pearl millet are also available and increasingly used in South Asia, although millet research lags behind that for sorghum (Murty *et al.,* 2007). Recent research suggests that millet hybrids provide good prospects for improving both grain and stover yields in arid zone pearl millet systems without significantly compromising crop duration (Yadav and Manjit, 2012).

Other water-related adaptations common in smallholder production systems include reduced plant populations (greater spacing) to mitigate water shortages, particularly in SSA (Fageria, 2011). No-till practices, application of fertilizer, and pest, disease, and weed management practices all further reduce yield losses due to water stress (Assefa *et al.,* 2010).

Environmental Impacts of Water Management

Few published data exist on the environmental impacts of water management in smallholder sorghum and millet systems, although some new research examines the crops' roles in more intensive multi-crop rotations in SA. Broadly, environmental impacts of current water management strategies include:

- *Water depletion*: Increasing irrigation of sorghum and pearl millet crops in South Asia may further deplete water resources, particularly when grown in rotation with other irrigated field crops. Studies suggest that while sorghum requires less water than water-intensive crops like rice, because sorghum yields are typically lower, the water productivity (crop production per unit water) of sorghum is also low. In a recent study on irrigated plots in Mauritania, water productivity was shown to be essentially the same for rice and sorghum (Garia-Ponce *et al.,* 2012).

- *Vulnerability to new stressors:* The increasing use of improved sorghum and millet varieties has helped overcome drought in SA, but with some negative environmental interactions. First, early maturation allows sorghum and millet to escape the influence of drought in dry years, but being harvested earlier also reduces the plant's potential to take full advantage of better growing conditions in wetter years. (Ahmed *et al.,* 2000). Meanwhile, varieties developed for earlier flowering expose developing grain to wet conditions in which it can deteriorate rapidly; as a result, many early improved varieties' flowers and seeds proved particularly susceptible to grain molds (Williams *et al.,* 1981).

Other adaptations to water constraints such as rainfall harvesting and improved tillage have had positive environmental impacts (Fageria, 2011; Assefa *et al.,* 2010). Rainfall harvesting, for example, increases water available to plants and also mitigates runoff and erosion from downpours. Using tied ridges enhances water harvesting and subsequent utilization by the crop over extended period of time. Use of multiple sorghum and millet varieties on plots to hedge against possible drought also has positive environmental benefits in the form of sustained or enhanced regional agro-biodiversity and reduced pest outbreaks.

Best Practices for Water Management

Sorghum and millet water requirements depend on overall climatic conditions (temperature, humidity, wind, sunlight), but also on soil quality, pests, diseases, and management practices. Best practices include:

- *Well-timed planting and irrigation*: Sorghum water requirements are higher from the boot stage through the middle of the growing cycle (Assefa *et al.,* 2010). Millet is hardier in response to drought but also requires water access throughout its life cycle to provide optimal yields.

- *Integrated soil management*: Improved soil management practices including erosion control and applying organic fertilizer improve water-use efficiency for sorghum (Fageria, 2011; Singh *et al.*, 2009). Synthetic fertilizer use has also been shown to increase the water use efficiency of millet (Amadou *et al.,* 1999).

- *Use of local and improved varieties*: Variation in sorghum root genotypes suggests selection could increase root development and water uptake (Assefa *et al.,* 2010). Similarly, hybrids of local millet landraces well-suited to drought conditions have been shown to withstand drought while producing high yields under optimal conditions (Yadav, 2010). To date, however, much of the breeding in sorghum and millet has focused on increasing yields under ideal conditions, rather than in variable climatic conditions or on marginal land (Schlenker & Lobell, 2010; Liu *et al.*, 2008; Adeiuwon, 2006; Butt *et al.*, 2005).

Continued efforts to develop more drought resistant and management-responsive cultivars of both sorghum and millet are needed. Singh *et al.* (2009) find that sorghum yields in three states in India could be doubled through use of improved varieties, nutrient management and timely sowing of the crop after the monsoon rains cease.

Soil and Nutrient Constraints

Sorghum and millet require fewer inputs than other cereal grains, but are still limited by soil nutrient constraints.

Soil infertility was found to be a major contributor to yield gaps in all six sorghum systems examined by Waddington *et al.* (2010). Improved varieties of sorghum typically require more nutrients than traditional varieties (Wortmann *et al.,* 2007). In addition, though sorghum grows on a wide variety of soil types, and in soils with a pH ranging from 5.0 to 8.5 (Fageria, 2011), in acidic soils (at pH values less than 5.5) calcium and magnesium deficiencies and aluminum toxicity can further reduce yields (Fageria, 2011). Sorghum can also be negatively affected by saline conditions early in the growing season, and the crop is more likely to suffer from iron deficiency than other grains.

For millet, Voortman (2002) observes that in the absence of drought, soil fertility is the primary factor limiting production in West Africa. Singh *et al.* (2009) similarly note that in addition to variable rainfall, constraints including soil acidity, low soil organic matter and soil nutrient deficiencies - particularly low phosphorus (P) - are the most important limiting factors to increasing productivity of millet-based systems. Studies have found some positive yield responses of millets to nitrogen (N) fertilizers, but this may be reduced or eliminated if P is inadequate.

Wind erosion and wind damage are additional soil-related constraints. Pearl millet is grown in the Sahel and West African Sudano-Sahelian Zone where wind and sandstorms can threaten plants (US National Research Council, 1996; Michels *et al.,* 1993). Wind erosion is exacerbated by intensified use of marginal land, overgrazing, and degradation of soil cover from drought (Michels *et al.,* 1993). Where soil crusts are formed by rain and soil drying, loose sand particles are more easily blown by wind dusts, causing crop damage (Michels *et al.,* 1993). The extent of damage often depends on the stage of growth, with older seedlings less impacted by blown dust than those at early growth stages. Sandblasting has also been shown to reduce photosynthesis in surviving plants.

Adaptations to Soil and Nutrient Constraints

While poor soil fertility is a significant constraint to sorghum and millet production, very few smallholder farmers in SSA and SA use fertilizer (and even more rarely are inorganic fertilizers applied on sorghum and millet plots). Moisture deficiencies during crop growth inhibit nutrient uptake, making fertilizer application even less beneficial and economical.

Sorghum: Clay (2004) reports that while some smallholder sorghum farmers have invested in hybrid improved seeds such as in India, fertilizer use remains uncommon. In contrast, in developed countries – and in some intensive commercial operations in South Asia – major increases in dryland yield have been attributed to increased fertilizer use and hybrid seed advancement (Assefa & Staggenborg, 2010).

- *Fertilizer use*: Returns to applying nitrogen (N) fertilizer for sorghum production in SSA and SA are not well documented. This differs greatly from U.S. sorghum production, where nitrogen (N) and phosphorous (P) are the most common limiting element (Schlegel, 2012). Indeed, 60-65% of yield gains in the U.S. by 1999 were attributed to nitrogen and irrigation (the remainder was attributed to improved varieties) (Duvick, 1999). More recent research by Fageria (2011) reports that sorghum yields increase with N application, but also that nitrogen use efficiency in sorghum varieties varies widely, and that under irrigated conditions the use of nitrogen-efficient varieties – along with reduced plant spacing - can reduce the need for N fertilizers.

Particularly in Africa, phosphorus (P) is often the limiting nutrient for sorghum production. But at the same time returns to P fertilizer quickly diminish as application levels increase (Voortman, 2002). Potassium (K) may be another source of nutrient deficiencies – K is typically replenished through dust storms and crop residues, but when crop residues are removed (see post-harvest section below) available K may be insufficient. Sorghum yields have been shown to increase linearly with increases in K application, but the yield gain is modest (Voortman, 2002).

- *Soil conservation*: Similar to other crops, soil quality and sorghum yields are higher in sorghum production systems where plant foliage remains in the field as a mulch following harvest – a practice relatively more common when the crop is grown for grain rather than silage (*Meyer et al.,* 1999). But while mulching can mitigate the nutrient-depleting effects of repeated cropping and short fallows, households often prefer to use mulch for building material, fuel, and fodder (Wezel, 2000). Cover crops, crop rotation, and continuous farming along with green manure can further reduce the fertilizer and water requirements of sorghum crops (Clay, 2004).

- *Legume intercropping*: Combining ridge planting, phosphorus fertilization and rotation with cowpea has been associated with a 200% increase in sorghum yield compared with the traditional production system (Singh *et al.,* 2009), although comprehensive studies of intercropping in SSA and SA sorghum systems have yet to be completed.

Millet: Millet is often grown on low fertility soils that may or may not respond to organic or inorganic fertilizers due to the soil's poor capacity to retain nutrients (Voortman, 2002). Effective nutrient management in millet thus demands interventions that jointly improve soil fertility and soil structure.

- *Fertilizer use and soil conservation*: Singh *et al.* (2009) find that on average, phosphorus fertilization improved pearl millet yield by 52%, but planting on ridges and phosphorus fertilization improved grain yield by nearly 135% (Singh *et al.,* 2009).

- *Fallowing*: Fallowing is commonly used in millet producing areas of SSA such as Niger, but increasing population has led to shorter fallow periods that do not restore soil fertility (Hiernaux *et al.*, 2009; Samake *et al.*, 2005).

- *Intercropping*: Pearl millet's deep root structure, reaching nutrients unavailable to other crops (US National Research Council, 1996), makes the crop ideally suited for intercropping with crops with shallower roots.

Where sand- and soil-related wind damage is a problem, farmers may replant millet crops up to several times after wind destruction (Michels *et al.,* 1993). In such contexts, improved soil management and fertilizer use can promote early plant growth, reducing the damage from sand storms (*ibid*). Reduced plant spacing is another strategy to reduce wind damage - widely spacing millet plants over 1 to 2 meters apart (a practice common on sites with limited soil moisture) has been found to increase the damaging effects of wind.

<u>Environmental Impacts of Soil and Nutrient Management</u>

Literature on the environmental impacts of soil fertility management in sorghum and millet production is limited. Potential impacts associated with either crop include:

- *Soil nutrient mining:* Sorghum is capable of thriving in marginal lands because of its efficiency in removing nutrients from the soil. As a consequence, it is a soil depleting crop (Clay, 2004), whose effects may be significant especially when sorghum is integrated into repeated crop rotations with insufficient nutrient management. Millets' net effects on soil nutrient balances are relatively under-studied in SSA and SA.

- *Soil erosion:* Sorghum cultivation has been associated with high levels of soil erosion even on slopes as low as 4 degrees. The problem is worsened when sorghum is grown for silage, since most of the sorghum plant matter is harvested and removed from the field, exposing the soil to greater wind and water erosion (Clay, 2004).

- *Fertilizer runoff*: Applying fertilizer on the thin and sandy soils where sorghum and millets are grown can result in more runoff and nitrogen leaching than fertilizer use on healthier soils. This may cause local groundwater pollution, and be inefficient in increasing yields (Voortman, 2002). On the other hand, there is some evidence to suggest that millets can remove potentially harmful fertilizer residue from lower layers of the soil that are not reached by other crops (US National Research Council, 1996).

- *Contamination of sorghum forage*: One unintended consequence of fertilizer use is an increase of naturally occurring hydrogen cyanide in sorghum forage, potentially threatening livestock health (Sher *et al.*, 2012).

Luxuriant growth following N application is likely to increase hydrogen cyanide content of sorghum. Care should be taken not to feed such sorghum foliage to livestock immediately after harvest.

- *Crop top-heaviness*: An additional unintended impact associated with inorganic fertilizer use on millet plots is environment-related crop lodging damages. Tall varieties of pearl millet normally grow taller than surrounding weeds, and when grown with fertilizer plants can become more susceptible to lodging (destruction from wind or rain) (US National Research Council, 1996). Breeding shorter varieties with stronger stalks minimizes such damage.

Best Practices for Soil and Nutrient Management

Generalizations about soil fertility limitations, even within a single region, are difficult due to micro-level variation and on-farm management practices (Mariac *et al.*, 2011). Differences in yield are often the result of interactions between seed variety, soil fertility, moisture availability, and other variables that make correlation with a single factor difficult to measure (Voortman, 2002). Broad best practices for sorghum and millet soil and nutrient management include:

- *Applying soil nutrients*: Sorghum yields are constrained by limited bio-availability of nitrogen (N), phosphorus (P), potassium (K), iron (Fe) and sulfur (S), and Zinc (Zn) (Sharma and Kumar, 2011). N, P, and K deficiencies can be mitigated by introducing legume crops and applying synthetic and organic fertilizers, including through irrigation water. Fe deficient soils can be addressed through basal application of organic chelates, and low S levels can be corrected through mixing elemental S or gypsum with surface soil well before sowing. Low Zn levels can be mitigated through applying zinc chelates; however, mixture with phosphate fertilizers should be avoided (Sharma and Kumar, 2011). Voortman (2002) recommends against blanket fertilizer application and the All India Millet Network (n.d.) claims sorghum grows better without synthetic fertilizer.

- *Managing nutrient toxicity*: Analyzing soil and plants can diagnose nutrient toxicities and deficiencies in sorghum - dolomitic lime and acidity tolerant varieties can reduce aluminum toxicity, for example (Fageria, 2011). Where irrigation is available, applying non-saline water to sorghum during the early stages of growth can also reduce sorghum yield losses from salinity.

- *Conservation agriculture*: For both sorghum and millet production, conservation tillage and no-till agricultural practices have been shown to reduce erosion by up to 80% (Meyer *et al.,* 1999). Sorghum plant matter is particularly beneficial to soil if it is chopped at the time of harvest. Subbarao *et al.* (2000) reported that in a long-term study conducted in Niger from 1986 to 1996, phosphorus fertilization, tillage and rotation with cowpea increased average millet yields to 710 kg/ha from 230 kg/ha with traditional management. Tied ridges have been used successfully in West Africa in low-rainfall areas to improve soil fertility and water-holding capacity. Pearl millet grown using tied ridging increased yields in both wet and dry years (US National Research Council, 1996). No-till methods for pearl millet were found to significantly reduce fertilizer run-off losses compared to conventional practices. In one pearl millet production study, 3.4 times more N and 2.7 more P were lost in run-off from conventional treatments than for the no-till treatments (Franklin *et al.*, 2012).

- *Improved varieties and windbreaks*: To reduce vulnerability to lodging by wind, modern pearl millet varieties are bred for shorter, stronger stalks. Tillering varieties, in which multiple productive shoots grow off an initial stalk, can reduce crop losses in bad years and increase yields in good years (US National Research Council, 1996). Vetiver hedges (a tall grass) may be effective windbreaks for millet where sand storms are a limitation (US National Research Council, 1996).

Crop Pest Constraints

Weeds are a primary constraint to sorghum production especially *Striga.* (Estep *et al.*, 2011; Waddington, 2010). Pests (birds and insects) and diseases (especially fungi, along with viruses, bacteria, and nematodes) also limit both sorghum and millet production (Clay, 2004).

Sorghum: Witchweed (*Striga* spp.) is a major inhibitor to sorghum production in SSA (Estep *et al.,* 2011; Waddington, 2010). *Striga* is a parasitic weed that attaches itself to sorghum roots from which it draws moisture and nutrients, inhibiting crop growth, reducing yields and in severe cases causing crop death. The two dominant *Striga* species are *Striga hermonthica* and *Striga asiatica. Striga* infestation is a problem in areas where sorghum is continuously cultivated and in some cases severe *Striga* can lead to abandonment of agricultural land (Estep *et al.*, 2011; Clay, 2004). In the past, some *Striga*-resistant sorghum varieties have been developed, but these generally offer lower yields than traditional cultivars and improved (but *Striga*-susceptible) varieties. However, recent efforts by Purdue University researchers have produced high yielding and *Striga* resistant cultivars under African conditions (Ejeta, 2007).

Grain molds also cause significant losses in sorghum grain yield and quality, particularly in areas where improved cultivars have been adopted. The grain mold problem is exacerbated when late rains arrive after grain fill. Important diseases include anthracnose, smuts, charcoal rot, downy mildew, ergot and leaf blight. In Africa, downy mildew incidence is frequently between 0 and 50% for sorghum, although crop loss is normally in the range of 0–20% (Jeger *et al.,* 1998).

Insect pests also constrain production (Waddington *et al.,* 2010). In sorghum, stem borers are endemic in all areas, with *Busseola fusca* and *Chilo partellus* dominating high and low altitudes, respectively. Head bugs and midges are most important in West Africa; and shoot fly causes substantial losses in late sowings in both Asia and Africa. Sorghum is also susceptible to bird damage.

Millet: In the African Sahel, major pests of pearl millet include the millet head miner, responsible for losses of between 1%-85% in Senegal, Burkina Faso, Gambia and Mali, and two species of short-horned grasshoppers, responsible for pearl millet losses of between 70%-90% in bad years, which occur an average of every five years (Abate *et al.,* 2000).

Like with sorghum, weeds (*Striga*) are a constant and serious threat to pearl millet production in many parts of Africa (Ejeta & Gressel 2007; Samake *et al.,* 2006). Efforts to identify crops with resistance to *Striga* have yielded mixed results, with essentially no success to date with pearl millet (Estep *et al.*, 2011). In Africa, weed problems are exacerbated by planting practices: millet is typically planted by broadcasting seeds, which makes weeding labor intensive (National Research Council, 1996).

In both SSA and SA downy mildew (*Scelerospora graminicola*) is the most destructive pearl millet disease causing severe economic losses. As mentioned previously, pearl millet hybrids are particularly susceptible to downy mildew, which evolves rapidly and has diverted crop research efforts to breeding for mildew resistance rather than for higher yield or quality. Pearl millet downy mildew disease is now considered the primary pearl millet constraint (Pray & Nagarajan, 2009), and has been reported in more than 20 countries (Singh *et al.* 2009). Other comparatively minor diseases affecting pearl millet are smut, ergot and rust (Murty *et al.,* 2007).

Diseases also plague some other millet species - finger millet blast disease is perhaps the most devastating, reported to cause over 50% yield losses in finger millet crops (Mgonja *et al.,* 2007). The Millet Network of India claims some traditionally-produced millets in SA such as foxtail millet are “pest free” under traditional cropping systems (Millet Network of India, 2009).

<u>Adaptations to Pest Constraints</u>

A number of strategies are currently employed to overcome biotic constraints in sorghum and millet production.

- *Improved varieties*: Farmers in both South Asia and SSA have adopted pest, weed and disease resistant sorghum and millet varieties to overcome biotic production constraints. Adugna (2007) reported that over 100,000 Ethiopian farmers had adopted *Striga*-resistant sorghum varieties, in some cases allowing for cultivation on lands that had previously been abandoned due to *Striga* infestation. In India, high yielding and downy mildew resistant pearl millet seeds contributed to a doubling of pearl millet productivity over the last five decades; increased disease and pest resistance in rainy season sorghum varieties contributed to an increase in average sorghum yields of 280 kg/ha from 1970-2003 (Pray & Nagarajan, 2009).

- *Fallowing, intercropping, rotation, and other improved management practices*: Fallowing agricultural fields can reduce weed prevalence in subsequent years. A study in Ghana found that continuous sorghum cropping led to increased presence of *Striga* and stem borers compared to crop rotations with legumes or sunflowers (Sauerborn *et al.,* 2001). In a study in Mali, fallowing for one, two, five, and seven years linearly reduced the prevalence of *Striga* on subsequently planted pearl millet fields (Samake *et al.,* 2006). Intercropping sorghum and millet with pest-repellant[2] plants such as *Desmodium*, along with border plantings that attract pests out of fields (push-pull systems) can also greatly reduce yield losses. A study in Kenya found that planting a border of a Sudan grass, a species related to sorghum that attracts stem borers, dramatically reduced the prevalence of stem borers in sorghum fields (Khan *et al.,* 2000). Management practices such as early planting can reduce the impact of shoot fly as well as *Striga*.

- *Pesticides and herbicides*: A wide variety of herbicides and pesticides are used on sorghum crops in intensive production systems, especially in SA (Clay, 2004; Khan *et al.,* 2000). In India, most seed companies treat pearl millet seed with the fungicide metalaxyl before marketing, in an effort to reduce downy mildew outbreaks (Thakur et al. 2011).

<u>Environmental Impacts of Pest Management</u>

Literature on environmental impacts of pest management practices specific to sorghum and millet production is limited. Herbicides and pesticides regularly used on intensive sorghum crops have been shown to cause harm to surrounding ecosystems (Clay, 2004; Ragnarsdottir, 2000; Kamrin, 1997), but few sorghum-specific studies exist.

For millet, the seed treatment chemical metalaxyl, though effective for moderately disease-resistant lines of pearl millet, has proven much less effective for higher-yielding hybrid millet varieties. The chemical is also recognized as a potential ground water contaminant, though usage levels are relatively low for sorghum and millet compared to other crops (tobacco, onions). Perhaps most importantly, the

[2] Generally, these plants reduce pest prevalence by either serving as a diversionary target of pest attack, for example as an attractive target for ovipositing insects, or because they are chemically repellant to pest species.

widespread use of metalaxyl for downy mildew management across SA risks fostering the emergence of fungicide resistant biotypes of the disease (Thakur *et al*., 2011). Ultimately efforts to control downy mildew disease through seed sanitation alone have proven largely ineffective for large quantities of seeds.

The introduction of improved mildew-resistant varieties represents an alternative to agro-chemical use. However at the same time this practice threatens to reduce the agro-biodiversity of millet systems, displacing varieties that are lower-yielding in good years, but out-perform improved varieties in bad years.

Best Practices for Pest Management

Best practices for pest management might include any of the strategies discussed in the adaptations section. However research is generally lacking, particularly for millet, as to the benefits of various pest control strategies in different situations. Because sorghum is often grown in a mixed farming system, addressing constraints may be better achieved through system improvement, rather than focusing on sorghum as an individual crop (Waddington *et al.,* 2010).

ICRISTAT and others have advocated increased investment in crop varietal improvements to improve tolerance of sorghum and millet to biotic stresses (Ashok Kumar, 2011; Chandrashekar & Satyanarayana, 2006). This approach, augmented by integrated pest management practices including more judicious application of agrochemicals, appears to be the best option for economical sorghum and millet production in SSA and SA.

Sorghum and Millet Post-Harvest

Post-Harvest Losses and Residue Management

Estimates on the magnitude of post-harvest losses in sorghum and millet varies. The African Postharvest Losses Information System (APHLIS) estimated that postharvest losses in sorghum production in SSA averaged about 12% of total annual production from 2003-2012; over the same time period post-harvest millet losses averaged about 10% of total production (APHLIS, 2012). Based on APHLIS loss data and FAO production statistics, a study by the World Bank (2011) estimated the value of annual post-harvest losses of sorghum and millet in Eastern and Southern Africa as USD139 million and USD60 million, respectively (World Bank, 2011). A report by ICRISAT (2007) estimated that post-harvest losses due to storage insect pests in sorghum and pearl millet were only 2.55% of production and Mejia (1999) estimated losses in traditional sorghum storage were only 5% of grain weight. Kajuna (2001) reported that millets had excellent storage properties and could generally be safely kept for 4-5 years using traditional granaries.

Although documentation on the causes of post-harvest losses is limited, studies from the FAO Information Network on Post-harvest Operations on millet and sorghum reported that much of the post-harvest loss with both crops likely comes from infestation by grain molds and insect pests during storage, although the type and seriousness of damage varied by region (Kajuna, 2001; Mejia, 1999). Insufficient drying increases the likelihood of mold infestation in food-grains (Hodges *et al.,* 2011), which not only leads to grain losses, but may also lead to negative human and animal health impacts due to mycotoxins (Bhat *et al.,* 2000). Other post-harvest losses may occur as part of the threshing, transportation and crop processing operations (Kajuna, 2001; Mejia, 1999).

Managing crop residues can also have environmental impacts. A 2012 review showed a substantial share of cereal residues across SSA and SA were reportedly used for fuel, construction, or for sale or consumption as animal feed, including in sorghum and millet systems in India, Ethiopia (tef straw) and West Africa (millet and sorghum stover) (Valbuena *et al.*, 2012). In many places the sale of millet and sorghum residues has become an economically significant source of farmer incomes; however residue removal exposes soils to wind and water erosion, and depletes soil nutrients that would otherwise be available to future crops.

Adaptations to Post-Harvest Constraints

Literature on adaptations to post-harvest losses in sorghum and millet is limited, however available information suggests common adaptations have included the following:

- *Traditional storage:* Earthenware pots, metal silos, jute bags, mud enclosures, open cribs, baskets and pits storage are all traditional methods of storing millet and sorghum (Kajuna, 2001; Mejia, 1999). More open storage methods, such as open cribs, provide better aeration, but do not keep out insect and rodent pests. Conversely, metal silos provide better protection from pests but worse aeration (Mejia, 1999), potentially increasing the risk of mycotoxin contamination (Ayalew *et al.,* 2005).

- *Harvest timing:* Some landraces and some improved varieties of pearl millet grains ripen after the end of the rainy season. This improves drying and storage and may reduce problems with disease and insects (National Research Council, 1996).

- *Fertilizer use:* As mentioned previously, one response to declining soil fertility (partly attributable to residue removal, exacerbated by erosion) is the addition of organic or synthetic soil nutrients. In some cases, where livestock numbers are relatively low, increasing fertilizer use has increased on-farm retention of crop residues owing to fodder surpluses (Valbuena *et al.*, 2012).

Environmental Impacts of Post-harvest Practices

Available evidence suggests the following potential impacts:

- *Wasted effort*: Post-harvest losses to insects, rodents or molds represent a waste of the resources devoted to crop production; such losses also minimize any gains made using integrated and improved crop management practices. Reducing post-harvest losses therefore reduces any potential negative environmental impacts of sorghum and millet production.

- *Contamination*: Sorghum is stored in underground pits in parts of SSA and is susceptible to mycotoxins, threatening human health (Ayalew *et al.,* 2005).

- *Soil nutrient depletion*: Long-term sorghum and millet production impacts on soil quality are only beginning to be studied, and depend significantly upon post-harvest management. If the entire sorghum plant is harvested for animal feed, a large amount of phosphorus is removed from soils, as much of the P is in the stalk and leaves, in addition to N which is concentrated in the grain (Fageria, 2011).

<u>Best Practices for Post-harvest Operations</u>

Best practices for post-harvest management of sorghum and millet include any of the current adaptations mentioned previously. Additional best practices include:

- *Improved drying*: Moisture and temperature both contribute to the probability of mold infestation. Assuring that sorghum and millet grain is dried properly prior to storage can decrease mold infection (Mejia, 1999). Sun drying is typically the most widely used method of drying in SSA. This should be done long enough to reduce grain moisture content to a safe storage level: published estimates suggest the maximum moisture content for safe storage of sorghum is approximately 12%, while that for millet is 16% (Stathers *et al.*, 2013).

- *Secure storage*: Secure storage can reduce damage from molds, insect and rodent pests, and is most beneficial if combined with good moisture management. Improved traditional storage methods, moisture-proof underground pits and granaries can all help minimize storage losses.

- *Chemical controls*: Prophylactic or curative use of pesticides and fumigants has been suggested to reduce grain loss due to sorghum and millet pests (ICRISAT, 2007).

- *Conservation agriculture and integrated crop-livestock management:* Conservation agriculture practices such as integrating crop residues into soils has significant potential to increase soil fertility, improve moisture retention, and reduce carbon dioxide emissions. However the mulching of economically valuable crop residues is unlikely in many parts of SSA and SA in the absence of expanding supplies of alternative sources of animal feed, fuel, and construction materials (Valbuena *et al.*, 2012).

Climate Change Impacts

Given their ability to withstand drought and survive on depleted soils, it is likely more sorghum and millet will be cultivated as an adaptation to climate changes (Cooper *et al.,* 2008). However, both crops also face climate change-related threats.

At temperatures over 36 degrees, sorghum seed growth rates decrease, and at temperatures above 32 degrees seed size decreases (Prasad *et al.,* 2006). Srivastava *et al.* (2010) projects that climate change will reduce monsoon sorghum grain yield in India by up to 14% and winter sorghum up to 7% by 2020. Zizka (2003) predicts increased weed competition for sorghum under climate change. On the other hand, sorghum cultivation may also serve to mitigate climate change because the crop’s high biomass means that it may act as a carbon sink and could be used in carbon sequestration programs (Clay, 2004).

Millet is the most tolerant of all major cereal crops to extreme conditions of heat and aridity, making it an important crop given increasing environmental constraints due to climate change (Bala Ravi, 2004). But recent simulation studies nevertheless predict sorghum and millet yield declines of up to 41% in West Africa, largely as a result of predicted temperature increases (Sultan *et al.,* 2013). Predicted yield declines vary greatly across cultivars (Roudier *et al.,* 2011) with the most severe declines among modern/improved millet and sorghum varieties. Traditional varieties currently grown are expected to offer lower total production, but greater resilience in the face of temperature changes, than improved cultivars (Sultan *et al.,* 2013).

Conclusions and Overall Best Practices

Sorghum and millets are known for being more tolerant of major environmental stresses including drought and poor soil quality than other major cereals. But water availability is still among the greatest constraints to increased grain production, and soil fertility also significantly limits yields, especially in cases where cultivation occurs on marginal lands and where crop residues are removed for alternative uses. Meanwhile biotic constraints such as downy mildew – a disease which arose directly from early efforts to breed early-flowering varieties to overcome water constraints – continue to hamper yield growth.

The environmental impacts of sorghum and millet cultivation are generally less severe than the effects of other crops – but the impacts also differ greatly by farming system. Although the area of intensively cultivated sorghum/millet is relatively small in SSA and SA, in intensive irrigated sorghum and millet cropping systems the overuse of agrochemicals and groundwater may have negative environmental impacts, either alone or as part of a multi-crop system. Inversely, in rainfed extensive cropping systems, increasing the judicious use of agricultural inputs may actually reduce environmental impacts by increasing productivity, expanding stover production, and slowing damaging agricultural land expansion.

Ultimately sorghum and millets' relatively higher tolerance to abiotic stresses is expected to promote an increase in global cropping area for sorghum and millets as an adaptation to climate change (Bala Ravi, 2004). ICRISAT and IFPRI have both advocated investment in high yielding, and pest and disease resistant varieties to further increase productivity of sorghum and millet (Reddy *et al.*, 2010; Pray & Nagarajan, 2009). However, improved seeds alone may not boost productivity without the adoption of other farm management practices: intercropping and crop rotation with legumes, as well as improved soil management and water harvesting practices have all shown some success at increasing sorghum and millet productivity using existing technologies (Ahmed *et al.*, 2000).

Methodology:

This literature review was conducted using databases and search engines including University of Washington Library, Google Scholar and Scopus, as well as the following websites: ICRISAT, African Development Bank, World Bank, UNFAO, UNEP, Millenium Ecosystem Assessment, FAOSTAT and IPCC. Searches used combinations of the following terms: sorghum, millet, pearl millet, environment, environmental, environmental impacts, developing world, Sub-Saharan Africa, South Asia, rain-fed agriculture, emissions, biodiversity, water, water resources, water quality, irrigation, soil, land, pests, pesticides, climate change, global warming, air pollution, smallholder, sustainability. The methodology also included searching for sources that were identified as central works and examining relevant lists of works cited. This literature review draws upon over 80 cited sources, and relied in equal parts on peer-reviewed publications and data and publications from major international organizations, especially FAO and ICRISAT.

Please direct comments or questions about this research to Leigh Anderson and Mary Kay Gugerty, at eparx@uw.edu.

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References:

Abate, T., Van Huis, A., & Ampofo, J. K. O. (2000). Pest management strategies in traditional agriculture: an African perspective. *Annual Review of Entomology*, *45*(1), 631-659.

Adugna, A. (2007). The role of introduced sorghum and millets in Ethiopian agriculture. *Journal of SAT Agricultural Research*, *3*.

Adejuwon, J. (2006). Food Crop Production in Nigeria II: Potential Effects of Climate Change. *Climate Research*, *32*(4), 229-245.

Ahmed, M.M., Sanders, J.H., & Nell, W.T. (2000). New sorghum and millet cultivar introduction in Sub-Saharan Africa: impacts and research agenda. *Agricultural Systems*, *64*, 55-65.

Amadou, M., Gandah, M., Bielders, C. L., and van Duivenbooden, N. (1999). Optimizing Soil Water Use in Niger: Research, Development, and Perspectives. In van Duivenbooden, N., Pala, M., Studer, C., & Bielders, C. L. (Eds.), *Efficient Soil Water Use – The Key to Sustainable Crop Production in Dry-Area Agriculture in West Asia, and North and Sub-Saharan Africa, Proceedings of the 1998 and 1999 workshops of the Optimizing Soil Water Use (OSWU) Consortium*, ICARDA, Aleppo, Syria and ICRISAT, Niamey, Niger (pp. 143–164).

Africa Postharvest Losses Information System (APHLIS). (2012). *Losses tables* [Data file]. Available from APHLIS Web site: http://www.aphlis.net/

Ashok Kumar, A., Reddy, B. V. S., Sharma, H. C., Hash, C. T., Srinivasa Rao, P., Ramaiah, B., & Reddy, P. S. (2011). Recent advances in sorghum genetic enhancement research at ICRISAT. *American Journal of Plant Sciences*, *2*(4), 589-600.

Assefa, Y., Staggenborg, S. A., and Prasad, V. P. V. (2010). Grain sorghum water requirement and responses to drought stress: A review. *Crop Management*. doi:10.1094/CM-2010-1109-01-RV

Assefa, Y. & Staggenborg, S.A. (2010). Grain Sorghum Yield with Hybrid Advancement and Changes in Agronomic Practices from 1957 through 2008. *Agron. J.*, *102*, 703–706. doi: 10.2134/agronj2009.0314. Retrieved from https://www.agronomy.org/publications/aj/articles/102/2/703

Ayalew, A., Fehrmann, H., Lepschy, J., Beck, R., & Abate, D. (2006). Natural occurrence of mycotoxins in staple cereals from Ethiopia. *Mycopathologia*, *162*(1), 57-63.

Bala Ravi, S. (2004). Neglected millets that save the poor from starvation. *LEISA India* (1): 34-36. Retrieved from http://www.agriculturesnetwork.org/magazines/india/1-valuing-crop-diversity/neglected-millets-that-save-the-poor-from/at_download/article_pdf

Basavaraj, G., Parthasarathy Rao, P., Bhagavatula, S., & Ahmed, W. (2010). Availability and utilization of pearl millet in India. *SAT eJournal*, *8*.

Bhat, R. V., Shetty, H. P. K., & Vasanthi, S. (2000). Human and animal health significance of mycotoxins in sorghum with special reference to fumonisins. In *Technical and Institutional options for sorghum grain mold management: Proceedings of an international consultation* (pp. 18-19).

Burke, M.B., Lobell, D.B., Guarino, L. (2009). Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. *Global Environmental Change*, *19*, 317-325.

Butt, T, McCarl, B., Angerer, J., Dyke, P., & Stuth, J. (2005). The Economic and Food Security Implications of Climate Change in Mali. *Climactic Change, 68*(3), 355-378. doi:10.1007/s10584-00506014-0.

Clay, J. (2004). *World Agriculture and the Environment.* Washington, DC: Island Press.

Chandrashekar, A. Satyanarayana, K.V. (2006). Disease and pest resistance in grains of sorghum and millet. *Journal of Cereal Science*, *44*, 287-304. Retrieved from http://ac.els-cdn.com/S0733521006001299/1-s2.0-S0733521006001299-main.pdf?_tid=eaed5f16-220b-11e2-bc16-00000aab0f6b&acdnat=1351544715_e43ee618c74ff8aa6e2b4d2e3602c415

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., & Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change?, *Agriculture, Ecosystems & Environment*, *126*(1-2), 24-35. doi: 10.1016/j.agee.2008.01.007

Duvick, D. N. (1999). Heterosis: Feeding People and Protecting Natural Resources. In J. G. Coors & S. Pandey (Eds.), *The Genetics and Exploitation of Heterosis in Crops* (pp. 19-29). Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc. Retrieved from http://www.biotech-info.net/heterosis_duvick1.pdf

Ejeta, G. (2007). Breeding for *Striga* resistance in sorghum: exploitation of an intricate host-parasite biology. *Crop Sci.*, *47*, S216-S227.

Ejeta, G., & Gressel, J. (2007). *Integrating new technologies for Striga control: Towards ending the witch-hunt*. World Scientific Publishing Company Incorporated.

Estep, M., Van Mourik, T., Muth, P., Guindo, D., Parzies, H,. Koita, O., Weltzein, E., & Bennetzen, J. (2011). Genetic Diversity of a Parasitic Weed, *Striga hermonthica*, on Sorghum and Pearl Millet in Mali. *Tropical Plant Biology*, *4*:2, 91-98.

Fageria, N.K. (2011). *Growth and Mineral Nutrition of Field Crops*. Boca Raton, FL: CRC Press Taylor & Francis Group.

FAOSTAT. (2012). Available from FAOSTAT Web site: http://faostat.fao.org/

FAO. (2010). Grassland Species Profiles. Retrieved from http://www.fao.org/ag/agp/agpc/doc/gbase/Default.htm

FAO. (1996). The world sorghum and millet economies: facts, trends and outlook. Retrieved from http://www.fao.org/docrep/W1808E/w1808e0h.htm#TopOfPage

Fisher, R.A, Byerlee, D., & Edmeades, G.O. (2009). *Can Technology Deliver on the Yield Challenge to 2050?* Paper presented at the FAO Expert Meeting on How to Feed the World in 2050 (Rome, June 24-26, 2009). Retrieved from ftp://ftp.fao.org/docrep/fao/012/ak977e/ak977e00.pdf

Franklin, D. Truman, C. Potter, T. Bosch, D. Strickland, T. Jenkins, M. Nuti, C. (2012). Nutrient losses in runoff from conventional and no-till pearl millet on pre-wetted Ultisols fertilized with broiler litter. *Agricultural Water Management*, *113*, 38-44.

García-Ponce, E., Gómez-Macpherson, H., Diallo, O., Djibril, M., Baba, C., Porcel, O., Mathieu, B., Comas, J., Mateos, L., & Connor, D.J. (2012). Contribution of sorghum to productivity of small-holder irrigation schemes: On-farm research in the Senegal River Valley, Mauritania, *Agricultural Systems*. doi: 10.1016/j.agsy.2012.09.009.

Garí, J.A. (2002). Review of the African millet diversity. *International workshop on fonio, food security and livelihood among the rural poor in West Africa*. IPGRI/IFAD, Bamako, Mali, 19-22 November 2001.

Global Crop Diversity Trust (GCDT). (2007). *Strategy for the Global Ex Situ Conservation of Sorghum Genetic Diversity* [White paper]. Rome: Global Crop Diversity Trust.

Hiernaux, P., Ayantunde, A., Kalilou, A., Mougin, E., Gérard, B., Baup, F., & Djaby, B. (2009). Trends in productivity of crops, fallow and rangelands in Southwest Niger: Impact of land use, management and variable rainfall. *Journal of Hydrology*, *375*(1), 65-77. Retrieved from http://hal.archives-ouvertes.fr/docs/00/40/62/03/PDF/Hiernaux_JoH_crops_2009.pdf

Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. *The Journal of Agricultural Science*, *149*(S1), 37-45.

ICRISAT. (2007). *Management of sorghum and pearl millet pests in bulk storage*. Andhra Pradesh, India: ICRISAT.

International Service for the Acquisition of Agri-biotech Applications (ISAAA) (2012). International consortium to develop drought tolerant pearl millet for Asia and Africa. *Crop Biotech Update*. Retrieved from: http://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=10391

Jeger, MJ, Gilijamse E, Bock CH, Frinking H. (1998). The epidemiology, variability and control of the downy mildews of pearl millet and sorghum, with particular reference to Africa. *Plant Pathology, 47*, 544–69.

Kajuna, S. (2001). *Millet: Post-harvest Operations*. Information Network on Post-harvest operations (FAO).

Kamrin, M. A. (1997). *Pesticide Profiles: Toxicity, Environmental Impact, and Fate*. CRC Press LLC. Boca Raton.

Khan, Z. R., Pickett, J. A., Berg, J. V. D., Wadhams, L. J., & Woodcock, C. M. (2000). Exploiting chemical ecology and species diversity: stem borer and *Striga* control for maize and sorghum in Africa. *Pest Management Science*, *56*(11), 957-962.

Leff, B., Ramankutty, N., & Foley, J. A. (2004). Geographic distribution of major crops across the world. *Global Biogeochemical Cycles*, *18*(1), GB1009.

Lipson, J., Po-Chedley, S., Smoliak, B., Cullen, A., & Anderson, L. *Crops & Climate Change: Sorghum and Millet*. Evans Policy Analysis and Research Group (EPAR).

Liu, J., Fritz, S., Vanwesenbeeck, C., Fuchs, M., You, L., Obersteiner, M., & Yang, H. (2008). A Spatially Explicit Assessment of Current and Future Hotspots of Hunger in Sub-Saharan Africa in the Context of Global Change. *Global and Planetary Change, 64*(3-4), 222-235. doi: 10.1016/j.gloplacha.2008.09.007

Mariac, C., Jehin, L., Saidou, A. A., Thuillet, A. C., Couderc, M., Sire, P. & Vigouroux, Y. (2011). Genetic basis of pearl millet adaptation along an environmental gradient investigated by a combination of genome scan and association mapping. *Molecular ecology*, *20*(1), 80-91.

Mejia, D. (Ed.). (1999). *Sorghum: Post-harvest Operations*. Information Network on Post-harvest Operations (FAO).

Meyer, L. D., Dabney, S. M., Murphree, C. E., Harmon, W. C., & Grissinger, E. H. (1999). Crop production systems to control erosion and reduce runoff from upland silty soils. *Transactions of the ASAE*, *42*(6), 1645-1652.

Mgonja, M. A., Lenné, J.M., Manyasa, E., & Sreenivasaprasad, S. (Eds.). (2007). *Finger Millet Blast Management in East Africa: Creating opportunities for improving production and utilization of finger millet*. Proceedings of the First International Finger Millet Stakeholder Workshop, Projects R8030 & R8445 UK Department for International Development – Crop Protection Programme held 13-14 September 2005 at Nairobi. Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Michels, K., Sivakumar, M. V. K., & Allison, B. E. (1993). Wind erosion in the Southern Sahelian Zone and induced constraints to pearl millet production. Agricultural and forest meteorology, *67*(1), 65-77.

Millet Network of India (n.d) Millets Future of Food & Farming. Retrieved November 15, 2012 from http://www.swaraj.org/shikshantar/millets.pdf

Mohamed, A. B., Van Duivenbooden, N., & Abdoussallam, S. (2002). Impact of climate change on agricultural production in the Sahel–Part 1. Methodological approach and case study for millet in Niger. *Climatic Change*, *54*(3), 327-348.

Murty, M.V.R., Singh, P., Wani, S.P., Khairwal, I.S., & Srinivas, K. (2007). *Yield gap analysis of sorghum and pearl millet in India using simulation modelling*. Global Theme on Agroecosystems Report No 37, ICRISAT, Patancheru, Andra Pradesh.

Mutava, R. N., Prasad, P. V. V., Tuinstra, M. R., Kofoid, K. D., & Yu, J. (2011). Characterization of sorghum genotypes for traits related to drought tolerance. *Field Crops Research*, *123*(1), 10-18.

Nagarajan, L., Smale, M., & Glewwe, P. (2005). *Comparing Farm and Village-Level Determinants of Millet Diversity in Marginal Environments of India: The Context of Seed Systems*. EPT Discussion Paper 139. Retrieved 1 December 2012 from http://www.ifpri.org/sites/default/files/pubs/divs/eptd/dp/papers/eptdp139.pdf

Palaniappan, S. P., Chandrasekaran, A., Kang, D. S., Singh, K., Rajput, R. P., Kauraw, D. L., . & Lal, R. (2009). Sustainable Management of Natural Resources for Food Security and Environmental Quality: Case Studies from India–A Review. *Climate Change, Intercropping, Pest Control and Beneficial Microorganisms*, 339-372.

Prasad, P. V., Vu, J. C., Boote, K. J., & Allen, L. H. (2009). Enhancement in leaf photosynthesis and upregulation of Rubisco in the C_4 sorghum plant at elevated growth carbon dioxide and temperature occur at early stages of leaf ontogeny. *Functional Plant Biology*, *36*(9), 761-769.

Pray, C. E., & Nagarajan, L. (2009). *Pearl millet and sorghum improvement in India*. IFPRI Discussion Papers. IFPRI.

Ragnarsdottir, K. Vala. (2000). Environmental fate and toxicology of organophosphate pesticides. *Journal of the Geological Society*, *157*, 859-876.

Reddy, B. V., Ashok Kumar, A., & Sanjana Reddy, P. (2010). Recent Advances in Sorghum Improvement Research at ICRISAT. *Kasetsart Journal (Natural Science)*, *44*, 499-506.

Samaké, O., Smaling, E. M. A., Kropff, M. J., Stomph, T. J., & Kodio, A. (2005). Effects of cultivation practices on spatial variation of soil fertility and millet yields in the Sahel of Mali. *Agriculture, ecosystems & environment*, *109*(3), 335-345.

Samaké, O., Stomph, T. J., Kropff, M. J., & Smaling, E. M. (2006). Integrated pearl millet management in the Sahel: effects of legume rotation and fallow management on productivity and *Striga hermonthica* infestation. *Plant and soil*, *286*(1), 245-257.

Sauerborn, J., Sprich, H., & Mercer-Quarshie, H. (2001). Crop Rotation to Improve Agricultural Production in Sub-Saharan Africa. *Journal of Agronomy and Crop Science*, *184*(1), 67-72.

Scherr, S., & Yadav, S. (2001). Land degradation in the developing world: Issues and policy options for 2020. In *The Unfinished Agenda: Perspectives on Overcoming Hunger, Poverty, and Environmental Degradation*. Washington, D.C.: IFPRI.

Sher, A., Ansar, M., Hassan, F.U., Shabbir, G., & Malik, M.A. (2012). Hydrocyanic acid contents variation amongst sorghum cultivars grown with varying seed rates and nitrogen levels. *Int. J. Agric. Biol*., 14: 720-726.

Schlegel, A. (2012). *Long-Term Nitrogen and Phosphorous Fertilization of Irrigated Corn and Grain Sorghum*. Annual Report for KS-23f (2012 season). Kansas State University.

Schlenker, W., & Lobell, D.B. (2010). Robust Negative Impacts of Climate Change on African Agriculture. *Environmental Research Letters, 5*(1) 014010. Doi: 10.1088/1748-9326/5/1/014010

Sharma, M.K., & Kumar, P. (2011). *A Guide to Identifying and Managing Nutrient Deficiencies in Cereal Crops*. International Maize and Wheat Improvement Center (CIMMYT).

Singh, P., Agrawal, P.K., Bhatia, V.S., Murthy, M.V.R., Pala, M., Oweis, T., Benli, B., Rao, K.P.C., & Wani, S.P. (2009). Yield gap analysis: Modelling of achievable yields at farm level. In *Rainfed Agriculture: Unlocking the Potential. Comprehensive Assessment of Water Management in Agriculture Series 7* (pp. 81-123). Wallingford Oxfordshire, UK: CAB International Publishing.

Srivastava, A. Kumar, S. N. (2010). Assessment on vulnerability to climate change in India. *Agriculture, Infrastructure, and Environment*, *138* (3-4), 160-169.

Stathers, T., Lamboll, R., & Mvumi, B. M. (2013). Postharvest agriculture in changing climates: its importance to African smallholder farmers. *Food Security*, 1-32.

Subbarao, G. V., Renard, C., Payne, W. A., & Bationo, A. (2000). Long-term effects of tillage, phosphorous fertilization and crop rotation on pearl millet-cowpea productivity in the West African Sahel. *Experimental Agriculture*, *36*(2),243-264.

Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., & Baron, C. (2013). Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environmental Research Letters*, *8*(1), 14-40.

Thakur, R. P., Rao, V. P., & Sharma, R. (2011). Influence of dosage, storage time and temperature on efficacy of metalaxyl-treated seed for the control of pearl millet downy mildew. *European journal of plant pathology*, *129*(2), 353-359.

US National Research Council. (1996). *Lost Crops of Africa. Volume I: Grains.* Washington, D.C.: National Academy Press.

Valbuena, D., Erenstein, O., Homann-Kee Tui, S., Abdoulaye, T., Claessens, L., Duncan, A. J., & van Wijk, M. T. (2012). Conservation Agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research*, *132*, 175-184.

Voortman, R. L., & Brouwer, J. (2003). An empirical analysis of the simultaneous effects of nitrogen, phosphorus and potassium in millet production on spatially variable fields in SW Niger. Nutrient Cycling in Agroecosystems, *66*(2), 143-164.

Waddington, S. R., Li, X., Dixon, J., Hyman, G., & De Vicente, M. C. (2010). Getting the focus right: production constraints for six major food crops in Asian and African farming systems. *Food Security*, *2*(1), 27-48.

Wezel, A. (2000). Scattered shrubs in pearl millet fields in semiarid Niger: Effect on millet production. *Agroforestry systems*, *48*(3), 219-228.

Williams, R. J., & Rao, K. N. (1981). A review of sorghum grain moulds. *International Journal of Pest Management*, *27*(2), 200-211.

Witcombe, J. R., & Beckerman, S. R. (1987). *Proceedings of the International Pearl Millet Workshop, International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India, 7-11 Apr 1986.*

World Bank. (2011). *Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa*. World Bank.

Wortman, C.C, Mamo, M., & Dobermann, A. (2007). Nitrogen response of grain sorghum in rotation with soybean. *Agron. J.*, *99*, 808-813.

Yadav, O. (2010). Drought Response of Pearl Millet Landrace-Based Populations and their Crosses with Elite Composites. *Field Crops Research*, *118* (1), 51-56. doi: 10.1016/j.fcr.2010.04.005

Yadav, O. & Manjit, S. (2012) Prospects of enhancing biomass yield to improve both grain and stover yields of arid zone pearl millet (*Pennisetum glaucum L. R. Br.*). *Euphytica*, *183*(1).

Ziska, L.H. (2003) Evaluation of yield loss in field sorghum from a C_3 and C_4 weed with increasing CO_2. *Weed Science*, *51*(6), 914-918.