Journal of Agronomy and Crop Science

J Agro Crop Sci (2016) ISSN 0931-2250

REVIEW ARTICLE

Drought Tolerance and Water Use of Cereal Crops: A Focus on Sorghum as a Food Security Crop in Sub-Saharan Africa

S. T. Hadebe, A. T. Modi & T. Mabhaudhi

Crop Science, School of Agricultural, Earth and Environmental Sciences,, University of KwaZulu–Natal, Pietermaritzburg, South Africa

Keywords
agro-ecological distribution; drought tolerance; nutritional water productivity; rainfed agriculture; water productivity; water stress

Correspondence
S. T. Hadebe
Crop Science
School of Agricultural
Earth and Environmental Sciences,
University of KwaZulu–Natal
Private Bag X01
Scottsville 3209, Pietermaritzburg
South Africa
Tel.: +27332605447
Fax: +27332606094
Email: hadebesta@gmail.com

Accepted September 29, 2016

doi:10.1111/jac.12191

Abstract

Sub-Saharan Africa (SSA) faces twin challenges of water stress and food insecurity – challenges that are already pressing and are projected to grow. Sub-Saharan Africa comprises 43 % arid and semi-arid area, which is projected to increase due to climate change. Small-scale, rainfed agriculture is the main livelihood source in arid and semi-arid areas of SSA. Because rainfed agriculture constitutes more than 95 % of agricultural land use, water scarcity is a major limitation to production. Crop production, specifically staple cereal crop production, will have to adapt to water scarcity and improved water productivity (output per water input) to meet food requirements. We propose inclusion and promotion of drought-tolerant cereal crops in arid and semi-arid agro-ecological zones of SSA where water scarcity is a major limitation to cereal production. Sorghum uniquely fits production in such regions, due to high and stable water-use efficiency, drought and heat tolerance, high germplasm variability, comparative nutritional value and existing food value chain in SSA. However, sorghum is socio-economically and geographically underutilized in parts of SSA. Sorghum inclusion and/or promotion in arid and semi-arid areas of SSA, especially among subsistence farmers, will improve water productivity and food security.

Introduction

Sub-Saharan Africa (SSA) has the highest percentage of food insecurity globally (Clover 2003, FAO, IFAD and WFP 2014). Almost two of every three people in SSA live in rural areas, relying principally on small-scale, rainfed agriculture for their livelihood (Food and Agriculture Organization (FAO) 2014). In rural households, most food is produced and consumed locally (Garrity et al. 2010), making household agricultural productivity critical to improving food security (Schmidhuber and Tubiello 2007). Rural poverty accounts for 83 % of the total extreme poverty in SSA, and about 85 % of the poor depend on agriculture for their livelihoods (Byerlee et al. 2005). Small-scale rainfed agriculture is the main livelihood source in arid and semi-arid areas of SSA. The yield levels in such farming systems are very low, especially during years of severe drought (Mavhura et al. 2015).

Sub-Saharan Africa comprises 43 % of the area classified to an extent as arid (Food and Agriculture Organization (FAO) 2008). Under these conditions, water becomes the single most limiting factor to successful crop production. Climate change predictions for SSA suggest rainfall reduction, variable distribution pattern, increased erratic rainfall, intraseasonal dry spells, and incidences of flooding, high temperatures, corresponding increased evaporative demand and higher frequency of droughts (Ringler et al. 2010, Schulze 2011). This causes SSA crop production to be vulnerable because rainfed agriculture constitutes more than 95 % of agricultural land use (Singh et al. 2011). This will effectively compound the existing challenges to crop production and food security, hence underscoring the need for improving effective use of water in rainfed agriculture (Blum 2009) as well as adoption of resilient crops (Headey et al., 2012). In this context, resilient crops are those with a high ability to withstand or recover from water-stress periods.

Cereal crops are a major source of dietary energy in the diets of people in SSA (Chauvin et al. 2012). In principle, producing cereal crops is water intensive. Past and current agricultural interventions have been focused on increasing production of high-energy crops in order to improve food availability and access. The approaches have also assumed that improved availability would lead to stability (less price volatility) and guarantee sustainable access. These efforts have mainly focused on a few energy-rich cereal crops such as maize, wheat and rice. While this has led to huge improvements in terms of crop production, it has also resulted in some of the cereal crops being cultivated in less suitable areas while suitable cereal crops have been relegated (Mabhaudhi et al. 2016a). This success has to be accompanied by matching cereal crops to suitable agro-ecologies and maximizing on their genetic potential (Sebastian 2009); this could have greater impacts on food security. To ensure and improve food security, crop production, especially for staple food crops, should be focused on water conservation and improved water productivity.

Cereals are an important food source for human consumption and food security (Food and Agriculture Organization (FAO) 2014), and SSA cropping systems among rural subsistence farmers are largely cereal based. The most widely cultivated cereal crops in SSA are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), millet (*Pennisetum glaucum* L.) and rice (*Oryza sativa* L.) (Edmonds et al. 2009). Other cereals under production include wheat (*Triticum* spp.), barley (*Hordeum vulgare* L.), oats (*Avena sativa*), buckwheat (*Fagopyrum esculentum*) and teff (*Eragrostis tef* Zucc.) (Haque et al. 1986, World Bank, 2008). Of these, maize has high water requirements, while wheat, barley and rice suffer high yield losses and crop failure under water stress and during drought periods. Millet and sorghum are indigenous crops to SSA renowned for their drought and heat tolerance. However, sorghum has a wider production distribution range, is produced on a larger area and has higher yield output than millet. Sorghum can tolerate temporal waterlogging, which confers an advantage in flooding situations. Sorghum's drought, heat and waterlogging tolerance as well as adoption by farmers make sorghum an ideal crop for production in SSA.

Despite sorghum being the second most grown cereal crop in SSA, the potential of sorghum's drought tolerance to contribute to improving water productivity is relatively still underutilized (Mabhaudhi et al. 2016b). This review proposes sorghum as an alternative cereal crop for cultivation in SSA to enhance water productivity and improve food security, especially in regions threatened by water scarcity. This article reviews water use of cereal crops produced in SSA and motivates for sorghum inclusion and/or promotion in arid areas of the region. This is carried out by reviewing cereal crop production in SSA, identifying agro-ecological zones (AEZs) and distribution thereof, identifying regions where inclusion and/or promotion of sorghum would benefit cereal production, and reviewing sorghum attributes, which make it uniquely poised as a niche crop in such regions.

Water Use of Cereals

Distribution of agro-ecological zones and comparative advantage of cereals

Land and water resources and the way they are used are central to the challenge of improving food security across the world. Agriculture in SSA is 95 % rainfed (Singh et al. 2011) with very limited use of external inputs such as fertilizers. This means that the land's agricultural production of cereals depends almost solely on the agro-ecological potential (Sebastian 2009). Agro-ecological zones are geographical areas exhibiting similar climatic conditions that determine their ability to support rainfed agriculture. Sub-Saharan Africa can be divided into six AEZs, differentiated by the length of the potential growing period for rainfed agriculture. Within these AEZs, rainfall ranges dramatically, from over 2000 mm year^{-1} in central Africa to <400 mm year^{-1} in arid areas (Bationo et al. 2006, Ringler et al. 2010). These AEZs are deserts, arid, semi-arid, humid, subhumid and highland regions. Sub-Saharan Africa comprises 17 % arid area, 17 % semi-arid and 9 % dry subhumid, totalling 43 % of the continent classified to an extent as arid (Food and Agriculture Organization (FAO) 2008). About 60 % of SSA is vulnerable to drought, with 30 % of it considered as highly vulnerable (Mavhura et al. 2015).

Production of cereal crops in suitable AEZs with a comparative advantage can potentially increase water productivity under rainfed cropping systems. This could increase crop yields without a corresponding increase in water use. Agriculture has seen a shift from increasing production through increasing area under cultivation to focusing on water conservation and increasing water productivity (Machethe et al. 2004, Fanadzo et al. 2010). Despite this, cereal production systems and trends in SSA remain largely unchanged and dominated by maize production, even in arid regions. Cereal crop production increases have been due to improvements in breeding and increased production area rather than improved water productivity.

Cereal crop production in SSA

Sub-Saharan Africa's rural economy remains strongly agro-based relative to other regions (Livingston et al. 2011). As such, economic growth focused on agriculture has a disproportionately positive impact in reducing food insecurity. In SSA, cereals are a staple food for, and mostly produced by, resource-poor farmers. Cereals and cereal products are an important source of energy, carbohydrate, protein and fibre, as well as containing a range of micronutrients such as vitamin E, some of the B vitamins, magnesium and zinc (McKevith 2004). Land under cereal production in SSA in 2008 was 92 132 298 hectares (World Bank, 2008). The most widely cultivated cereal crops in SSA are maize, sorghum, millet and rice, respectively (Edmonds et al. 2009). Being the largest crop produced, maize has cultural, economic and political significance in SSA and is the dominant staple food for much of eastern and southern Africa, while greater dependence on millet, rice and sorghum is found in western Africa (Doward et al. 2004).

Among the staple cereal crops, rice and maize have high water requirements (Table 1); hence, the production of cereal crops with low water requirements provides a comparative advantage in water-scarce areas (Table 2). In large parts of SSA, maize is the principal staple crop, covering a total of approximately 27 Mha. Maize accounts for 30 % of the total area under cereal production in this region: 19 % in West Africa, 61 % in central Africa, 29 % in eastern Africa and 65 % in southern Africa (Food and Agriculture Organization (FAO) 2010; Cairns et al. 2013). In southern Africa, maize is particularly important, accounting for over 30 % of the total calories and protein consumed (Food and Agriculture Organization (FAO) 2010). Among SSA AEZs, the subhumid zone constitutes 38 % of the total land area in SSA and has favourable rainfall (700–200 mm per annum) for maize production (Zingore 2011). Maize yields have stagnated and in some areas declined in SSA. One of the primary reasons is the lack of use of drought ameliorative measures (Fischer et al. 2014). This AEZ land area and rainfall is sufficient for the production of maize and other high water requirement cereals lacking drought and heat tolerance. Rice lies fourth in area SSA area under production. In the decade, the growth of rice yield has dropped below 1 % per year worldwide and low yield constitutes one of the main challenges of rice production in SSA. Rice production is increasingly constrained by water limitation and increasing pressure to reduce water use in irrigated production as a consequence of global water crisis (Zhang et al. 2012). Breeding attempts have resulted in NEw RICe for Africa (NERICA) initiative, which has led to the release of upland NERICA varieties with relatively less water use compared to traditional lowland rice (Akinbile et al. 2007). However, even the NERICA varieties still have significantly

Table 1 Growing conditions, production statistics and water-use characteristics of major cereals in SSA

Cereal type	Water use (mm) per growing season[1]	Average growing period (days)[1]	Stress tolerances	Water productivity (WP) (kg m^{-3})	Water-use efficiency (WUE) (kg ha^{-1} mm^{-1})
Maize	500–800	125–180	–	1.1–2.7[5]	7.6–10.4[14]
Sorghum	450–650[3,6]	115–130	Heat, drought, temporal waterlogging and salinity	0.6–2.7[8]	12.4–13.4[4]
Wheat	450–650	120–150	–	0.6–2.0[5,16]	9.7–11.0[2]
Rice (paddy)	450–940[11]	90–150	Waterlogging and flooding	0.6–1.6[5]	4.5–10.9[11]
Barley	450–650	120–150	–	0.7–1.5[7]	7.7–9.7[15]
Millet	450–650	105–140	Heat and drought	0.4–1.0[12]	5.1–10.4[4,10]
Teff	450–550	150–165	Drought and waterlogging	0.6–1.2[9]	4.2–11.2[13]

WP and WUE values were quoted for grain yields where water use was above the minimum crop water requirements. However, rainfall distribution was disregarded (sources: [1]Food and Agricultural Organization (FAO), 1991; [2]Zhang et al., 1998; [3]Hensley et al., 2000; [4]Maman et al. 2003, [5]Zwart and Bastiaanssen 2004, [6]Jewitt et al. 2009, [7]Araya et al. 2011b, [8]Mativavarira et al. 2011, [9]Abdul-Ganiyu et al. 2012, [10]Ismail 2012, [11]Zhang et al. 2012, [12]Mokh et al. 2013, [13]Yihun et al. 2013, [14]Ofori et al. 2014, [15]Barati et al. 2015, [16]Virupakshagowda et al. 2015).

Table 2 Agro-ecological zones, their distribution in SSA and cereal crops with comparative advantage in each region

Agro-ecological zone[1]	Length of growing period (days)[1]	Average annual rainfall (mm)[1]	Land area (% of SSA)[1,3]	Main soil types[1]	Main cereal crops produced[1,2]	Cereal crops with comparative advantage
Arid	<90	0–600	17	Lithosols, xerosols	Maize, sorghum, millet	Sorghum, millet
Semi-arid	90–179	600–1400	17	Lixisols, arenosols, vertisols	Maize, sorghum, millet	Sorghum, millet
Subhumid	180–269	1400–3000	38[3]	Ferralsols, lixisols, acrisols	Maize, sorghum, millet	Maize, wheat, barley
Humid	>270	3000–4500	20	Ferralsols, acrisols	Maize and rice	Maize, rice
Highlands	180–270	1400–4500	3	Vertisols, cambisols	Wheat and barley	Rice

Soil forms have been simplified for purposes of this review (sources: [1]Livingston et al. 2011, [2]Food and Agriculture Organization Statistics (FAOSTAT) 2013; [3]Zingore 2011).

higher water requirement and are still subject to extensive testing and drought evaluation (Matsumoto et al. 2014). Heat and drought stress usually occur concurrently (Rizhsky et al. 2002), and hence, the lack of heat stress in NERICA rice remains a concern for production in arid and semi-arid SSA.

Wheat and barley have lower water requirements in comparison with maize and rice, which makes them suitable for cultivation in low rainfall areas. However, these crops are still susceptible to drought and heat stress and suffer high yield losses under water stress. Teff, millet and sorghum have low water requirements befitting rainfall ranges in arid and semi-arid regions. Additionally, these three crops exhibit drought and heat stress tolerance. Sorghum and millet are highly drought tolerant, while teff exhibits a moderately sensitive and linear response to water stress (Araya et al. 2011a). Sorghum, among the three cereals, is particularly suited for arid and semi-arid AEZs in SSA as it is uniquely tolerant to temporal waterlogging. Temporal waterlogging tolerance is important under conditions of extreme, erratic rainfall which is experienced by crops in SSA.

It has previously been suggested that increasing productivity of cereals will improve food security in the region (Romney et al. 2003). However, it is not about 'any' but rather about improving the production of cereal crops that are suited to SSA's AEZs. Cereal crops that have desirable water-use characteristics are currently being overshadowed by the major crops in terms of production area, consumption trends and research attention. This 'business-as-usual' approach to cereal production has resulted in declining yields for major crops such as maize (Fischer et al. 2014) and general neglect of alternative cereal crops with potential to contribute to food security in marginal AEZs. Because water is the predominant limiting factor in crop production within SSA, a starting step would be reviewing the water use of the different cereal crops. This would allow fitting them into specific AEZs where each cereal crop possesses a comparative advantage.

Water-use characteristics of cereal production in SSA

To improve cereal yield in arid and semi-arid AEZs, it is important to understand their crop water use. Under rainfed agriculture, water-use efficiency (WUE) of major cereal crops becomes a key factor in increasing yield under water scarcity (Blum 2005). Water-use efficiency is the yield output per unit evapotranspiration (soil evaporation plus crop transpiration) (Mabhaudhi et al. 2016a). To obtain WUE in cereal grain crops, the mass of the yield portion (pinnacle, cob, head, etc.) is divided by crop water use (evapotranspiration) from sowing to physiological maturity. This should not be confused with water productivity (WP), which is the yield output per unit of water transpired by the crop (Steduto et al. 2007). The difference between WUE and WP is highlighted below in the equations used to calculate them.

$$\text{WUE} = \text{total biomass or yield}/\sum \text{evapotranspiration} \quad (1)$$

$$\text{WP} = \text{total biomass or yield}/\sum \text{transpiration}. \quad (2)$$

Water-use efficiency is a function of several factors, including crop physiological and morphological characteristics, genotype, planting population, soil characteristics such as soil water holding capacity, meteorological conditions and agronomic practices. In order to optimize yield under water-limiting conditions, an ideal cereal crop should have a long and dense root structure, stay green characteristics, high harvest index and maintain high WUE under stress. To improve WUE, integrative measures should aim to optimize cultivar selection and agronomic practices (Azizian and Sepaskhah 2014).

Among the agronomic practices for improving WUE is crop selection. Multiple approaches have been proposed to improve cereal production in arid and semi-arid environments of SSA, for example supplementary irrigation and breeding for drought tolerance in major crops (Edmeades et al. 1997, Ortiz et al. 2007, Kijne et al. 2009, Cairns et al. 2013). In this review, we propose production, promotion and inclusion of suitable drought-tolerant cereal crops to improve water-use efficiency under arid and semi-arid AEZs of SSA. In comparison with teff and millet, sorghum has higher WUE (Table 1). Additionally, sorghum has the highest tonnage and number of SSA countries producing it. Lowest annual rainfall is experienced in arid and semi-arid AEZs of SSA. The situation is exacerbated by that received annual rainfall generally is not available throughout a crop's growing season (Table 2). Therefore, actual rainfall received during a growing season is often lower than quoted figures and also highly irregular. This makes sorghum production in arid and semi-arid regions of SSA a viable alternative (Table 2) for increasing water productivity in the region.

Maize and sorghum have the highest upper water productivity thresholds compared with other cereals discussed in this review (Table 1). This implies that both crops have the highest water-use potential and are preferred for production under conditions of zero or minimal soil evaporation. This can be attributed to relatively high yields in maize compared with sorghum, and relatively low crop water requirements in sorghum compared with maize. This means that maize can attain higher yields using more water than sorghum, while sorghum attains lower yields using less water than maize. High yield potential thus gives maize comparative advantage for production in sub-humid and humid regions of SSA (Table 2). However, sorghum has higher water-use efficiency than maize mainly due to high tolerance to abiotic and biotic stresses (Table 1). Thus, cropping sorghum is advantageous for production under water-limited areas and arid and semi-arid regions of SSA.

Climate change and variability impacts in SSA will mainly be felt through water, that is increased frequency of rainfall extremes such as droughts and floods (Schulze 2011). Increasing rainfall variability will also expose crops to episodes of intermittent water stress (Chivenge et al. 2015). In addition, the percentage semi- and arid area of SSA is predicted to increase, thus suggesting an increase in marginal agricultural production areas. Therefore, we can no longer afford to side-line the production of drought- and heat stress-tolerant cereals.

Impacts of climate change on cereal crop production

Cereal crop production in SSA is projected (based on IFPRI IMPACT modelling) to decline by a net 3.2 % by 2050 as a result of climate change. This will largely be due to projected increased incidence of drought and temperatures warming above global average. The largest negative yield impacts are projected for wheat (−22 %), maize (−5 %) and rice (−2 %), respectively. Increasing the area under cereal crop production by 2.1 % will partially compensate for the overall yield growth decline. On the contrary, millet and sorghum yields are projected to increase slightly under climate change given their drought and heat stress tolerance (Ringler et al. 2010). This highlights that the major cereals' (maize, rice and wheat) capacity to meet the food requirements of a growing population will be negatively impacted. As such, current research efforts for major cereal crops are targeted at breeding drought- and heat stress-tolerant cultivars that will be able to produce under these conditions.

On a positive note, these simulations suggest that under conditions of increasing water scarcity and high temperature, millet, sorghum and other drought- and heat-tolerant crops may become future cereal crops for production in SSA. However, current trends show that, in terms of land area under cereal production, sorghum and millet still lag behind maize even in arid regions of SSA. This implies that potential of sorghum is currently underutilized in the region. There is a need to promote sorghum as a possible future crop. In order to do this, there is need for empirical data describing its morphological, phenological and physiological characteristics that make it suited for production in water-scarce regions. This knowledge will be important in exploiting the potential of sorghum in arid and semi-arid regions of SSA.

Sorghum Adaptation to Water Stress

The effect of drought stress depends on the plant developmental stage at the onset of stress. Under field conditions, drought stress can occur at any stage of crop growth ranging from seedling establishment, vegetative, panicle development and post-flowering, and the period between grain filling and physiological maturity (Rosenow and Clark 1995, Rosenow et al. 1996). Sorghum is reputed for its ability to tolerate water stress, both intermittent and terminal stress. This is mostly attributed to its dense and prolific root system, ability to maintain relatively high levels of stomatal conductance, maintenance of internal tissue water potential through osmotic adjustment and phenological plasticity (Tsuji et al. 2003). Water-stress responses in sorghum can be of physiological, morphological and phenological in nature. Sorghum genotypes differ in their degree of drought tolerance, especially with respect to the timing of stress. Sorghum genotypes that exhibit good tolerance during one developmental stage may be susceptible to drought during other growth stages (Akram et al. 2011). Such genotypic variation with respect to responses to water stress allows for farmers to select varieties which best suit local farming conditions and hence making sorghum suitable to a range of conditions.

Physiological adaptation

Ability to maintain key physiological processes, such as photosynthesis, during drought stress is indicative of the potential to sustain productivity under water deficit. Sorghum exhibits physiological responses that allow a continued growth under water stress (Dugas et al. 2011). Delayed senescence, high chlorophyll content and chlorophyll fluorescence as well as low canopy temperature and high transpiration efficiency are physiological traits that confer drought tolerance to sorghum (Harris et al. 2006, Kapanigowda et al. 2013). From a crop improvement perspective, manipulating these traits can increase drought tolerance in sorghum.

Crop species reduce photosynthesis through the modification of photosynthetic apparatus under water stress. Reduction in chlorophyll content forms part of that modification (Kapanigowda et al. 2013) to water stress. Chlorophyll content is genotype dependent and varies according to plant stage (Van Oosterom et al. 2010, Wang et al. 2014). Delayed senescence or 'stay green' is the ability of the plant to retain greenness during grain filling under water-limited conditions (Borrell et al. 2014). Delayed leaf senescence in sorghum allows the continued photosynthesis under drought conditions, which can result in normal grain fill and larger yields compared with senescent cultivars (Tolk et al. 2013).

Stomatal conductance mediates the exchanges of water vapour and carbon dioxide between leaves and the atmosphere. Sensitivity of sorghum stomatal conductance to soil water availability and vapour pressure deficit varies between genotypes. Sorghum partially closes stomata, rolls leaves and has a narrow leaf angle in response to water and heat stress, effectively reducing transpiration and exposure area to solar radiation. Under intermittent water stress, partial closure of stomata is used to sustain reduced photosynthetic activity, which ultimately results in high and stable WUE in sorghum compared with other drought-susceptible cereals (Takele and Farrant 2013).

Osmotic adjustment is conservation of cellular water content. In sorghum, osmotic adjustment is associated with sustained biomass yield under water-limited conditions across different cultivars (Blum 2005). Osmotic adjustment helps maintain higher leaf relative water content at low leaf water potential under water stress; this sustains growth while the plant is meeting transpirational demand by reducing its leaf water potential (Blum 2005). The osmotic potential is adjusted through changes in the accumulation of proline, inorganic ions and other osmotic solutes (Sonobe et al. 2011). Increased deep soil water capture has also been found to be a major contribution of osmotic adjustment in sorghum (Blum 2005). Typically, in sorghum older leaves are selectively senesced under stress, while the remaining young leaves retain turgor, stomatal conductance and assimilation as a result of high osmotic adjustment in the younger leaves (Blum and Arkin 1984). This ensures photosynthetic activity by keeping top leaves green, and reduced transpiration water losses by older shaded leaves under water stress. In addition, sorghum has an effective transpiration ratio of 1 : 310, as the plant uses only 310 parts of water to produce one part of dry matter, compared with a ratio of 1 : 400 for maize (Du Plesis 2008). Hence, production of sorghum in water-scarce regions as an alternative to maize will conserve water and increase water productivity.

Morphological adaptation

Drought tolerance in sorghum is consistent with its evolution in Africa where domestication occurred in arid and semi-arid areas parts of northern Africa (Morris et al., 2013). This resulted in the development of heritable morphological and anatomical characteristics (Dugas et al. 2011). These attributes minimize yield losses associated with water stress.

The root system is the plant organ in charge of capturing water and nutrients, besides anchoring the plant into the ground. It is naturally viewed as a critical organ to improve crop adaptation to water stress (Vadez 2014). Under water-limiting conditions, water extraction by a dryland crop is limited by root system depth and by the rate of degree of extraction (Robertson et al. 1993). Sorghum has long roots with high root density at deeper depths (Schittenhelm and Schroetter 2014) with roots that can reach up to 2 m (Robertson et al. 1993) in the absence of impeding soil layers. This allows sorghum to access water lower down the soil profile during water-scarce periods. Water stress can be detrimental at vegetative stage if it inhibits root growth (Comas et al., 2013). However, this is seldom the case as under water stress dry matter partitioning will often favour root growth at the expense of vegetative growth (Mabhaudhi 2009). Maximum rooting depth usually occurs after anthesis (Robertson et al. 1993). Drought tolerance and water extraction efficiency in sorghum are associated with maintaining high root length density, the number of nodal roots and late metaxylem vessels per nodal root under water scarcity (Tsuji et al. 2005). For optimal root development, it is important that pre-flowering water stress is avoided.

Long, narrow, pointy leaves reduce the contact surface area with direct sunlight during high temperatures, hence preventing desiccation. Sorghum leaves and stem are covered by a waxy cuticle and epicuticular wax (Saneoka and Ogata 1987) preventing excessive water loss during water stress. This suggests that cuticle and epicuticular wax enhance WUE in sorghum during water stress.

Tillering ability is commonly associated with sorghum in regions with limited rainfall. Tillering is generally recognized as one of the most plastic traits affecting biomass accumulation and ultimately grain yield in many field crops (Kim et al. 2010). Genetic variation in tillering affects the dynamics of canopy development and hence the timing and nature of crop water limitation (Hammer et al. 2006). Simulation studies on sorghum (Hammer et al. 1996) indicated a significant yield advantage of high-tillering types in high-yielding seasons when water was plentiful, whereas such types incurred a significant disadvantage in lower-yielding water-limited circumstances. However, tillering has been bred out of commercial cereal cultivars to ensure maximum biomass partitioning to the yield portion. Nonetheless, tillering is a prominent feature in sorghum landraces cultivated by subsistence farmers (Pandravada et al. 2013) as these have not been the subject of deliberate crop improvement. Whether tillering in landraces is beneficial in arid and semi-arid SSA remains unclear; however, the fact that landraces still tiller may suggest that subsistence farmers find an advantage to this trait. It may be that such farmers associate tillering with yield compensation under stressful conditions. Studies conducted by Lafarge et al. (2002) could not associate tillering with either yield or drought tolerance. However, it is likely that emergence of tillers is genetically controlled and partly serves as a survival mechanism under water-stress conditions. Hence, the selection of the best genotype is confounded by genotype-by-environment interactions for tillering (Hammer et al. 2005).

Phenological adaptation

Sorghum utilizes quiescence adaptive mechanisms to allow for extreme drought tolerance (Dugas et al. 2011). It can remain visually dormant during drought conditions, resuming growth once conditions are favourable (Assefa et al. 2010) ensuring crop survival and yield under terminal stress. Water stress affects sorghum at both pre- and post-flowering stages of development. Pre-flowering drought stress response occurs when plants are under significant water stress prior to flowering, particularly at or close to panicle differentiation and until flowering (Kebede et al. 2001). The most adverse effect of water stress on yield occurs during and after anthesis (Blum 2004). Post-flowering drought stress significantly reduces the number and size of the seeds per plant (Rosenow and Clark 1995), which are the main causes for lower grain yield in sorghum (Assefa et al. 2010). Phenological plasticity of sorghum allows for shorter or delayed seasons in sorghum to minimize the effect of water stress on yield.

Water-use efficiency

Water-use efficiency captures the yield response of physiological, morphological and phenological adaptations to water stress. When water is scarce, understanding the magnitude of water consumption is important. In most cases, evaluation for decision-making requires information about efficiency – when water is being used, it is being used effectively. Water-use efficiency in sorghum is variety specific. During water stress, reduction in sorghum biomass production is minimized while water use is significantly lowered. Hence, maximal water-use efficiency (WUE) is attained under water scarcity conditions, while lowest WUE values are obtained when environmental conditions are optimal for crop growth (Abdel-Montagally 2010).

Sorghum daily water requirements vary according to crop growth stage (Boyer 1982, Abdel-Montagally 2010), with maximal water requirement occurring from booting until after anthesis. Consequently, at this stage, sorghum is most sensitive to water stress. During the grain filling stage, physiological maturity and senescence, water requirements decrease gradually. Maximum sorghum yield requires 450 to 650 mm of water distributed evenly over the growing season (Doorenbos and Hassam 1979, Assefa et al. 2010). Sorghum grain yields are comparable to maize and higher than those of other major cereals under optimal water availability (Table 1). Under water stress, sorghum produces more yield than other major cereals due to a superior WUE (Table 1). This reaffirms the fact that sorghum is a drought-tolerant crop capable of producing reasonable yields under water stress. Therefore, sorghum is uniquely poised as a niche crop in semi-arid and arid regions of SSA.

Sorghum Nutritional Value and Utilization

Nutritional responses to water stress

Cereal grains are an optimal source of energy, carbohydrates, protein, fibre and macronutrients, especially magnesium and zinc (Kowieska et al. 2011). Water stress negatively affects grain nutritional content in cereals. A reduction in nutritional value of grains is most pronounced when water stress occurs during grain filling (Zhao et al. 2009). Knowledge of the extent to which water stress affects grain nutritional content in sorghum is lacking. Nutritional water productivity (NWP) is an emerging concept that combines information of nutritional value with that of crop water productivity. The result is an index that includes nutritional value-based output per unit of water use. This concept is important in addressing food security issues, especially in arid and semi-arid regions where malnutrition remains high. The review of literature showed that no NWP values have been developed for major cereals, including sorghum. This complicates assessment of which cereals crops have nutritional advantage in water-scarce regions of SSA. Because sorghum exhibits superior drought tolerance to major cereals, it is expected that reduction in nutrient content is minimized under water stress. However, studies need to be conducted to ascertain the effect of water stress on the nutritional value of sorghum.

Utilization, nutrition and health

Sorghum is used in a variety of food products across SSA. Food type and preparation varies by country and cultural practices. Sorghum is part of diets of many people in SSA and is consumed as traditional foods or commercial products (Taylor 2003). These include *bouillie* (thin porridge), *tô* (stiff porridge prepared by cooking slurry of sorghum flour), *couscous* (steamed and granulated traditional food), *injera* (fermented pancake-like bread prepared from sorghum in Ethiopia), *nasha* and *ogi* (traditional fermented sorghum foods used as weaning food), *kisra* (traditional bread prepared from fermented dough of sorghum), baked products and traditional beers (*dolo, tchapallo, pito, burukutu* (Mahgoub et al. 1999, Yetneberk et al. 2004, Achi 2005, Dicko et al. 2005). Pre-cooked sorghum flour mixed with vitamins and exogenous sources of proteins are commercially available in many African countries for the preparation of instant soft porridge for infants. Sorghum can also be puffed, popped, shredded and flaked to produce ready-to-eat breakfast cereals (Dicko et al. 2006).

Sorghum nutritional composition is comparable to other major cereals (Hulse et al. 1980, Food and Agriculture Organization (FAO) 1995; Ragaee et al. 2006), which makes promotion and inclusion of sorghum in water-scarce regions of SSA a good alternative from a nutrition standpoint. The average energy value of whole sorghum grain flour is 356 kcal per 100 g, which is comparable to other cereals (Fig. 1). Starch is the main component of sorghum grain, followed by proteins, non-starch polysaccharides and fat. The protein content in whole sorghum grain is in the range of 7–15 % (Dicko et al. 2006). The fat content, present mainly in the germ of the sorghum grain, is rich in polyunsaturated fatty acids, with a composition similar to maize fat. Sorghum is a good source of vitamins, mainly the B vitamins and the liposoluble vitamins A, D, E and K, and is a good source of more than 20 minerals including phosphorus, potassium, iron and zinc (Glew et al. 1997, Anglani 1998). Sorghum is important for human health in other respects. It is rich in fibre, bioactive compounds and antioxidant-rich phytochemicals that are desirable in human health (Awika and Rooney 2004, Dicko et al. 2005; Rooney 2007). Decreasing human consumption of sorghum in SSA (Sheorain et al. 2000, Adegbola et al. 2013) indicates that sorghum may be underutilized in SSA despite comparable nutritional composition to major cereals.

Aspects of Sorghum Underutilization of in SSA

Is sorghum an underutilized crop of SSA? This question calls into debate the issue of what are underutilized crops. The critical issue here is the lack of a consensus definition describing neglected and underutilized crop species (NUS) (Mabhaudhi et al. 2016b). A number of studies have described the typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources (Padulosi et al. 1999, 2008, Williams and Haq 2002, Galluzi and López Noriega 2014). Neglected and underutilized crop species are generally referred to as those species whose potential to improve people's livelihoods, as well as food security and sovereignty, is not being fully realized because of their limited competitiveness with commodity crops in mainstream agriculture (Padulosi et al. 2011). There is

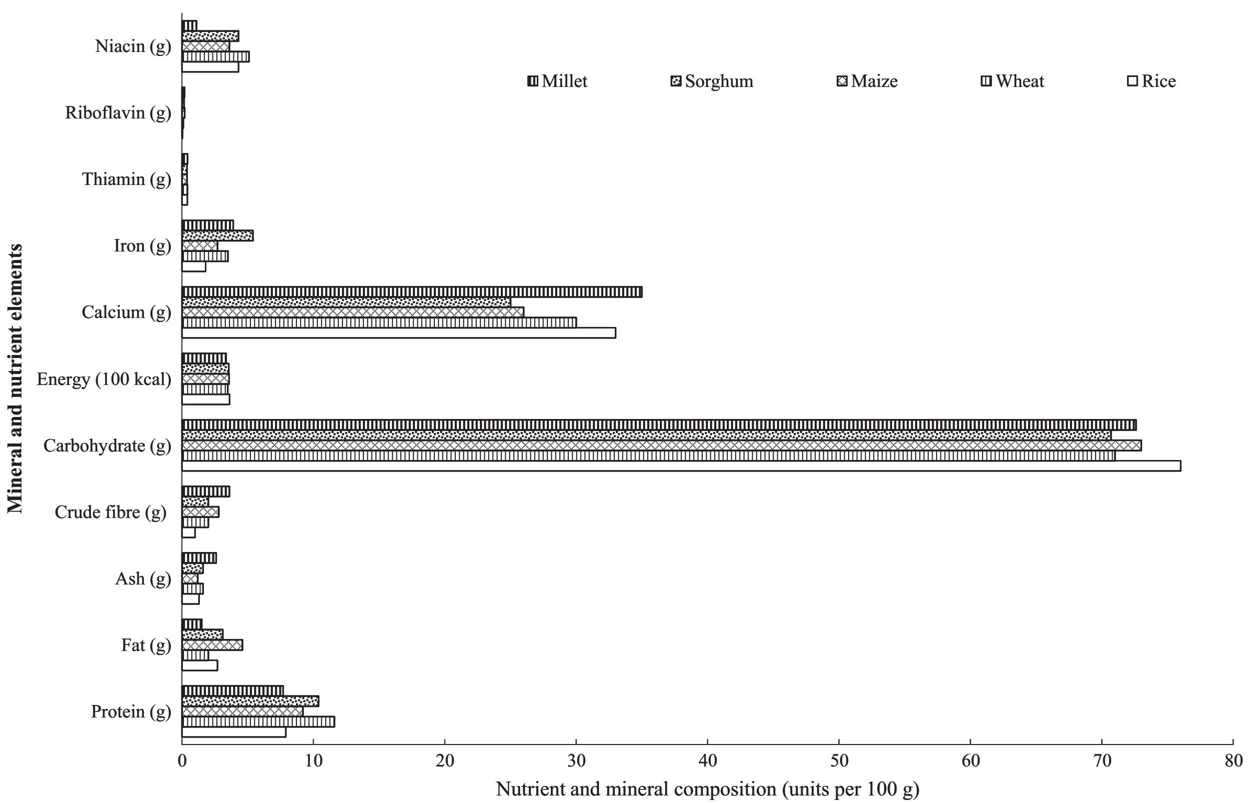

Fig. 1 Grain nutrient composition (per 100 g at 12 percent moisture) of five major cereals produced in sub-Saharan Africa (sources: Food and Agriculture Organization (FAO) 1995; Dicko et al. 2006).

also the question of underutilized by who, where and to what extent (Padulosi et al. 1999). Elsewhere, the term ‘underutilized’ has been associated with a crop being under-researched (Mabhaudhi et al. 2016a). Mabhaudhi et al. (2016b) described underutilized crops ‘as a subset of biodiversity that has been primarily maintained by resource-poor farmers in low input, mixed systems, and which is declining in significance due to a range of factors’.

Regarding typical features of NUS and the overriding issues affecting the conservation and use of their genetic resources, sorghum in SSA can be excluded from classification as underutilized. The existence of International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), large collections of germplasm collections and large-scale production throughout the region disqualify sorghum on basis of such features. An estimate of 168 500 accessions (most of which are duplicates of the ICRISAT 36 774 world collection accessions) is contained in sorghum germplasm collections globally at multiple sorghum genetic resources conservation sites (Rosenow and Dahlberg 2000).

Landraces constitute 85.3 %, breeding material 13.2 %, wild species accessions 1.2 % and named cultivars 0.3 % of the total collection. The high percentage of landraces in comparison with improved varieties in the total collection suggests that sorghum genetic resources are underutilized in respect to crop improvement. Landraces and obsolete cultivars can be considered as a valuable portion of the gene pool because they represent the broad intraspecific genetic diversity of crops, and therefore, it provides valuable characteristics important for breeding (Dotlačil et al., 2010). However, this presents a breeding advantage over major cereals like maize, wheat and barley where the breeding material is below 10 %.

Advanced features used in determining whether a crop is underutilized are geographical distribution and socio-economic status. With regard to geographical distribution, a species could be underutilized in some regions, but not in others. Regarding the socio-economic implication of the term, many species represent an important component of the daily diet of millions of peoples, but their poor marketing conditions make them largely underutilized in economic terms. As such, a crop can be widely cultivated across a region and still be underutilized. Geographically, maize remains the main crop under production (Table 3 and Fig. 2) even in semi-arid and arid parts of SSA where sorghum production confers a comparative advantage. Socio-economically, human consumption of sorghum is decreasing with enhanced socio-economic status of population and easy availability of much preferred cereals in abundance and at affordable prices (Sheorain et al. 2000, Adegbola et al. 2013, Orr et al. 2016). The grain stands to contribute more to food security than at present, especially for in arid and semi-arid SSA (Adegbola et al. 2013) if promoted and included more in the cereal food value chain. Relative to its potential, sorghum in SSA is therefore underutilized in terms of ‘extent’ (socio-economic) and ‘where’ (geographical).

Challenges and Outlook to Increasing Sorghum Production and Utilization in SSA

Multiple challenges account for sorghum underutilization in SSA. The major challenges identified in literature being:

- Sorghum cultivation is characterized by low inputs traditional farming practices, using traditional cultivars or landraces, which results in low yields (Taylor 2003).
- Lack of surplus sorghum, without which processing industries fail to establish which hampers the promotion of sorghum-based food products (Taylor 2003).
- False perception of sorghum and historical stereotype of sorghum as a ‘poor man’s crop’, which shifts consumer food preference to maize-, wheat- and rice-based foods (Williams et al. 2012, Orr et al. 2016).
- Low availability of high-end sorghum food processing in comparison with other major cereals (Oot et al. 1996).
- Bird destruction still remains a key sorghum yield reduction threat in the region, forcing smallholder farmers to trade off high yield potential and palatability for bird proof characteristics (Habindavyi 2009).
- Low research attention, breeding efforts and adoption rates of improved varieties by farmers in favour of other major cereal crops (Mwadalu and Mwangi 2013).

In this review, we suggest the following strategies to mitigate and improved sorghum production in SSA.

- green revolution (application of fertilizer, cultivation of improved cultivars) has potential to increase yields, thereby providing surplus produce to drive the agro-processing industry of sorghum.
- Research into discriminatory mechanisms to remove tannins from seeds at the post-harvest stage could assist resolve the ‘unhealthy dilemma’ of choosing between bird proof traits and palatability.
- Use of participatory fashioned research approaches towards development and distribution of new cultivars to improve cultivar adoption and sorghum breeding in the region.
- A drive towards marketing and distribution of existing sorghum high-end products, accompanied by investment and development of new processed products that compete well with that of other major cereals.

Table 3 Cereal production statistics in countries with arid and semi-arid AEZs in SSA

	Country area[1,2]	Agricultural area[1]	Cereal production area[1]	Ranking of five main cereals and area under production (1000 ha)[1]									
				1		2		3		4		5	
Country	(1000 ha)			Crop	Area	Crop	Area	Crop	Area	Crop	Area	Crop	Area
Botswana	58 173	25 920	146	A	870	B	500	C	580	–	–	–	–
B. Faso	27 422	11 770	4210	B	1807	C	1327	A	9136	D	139	–	–
Chad	128 400	49 932	2542	B	850	C	800	A	300	C	205	E	17
Cameroon	47 544	9750	–	A	832	B	800	D	167	C	70	E	1
Eritrea	11 760	7592	440	B	250	C	55	F	45	E	25	A	20
Ethiopia	110 430	36 325	10 243	A	2069	B	1847	E	1706	F	1048	C	432
Kenya	58 037	27 430	2494	A	2028	B	189	E	313	C	88	D	30
Malawi	11 848	5585	1881	A	1677	B	89	D	65	C	49	E	1
Mali	124 019	41 651	3661	C	437	B	938	A	641	D	605	E	7
Namibia	82 429	38 809	276	C	230	A	28	B	16	E	2	–	–
Niger	126 700	44 482	10 242	C	7100	B	3100	A	15	D	13	E	2
Nigeria	92 377	71 000	17 545	B	5500	A	5200	C	4000	D	2600	E	80
Senegal	19 671	9015	1117	C	714	A	152	B	140	D	108	–	–
Somalia	63 766	44 129	398	B	270	A	124	E	3	D	1	–	–
S. Africa	121 909	96 374	3993	A	3250	E	520	F	80	B	60	G	27
Sudan	112 702	108 678	10 088	B	7136	C	2782	E	136	A	27	D	8
Tanzania	93 300	–	–	A	–	D	–	B	–	C	–	E	–
Zambia	75 261	23 636	1145	A	998	E	42	D	39	C	34	B	23
Zimbabwe	39 076	16 400	1379	A	900	C	230	B	230	E	10	F	<1
Total				A	4907	B	4125	C	2687	D	1175	E	1159

Sources: [1]Food and Agriculture Organization Statistics (FAOSTAT) 2013; [2]WDI, 2015. Ranking of five main cereals and area under production in Eritrea and Ethiopia according to Food and Agriculture Organization Statistics (FAOSTAT) (2013) excludes teff, which is the main grain cereal under production (Yihun et al. 2013), where A is maize; B is sorghum; C is millet; D is rice; E is wheat; F is barley; and G is oats.

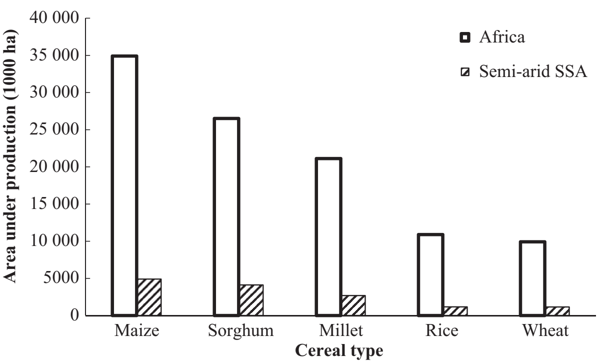

Fig. 2 Cereal production statistics in terms of area under production in Africa and in 19 selected countries (see Table 3) with arid and semi-arid agro-ecological zones in sub-Saharan Africa.

Conclusion

Sorghum is socio-economically and geographically underutilized in SSA. Sorghum production still lags behind maize even in arid and semi-arid AEZs where sorghum confers a comparative advantage. High WUE, adaptation to water stress, high germplasm variability, comparative nutritional value and existing food value chain make sorghum uniquely suited to improving cereal water productivity under water scarcity. How sorghum grain nutrients compare with those of other major cereals under water stress is unclear due to the lack of NWP values for grain cereals. Rainfed cultivation of sorghum as an alternative to major cereals in arid, semi-arid and drought-prone AEZs of SSA, and promotion of sorghum traditional and commercial food products can potentially improve food security in the region. The main challenges affecting sorghum underutilization in SSA are low availability of surplus produce for the production of high-end product processing, relatively low research attention afforded to sorghum and the number of improved genotypes, low adoption rate of improved varieties, significant yield reduction due to bird damage and consumer dietary preferences driven by perceptions of sorghum as a poor man's crop. Use of green revolution principles by small-scale farmers, participatory fashioned research approaches, development of tannin discriminating post-harvest processing technologies and improved marketing and distribution of sorghum products can potentially improve sorghum production in SSA agriculture.

Acknowledgements

The Water Research Commission of South Africa is acknowledged for initiating, funding and directing the study through WRC Project No. K5/2274//4 'Determining water use of indigenous grain and legume food crops' (Water Research Commission (WRC) 2014).

References

Abdel-Montagally, F. M. F., 2010: Evaluation of water use efficiency under different water regimes in sorghum (*Sorghum bicolor* (L.) Moench). World J. Agric. Sci. 6, 499–505.

Abdul-Ganiyu, S., M. K. Amaanatu, and J. K. Korese, 2012: Water use efficiency and productivity for rice (*Oryza sativa*) in the Bontanga irrigation scheme of northern region of Ghana. Agric. Sci. Res. J. 2, 362–368.

Achi, O. K., 2005: The potential for upgrading traditional fermented foods through biotechnology. Afr. J. Biotechnol. 4, 375–380.

Adegbola, A. J., E. F. Awagu, and R. Q. Kashetu, 2013: Sorghum: the most under-utilized grain of the semi-arid Africa. Adv. J. Agric. Res. 1, 11–19.

Akinbile, C. O., A. Y. Sangondoyin, F. E. Nwilene, and K. Futakuchi, 2007: Growth and yield responses of upland rice (NERICA2) under different water regimes in Ibadan, Nigeria. Res. J. Agron. 1, 71–75.

Akram, Z., M. M. Khan, G. Shabbir, and F. Nasir, 2011: Assessment of genetic variability in sorghum genotypes for drought tolerance based on RAPD analysis. J. Agric. Res. 49, 455–463.

Anglani, C., 1998: Sorghum for human food: a review. Plant Foods Human Nutr. 52, 85–89.

Araya, A., L. Stroosnijder, G. Girmay, and S. D. Keestra, 2011a: Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.)). Agric. Water Manage. 98, 775–783.

Araya, A., H. Solomon, H. Mitiku, F. Sisay, and D. Tadesse, 2011b: Determination of local barley (*Hordeum vulgare*) crop coefficient and comparative assessment of water productivity for crops grown under the present pond water in Tigray, northern Ethiopia. Momona Ethiopian J. Sci. 3, 65–79.

Assefa, Y., S. A. Staggenborg, and V. P. V. Prasad, 2010: Grain sorghum water requirement and responses to drought stress: a review. Crop Manag. 10, 1109–1116.

Awika, J. M., and L. W. Rooney, 2004: Sorghum phytochemicals and their potential aspects on human health. Phytochemistry 65, 1199–1221.

Azizian, A., and A. R. Sepaskhah, 2014: Maize response to different water, salinity and nitrogen levels: yield–water relation, water-use and water uptake reduction function. Inter. J. Plant Prod. 8, 1735–8043.

Barati, V., H. Ghadiri, S. Zand-Parsa, and N. Karimian, 2015: Nitrogen and water use efficiencies and yield response of barley cultivars under different irrigation and nitrogen regimes in a semi-arid Mediterranean climate. Archives Agron. Soil Sci. 61, 15–32.

Bationo, A., A. Hartemink, O. Lungu, M. Niami, P. Okoth, P. Smaling, and L. Thiombiano, 2006: African soils – Their productivity and profitability of fertilizer use. Background paper for the Africa fertilizer summit. June 2006, Nigeria.

Blum, A. 2004: Sorghum physiology. In: H. T. Nguyen, and A. Blum, eds. Physiology and Biotechnology Integration for Plant Breeding, pp. 141–223. Marcel Dekker, New York, NY, USA.

Blum, A., 2005: Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res. 56, 1159–1168.

Blum, A., 2009: Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field. Crop. Res. 112, 119–123.

Blum, A., and G. F. Arkin, 1984: Sorghum root growth and water-use as affected by water supply and growth duration. Field Crops Res. 9, 131–142.

Borrell, A. K., J. E. Mullet, B. George-Jaeggli, E. J. Van Oosterom, G. L. Hammer, P. E. Klein, and D. R. Jordan, 2014: Drought adaptation of stay–green sorghum is associated with canopy development, leaf anatomy, root growth, and water uptake. J. Exp. Bot. 65, 6251–6263.

Boyer, J. S., 1982: Plant productivity and environment. Science 218, 443–448.

Byerlee, D., X. Diao, and C. Jackson, 2005: Agriculture, rural development, and pro-poor growth: Country experiences in the post-reform era. Synthesis paper for the operationalizing pro-poor growth in the 1990s project. Washington DC: The World Bank.

Cairns, J. E., J. Hellin, K. Sonder, J. L. Araus, J. F. Macrobert, C. Thierfelder, and B. M. Prasanna, 2013: Adapting maize production to climate change in sub-Saharan Africa. Food Sec. 5, 345–360.

Chauvin, N. D., F. Mulangu, and G. Porto, 2012: Food production and consumption trends in Sub–Saharan Africa: Prospects for the transformation of the agricultural sector. United Nations Development Programme (UNDP). Regional Bureau for Africa. WP 2012–011: February 2012.

Chivenge, P., T. Mabhaudhi, A. T. Modi, and P. Mafongoya, 2015: The potential role of neglected and underutilised crop species as future crops under water scarce conditions in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 12, 5685–5711.

Clover, J., 2003: Food security in Sub-Saharan Africa. Afr. Security Rev. 12, 5–14.

Comas, L. H., S. R. Becker, V. M. V. Cruz, P. F. Byrne, and D. A. Dierig, 2013: Root traits contributing to plant productivity under drought. Front. Plant Sci. 4, 1–13.

Dicko, M. H., H. Gruppen, A. S. Traore, W. J. H. Van Berkel, and A. G. J. Voragen, 2005: Evaluation of the effect of germination on phenolic compounds and antioxidant activities in sorghum varieties. J. Agric. Food Chem. 53, 2581–2588.

Dicko, M. H., H. Gruppen, A. S. Traore, A. Voragen, and W. Berkel, 2006: Sorghum grain as human food in Africa: relevance of content of starch and amylase activities. Afr. J. Biotechnol. 5, 384–395.

Doorenbos, J., and A. H. Hassam, 1979: Yield Response to Water. FAO. Irrigation and Drainage Paper 33. Rome, Italy.

Dotlačil, L., J. Hermuth, Z. Stehno, V. Dvořáček, J. Bradová, and L. Leišová, 2010: How can wheat landraces contribute to present breeding? Czech J. Genet. Plant Breed. 46, S70–S74.

Doward, A., J. Kydd, and M. Stockbridge, 2004: Agricultural liberalization in Sub Saharan Africa. Inception Report for ECPrep.

Du Plesis, J. 2008: Sorghum production. pp 1–22. Department of Agriculture: Republic of South Africa and Agricultural Research Council.

Dugas, D. V., M. K. Monaco, A. Olsen, R. R. Klein, S. Kumari, D. Ware, and P. E. Klein, 2011: Functional annotation of the transcriptome of *Sorghum bicolor* in response to osmotic stress and abscisic acid. BMC Gen. 12, 1–22.

Edmeades, G. O., M. Bänziger, H. R. Mickelson, and C. B. Peña–Valdivia, 1997: Developing drought- and low N-tolerant maize. Proceedings of a Symposium, March 25–29, 1996, CIMMYT, El Batán, Mexico. Mexico, D.F.: CIMMYT.

Edmonds, D. E., S. L. Abreu, A. West, D. R. Caasi, T. O. Conley, M. C. Daft, B. Desta, B. B. England, C. D. Farris, T. J. Nobles, N. K. Patel, E. W. Rounds, B. H. Sanders, S. S. Shawaqfeh, L. Lakmini, R. Manandhar, and W. R. Raun, 2009: Cereal nitrogen use efficiency in Sub Saharan Africa. J. Plant Nutr. 32, 2107–2122.

Fanadzo, M., C. Chiduza, P. N. S. Mnkeni, I. Van Der Stoep, and J. Stevens, 2010: Crop production management practices as a cause for low water productivity at Zanyokwe Irrigation Scheme. Water SA 36, 27–36.

FAO, IFAD and WFP, 2014: The state of food insecurity in the world. Strengthening the enabling environment for food security and nutrition. Rome, FAO.

Fischer, R. A., D. Byerlee, and G. O. Edmeades, 2014: Crop yields and global food security: will yield increase continue to feed the world? Canberra: Australian Centre for International Agricultural Research. http://aciar.gov.au/biblio/mn158. (last accessed on 15 April 2015)

Food and Agriculture Organisation (FAO), 1991: Water and soil requirements. In: W. Critchley, and K. Siegert eds. Water Harvesting (AGL/MISC/17/91) – A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. http://www.fao.org/docrep/u3160e/u3160e04.htm#2. (last accessed on 02 May 2015).

Food and Agriculture Organization (FAO), 1995: Sorghum and millets in human nutrition. FAO Food and Nutrition Series, No. 27. Rome, Italy.

Food and Agriculture Organization (FAO), 2008: The state of food and agriculture. Biofuels: prospects, risks and opportunities. Rome, Italy.

Food and Agriculture Organization (FAO), 2010: FAO statistical database. Rome, Italy.

Food and Agriculture Organization (FAO), 2014: Food and nutrition in numbers. Rome, Italy.

Food and Agriculture Organization Statistics (FAOSTAT), 2013: FAO statistical yearbook 2013. World food and agriculture. Rome, Italy.

Galluzi, G., and I. López Noriega, 2014: Conservation and use of genetic resources of underutilized crops in the Americas—A continental analysis. Sustainability 6, 980–1017.

Garrity, D., F. Akinnifesi, O. Ajayi, G. W. Sileshi, J. G. Mowo, A. Kalinganire, M. Larwanou, and J. Bayala, 2010: Evergreen agriculture: a robust approach to sustainable food security in Africa. Food Sec. 2, 197–214.

Glew, R. H., D. J. Vanderjagt, C. Lockett, L. E. Grivetti, G. C. Smith, A. Pastuszyn, and M. Millson, 1997: Amino acid, fatty acid, and mineral composition of 24 indigenous plants of Burkina Faso. J. Food Comp. Anal. 10, 205–217.

Habindavyi, E. 2009: Morphological characterization of sorghum (*Sorghum bicolor*) diversity in Burundi. CBM Swedish Biodiversity Centre, Uppsala University.

Hammer, G. L., D. Butler, R. C. Muchow, and H. Meinke, 1996: Integrating physiological understanding and plant breeding via crop modelling and optimisation. In: M. Cooper, and G. L. Hammer, eds. Plant Adaptation and Crop Improvement, pp. 419–441. CAB International, ICRISAT & IRRI, Wallingford, UK.

Hammer, G. L., S. C. Chapman, E. J. Van Oosterom, and D. W. Podlich, 2005: Trait physiology and crop modelling as a framework to link phenotypic complexity to underlying genetic systems. Austr. J. Agric. Res. 56, 947–960.

Hammer, G., M. Cooper, F. Tardieu, S. Welch, B. Walsh, F. Van Eeuwijk, S. Chapman, and D. Podlich, 2006: Models for navigating biological complexity in breeding improved crop plants. Trends Plant Sci. 11, 587–593.

Haque, I., S. Jutzi, and P. J. H. Neate, eds. 1986: Potentials of Forage Legumes in Farming Systems of Sub-Saharan Africa. Proceedings of a workshop held at ILCA, Addis Ababa, Ethiopia, 16–19 September 1985. ILCA, Addis Ababa.

Harris, K., P. K. Subudhi, A. K. Borrell, D. B. Jordan, D. Rosenow, H. Nguyen, P. Klein, R. Klein, and J. Mullet, 2006: Sorghum stay-green QTL individually reduce post–flowering drought-induced leaf senescence. J. Exp. Bot. 58, 327–338.

Hensley, M., J. J. Botha, J. J. Anderson, P. P. Van Staden, and A. Du Toit, 2000: Optimizing Rainfall Use Efficiency for Developing Farmers with Limited Access to Irrigation Water. WRC Report No. 878/1/00. Water Research Commission, Pretoria , South Africa.

Hulse, J. H., E. M. Laing, and O. E. Pearson, 1980: Sorghum and the Millets: Their Composition and Nutritional Value, pp. 90. Academic Press, New York, NY, USA.

Ismail, S. M., 2012: Optimizing productivity and irrigation water use efficiency of pearl millet as a forage crop in arid regions under different irrigation methods and stress. Afr. J. Agric. Res. 7, 2509–2518.

Jewitt, G. W. P., H. W. Wen, R. P. Kunz, and van Rooyen A. M., 2009: Scoping study on water use of crops/trees for biofuels in South Africa. Water Research Commission (WRC) report no. 1772/1/09.

Kapanigowda, M., R. Perumal, M. Djanaguiraman, R. M. Aiken, T. Tesso, P. V. V. Prasad, and C. R. Little, 2013: Genotypic variation in sorghum [*Sorghum bicolor* (L.) Moench] exotic germplasm collections for drought and disease tolerance. SpringerPlus 2, 650–657.

Kebede, H., P. K. Subudhi, D. T. Rosenow, and H. T. Nguyen, 2001: Quantitative trait loci influencing drought tolerance in grain sorghum (*Sorghum bicolor* L. Moench). Theor. Appl. Genet. 103, 266–276.

Kijne, J., J. Barron, H. Hoff, J. Rockström, L. Karlberg, J. Gowing, S. P. Wani, and D. Wichelns, 2009: Opportunities to increase water productivity in agriculture with special reference to Africa and South Asia. A report prepared by Stockholm Environment Institute, for the Swedish Ministry of Environment presentation at CSD 16, New York.

Kim, H. K., D. Luquet, E. Van Oosterom, M. Dingkuhn, and G. Hammer, 2010: Regulation of tillering in sorghum: genotypic effects. Annals Bot. 106, 69–78.

Kowieska, A., R. Lubowicki, and I. Jaskowska, 2011: Chemical composition and nutritional characteristics of several cereal grain. Acta Sci. Pol. 10, 37–50.

Lafarge, T. A., I. J. Broad, and G. L. Hammer, 2002: Tillering in grain sorghum over a wide range of population densities: identification of a common hierarchy for tiller emergence, leaf area development and fertility. Annals Bot. 90, 87–98.

Livingston, G., S. Schonberger, and S. Delaney, 2011: Sub-Saharan Africa: The state of smallholders in agriculture. Conference on new directions for smallholder agriculture. IFAD, Rome, Italy.

Mabhaudhi, T. 2009: Responses of maize (*Zea mays* L.) landraces to water stress compared with commercial hybrids. MSc thesis. University of KwaZulu–Natal, Pietermaritzburg, South Africa.

Mabhaudhi, T., T. Chibarabada, and A. Modi, 2016a: Water–food–nutrition–health nexus: linking water to improving food, nutrition and health in Sub-Saharan Africa. Int. J. Environ. Res. Public Health 13, 107–136.

Mabhaudhi, T., P. O'Reilly, S. Walker, and S. Mwale, 2016b: Opportunities for underutilised crops in Southern Africa's post-2015 development agenda. Sustainability 8, 302.

Machethe, C. L., N. M. Mollel, K. Ayisi, M. B. Mashatola, F. D. K. Anim, and F. Vanasche, 2004: Smallholder irrigation and agricultural development in the Olifants river basin of Limpopo province: Management, transfer, productivity, profitability and food security issues. WRC Report No. 1050/1/04. Water Research Commission, Pretoria, South Africa.

Mahgoub, S. E. O., B. M. Ahmed, M. M. O. Ahmed, and N. N. A. El Agib, 1999: Effect of traditional Sudanese processing of kisra bread and hulumur drink on their thiamine, riboflavin and mineral contents. Food Chem. 67, 129–133.

Maman, N., D. J. Lyon, S. Mason, T. D. Galusha, and R. Higgins, 2003: Pearl millet and grain sorghum yield response to water supply in Nebraska. Agron. J. 95, 1618–1624.

Mativavarira, M., J. Dimes, P. Masikati, A. Van Rooyen, E. Mwenje, J. L. N. Sikosana, and S. H. K. Tui, 2011: Evaluation of water productivity, stover feed quality and farmers' preferences on sweet sorghum cultivar types in the semi-arid regions of Zimbabwe. J. SAT Agril. Res. 9, 1–9.

Matsumoto, S., T. Tsuboi, G. Asea, A. Maruyama, M. Kikuchi, and M. Takagaki, 2014: Water response of upland rice varieties adopted in Sub-Saharan Africa: a water application experiment. J. Rice Res. 2, 1–6.

Mavhura, E., D. Manatsa, and T. Mushore, 2015: Adaptation to drought in arid and semi-arid environments: case of the Zambezi Valley, Zimbabwe. Jàmbá: J. Disast. Risk Stud. 7, 1–7.

McKevith, B., 2004: Nutritional aspects of cereals. British nutrition foundation. Nutri. Bulletin 29, 111–142.

Mokh, F. E., K. Nagaz, M. M. Masmoudi, and N. B. Mechlia, 2013: Soil salinity and water productivity of carrot–millet system as influenced by irrigation regimes with saline water in arid regions of Tunisia. J. Agric. Envir. Inter. Dev. 107, 179–199.

Morris, G. P., P. Ramu, S. P. Deshpande, C. T. Hash, T. Shah, H. D. Upadhyaya, O. Riera-Lizarazu, P. J. Brown, C. B. Acharya, S. E. Mitchell, J. Harriman, J. C. Glaubitz, E. S. Buckler, and S. Kresovich, 2013: Population genomic and genome-wide association studies of agroclimatic traits in sorghum. Proc Natl Acad Sci 110, 453–458.

Mwadalu, R., and M. Mwangi, 2013: Potential role of sorghum in enhancing food security in semi-arid eastern Kenya. J. Appl. Biosci. 71, 5786–5799.

Ofori, E., P. Oteng-Darko, J. N. Berchie, F. O. Nimako, S. Yeboah, and E. O. Danquah, 2014: Monitoring of soil moisture regime and water use efficiency under maize cowpea cropping system. Int. J. Curr. Microbiol. App. Sci. 3, 837–848.

Oot, D. A, J.Hicks, and N. Borton, 1996: Lost Crops of Africa, Volume I, Grains. Board on Science and Technology for International Development. National Research Council, National Academy Press, Washington, D.C., USA.

Orr, A., C. Mwema, A. Gierend, and S. Nedumara, 2016: Sorghum and millets in eastern and southern Africa. Facts, trends and outlook. Working Paper Series No. 62. ICRISAT Research Program, Markets, Institutions and Policies. Patancheru 502 324, Telangana, India: International Crops Research Institute for the Semi-Arid Tropics. pp 76.

Ortiz, R., M. Iwanaga, M. P. Reynolds, H. Wu, and J. Crouch, 2007: Overview on crop genetic engineering for drought prone environments. J. Semi-Arid Tropic. Agric. Res. 4, 1–30. http://ejournal.icrisat.org/SpecialProject/sp3.pdf

Padulosi, S., P. Eyzaquirre, and T. Hodgkin, 1999: Challenges and strategies in promoting conservation and use of neglected and underutilised crop species. In: J. Janick, ed. Perspectives on New Crops and New Uses, pp. 140–145. ASHS Press, Alexandria, VA, USA.

Padulosi, S., I. Hoeschle–Zeledon, and P. Bordoni, 2008: Minor crops and underutilised species: lessons and prospects. In: N. Maxted, B. V. Ford-Lloyd, S. P. Kell, J. M. Iriondo, M. E. Dulloo, and J. Turok, eds. Crop Wild Relative Conservation and Use, pp. 605–624. CAB International, Wallingford, UK.

Padulosi, S., V. Heywood, D. Hunter, and A. Jarvis, 2011: Underutilized species and climate change: current status and outlook. In: S. S. Yadav, R. J. Redden, J. L. Hatfield, H. Lotze-Campen, and A. E. Hall, eds. Crop Adaptation to Climate Change, 1st ed, pp. 507–521. Blackwell Publishing Ltd, Oxford, UK.

Pandravada, S. R., N. Sivaraj, N. Sunil, R. Jairam, Y. Prasanthi, S. K. Chakrabarty, P. Ramesh, I. S. Bisht, and S. K. Pareek, 2013: Sorghum landraces patronized by tribal communities in Adilabad district, Andhra Pradesh. Ind. J. Tradition. Know. 4, 465–471.

Ragaee, S., E. M. Abdel-Aal, and M. Noaman, 2006: Antioxidant activity and nutrient composition of selected cereals for food use. Food Chem. 98, 32–38.

Ringler, C., T. Zhou, J. Koo, and D. Wang, 2010: Climate change impacts on food security in Sub-Saharan Africa. Insights from comprehensive climate change scenarios. IFPRI Discussion Paper 01042.

Rizhsky, L., H. Liang, and R. Mittler, 2002: The combined effect of drought stress and heat shock on gene expression in tobacco. Plant Physiol. 130, 1143–1151.

Robertson, M. J., S. Fukai, and G. L. Hammer, 1993: Water extraction by grain sorghum in a sub-humid environment. I. Analysis of the water extraction pattern. Field Crops Res. 33, 81–97.

Romney, D. L., P. Thorne, B. Lukuyu, and K. Thornton, 2003: Maize as food and feed in intensive smallholder systems: management options for improved integration in mixed farming systems of east and southern Africa. Field Crops Res. 84, 159–168.

Rooney, L. W. 2007: Food and nutritional quality of sorghum and millet. pp. 91–93. INTSORMIL 2007 Annual Report, Lincoln, Nebraska, USA.

Rosenow, D. T., and L. E. Clark, 1995: Drought and lodging resistance for a quality sorghum crop. In: Proceedings of the 5th annual corn and sorghum industry research conference (Chicago, IL, 6–7 December 1995), pp 82–97 American Seed Trade Association, Chicago, IL.

Rosenow, D. T., G. Ejeta, L. E. Clark, M. L. Gilbert, R. G. Henzell, A. K. Borrell, and R. C. Muchow, 1996: Breeding for pre- and post-flowering drought stress resistance in sorghum. In: D. T. Rosenow, and J. M. Yohe, eds. Proceedings of the International Conference on Genetic Improvement of Sorghum and Pearl Millet, pp. 400–411. (Lubbock, TX, 22–27 September 1996), ICRISAT, Lubbock, India.

Rosenow, D. T., and J. A. Dalhberg, 2000: Collection, conversion and utilization of sorghum. In: C. W. Smith, and A. R. Frederiksen eds. Sorghum, Origin, History, Technology and Production: Wiley Series in Crop Science. pp 309–328. John Wiley and Sons, New York, USA.

Saneoka, H., and S. Ogata, 1987: Relationship between water use efficiency and cuticular wax deposition in warm season forage crops grown under water deficit conditions. Soil Sci. Plant Nutr. 33, 439–448.

Schittenhelm, S., and S. Schroetter, 2014: Comparison of drought tolerance of maize, sweet sorghum and sorghum–sudangrass hybrids. J. Agron. Crop Sci. 200, 46–53.

Schmidhuber, J., and F. N. Tubiello, 2007: Global food security under climate change. Proc. Natl Acad. Sci. 104, 19703–19708.

Schulze, R. E., 2011: Approaches towards practical adaptive management options for selected water related sectors in South Africa in a context of climate change. Water SA 37, 621–646.

Sebastian, K. 2009: Agro-ecological zones of Africa. International Food Policy Research Institute. Washington, DC.

Sheorain, V., R. Banka, and M. Chavan, 2000: Ethanol production from sorghum. In: A. Chandrashekar, R. Bandyopadyay, and A. J. Hall, eds. Technical and Institutional Options for Sorghum Grain Mold Management: Proceedings of an International Consultation, pp. 228–239. 18–19 May 2000. ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru, India.

Singh, P., S. P. Wani, P. Pathak, K. L. Sahrawat, and A. K. Singh, 2011: Increasing crop productivity and effective use of water in rainfed agriculture. In: E. Boelee ed. Integrated Watershed Management in Rainfed Agriculture, pp. 315–347. CRC Press (Taylor & Francis), London, UK.

Sonobe, K., T. Hattori, P. An, W. Tsuji, A. E. Eneji, S. Kobayashi, Y. Kawamura, K. Tanaka, and S. Inanaga, 2011: Effect of silicon application on sorghum root responses to water stress. J. Plant Nutr. 34, 71–82.

Steduto, P., T. C. Hsiao, and E. Fereres, 2007: On the conservative behavior of biomass water productivity. Irri. Sci. 25, 189–207.

Takele, A., and J. Farrant, 2013: Water relations, gas exchange characteristics and water use efficiency in maize and sorghum after exposure to and recovery from pre and post–flowering dehydration. Afr. J. Agric. Res. 8, 6468–6478.

Taylor, J. R. N. 2003: Overview: Importance of sorghum in Africa. In Proceedings of AFRIPRO Workshop on the proteins of sorghum and millets: Enhancing nutritional and functional properties for Africa, Vol. 9. Pretoria, South Africa.

Tolk, J. A., T. A. Howell, and F. Miller, 2013: Yield component analysis of grain sorghum grown under water stress. Field Crops Res. 145, 44–51.

Tsuji, W., M. E. K. Ali, S. Inanaga, and Y. Sugimoto, 2003: Growth and gas exchange of three sorghum cultivars under drought stress. Biologia Planta. 46, 583–587.

Tsuji, W., I. Shinobu, A. Hideki, M. Shigenor, P. An, and K. Sonobe, 2005: Development and distribution of root system in two grain sorghum cultivars originated from Sudan under drought stress. Plant Prod. Sci. 8, 553–562.

Vadez, V., 2014: Root hydraulics: the forgotten side of roots in drought adaptation. Field Crops Res. 165, 16–24.

Van Oosterom, E. J., S. C. Chapman, A. K. Borrell, I. J. Broad, and G. L. Hammer, 2010: Functional dynamics of the nitrogen balance of sorghum II. Grain filling period. Field Crops Res. 115, 29–38.

Virupakshagowda, C. P., A. A. Khalid, M. Rangaswamy, H. M. T. El-Kamil, M. Samy, A. Ali, M. B. Chandrashekhar, and H. G. Prasanna, 2015: Assessing agricultural water productivity in desert farming system of Saudi Arabia. IEEE J. Select. Topics Appl. Earth Obs. Remote Sens. 8, 284–297.

Wang, Y., D. Wang, P. Shi, and K. Omasa, 2014: Estimating rice chlorophyll content and leaf nitrogen concentration with a digital still color camera under natural light. Plant Methods 10, 1–11.

Water Research Commission (WRC) 2014: WRC Knowledge Review 2013/14. Project No. K5/2274//4 Determining water use of indigenous grain and legume food crops. Pretoria, South Africa.

Williams, J. T., and N. Haq, 2002: Global research on underutilised crops. An assessment of current activities and proposals for enhanced cooperation. International Centre for Underutilised Crops (ICUC), Southampton, UK.

Williams, S. B., S. J. Gray, H. C. K. Laidlaw, and I. D. Godwin, 2012: Particle inflow gun-mediated transformation of *Sorghum bicolor*. In: I. S. Curtis, ed. Transgenic Crops of the World: Essential Protocols, pp. 89–101. Kluwer Academic Publishers, Dordrecht, Netherlands.

World Bank 2008: World development report 2008: Agriculture for development. The World Bank, Washington, DC.

World Development Indicators (WDI), 2015: Data – The World Bank. (WDI) http://knoema.com/atlas/ranks/Land-under-cereal-production?baseRegion=BW. (last accessed on 12 June 2015).

Yetneberk, S., H. L. De Kock, L. W. Rooney, and J. R. N. Taylor, 2004: Effects of sorghum cultivar on injera quality. Cereal Chem. 81, 314–321.

Yihun, Y. M., A. M. Haile, B. Schultz, and K. Erkossa, 2013: Crop water productivity of irrigated teff in a water stressed region. Water Resour. Manage 27, 3115–3125.

Zhang, H., T. Oweis, S. Garabet, and M. Pala, 1998: Water use efficiency and transpiration efficiency of wheat under rain-fed and irrigation conditions in Mediterranean environment. Plant Soil 201, 295–305.

Zhang, Y., Q. Tang, S. Peng, D. Xing, J. Qin, R. C. Laza, and B. R. Punzalan, 2012: Water use efficiency and physiological response of rice cultivars under alternate wetting and drying conditions. Sci. World J. 2012, 1–10.

Zhao, C.-X., M.-R. He, Z.-L. Wang, Y.-F. Wang, and Q. Lin, 2009: Effects of different water availability at post-anthesis stage on grain nutrition and quality in strong–gluten winter wheat. C. R. Biologies 332, 759–764.

Zingore, S., 2011: Maize productivity and response to fertilizer use as affected by soil fertility variability, manure application, and cropping system. Better Crops 95, 4–6.

Zwart, S. J., and W. M. Bastiaanssen, 2004: Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric. Water Manag. 69, 115–133.