Evans School of Public Affairs
UNIVERSITY OF WASHINGTON
Evans School Policy Analysis and Research (EPAR)
Professor Leigh Anderson, PI and Lead Faculty
Associate Professor Mary Kay Gugerty, Lead Faculty

Agriculture-Environment Series:
Current Knowledge of Crop-Environment Interactions in Sub-Saharan Africa and South Asia

EPAR Technical Report No. 254

Travis Reynolds, Stephen R. Waddington, Alexander Chew, Zoe True
C. Leigh Anderson, Alison Cullen and Mary Kay Gugerty

Prepared for the Agricultural Policy Team
of the Bill & Melinda Gates Foundation

March 20, 2014

Introduction

This overview introduces a series of EPAR briefs in the Agriculture-Environment Series that examine crop-environment interactions for a range of crops in smallholder food production systems in Sub-Saharan Africa (SSA) and South Asia (SA). The briefs cover the following important food crops in those regions; rice (#208), maize (#218), sorghum/millets (#213), sweet potato/yam (#225), and cassava (#228).

Drawing on the academic literature and the field expertise of crop scientists, these briefs highlight crop-environment interactions at three stages of the crop value chain: pre-production (e.g., land clearing and tilling), production (such as water, nutrient and other input use), and post-production (e.g., waste disposal and crop storage). At each stage we emphasize environmental constraints on crop yields (including poor soils, water scarcity, crop pests) and impacts of crop production on the environment (such as soil erosion, water depletion and pest resistance). We then highlight best practices from the literature and from expert experience for minimizing negative environmental impacts in smallholder crop production systems.

This overview (along with the accompanying detailed crop briefs) seeks to provide a framework for stimulating across-crop discussions and informed debates on the full range of crop-environment interactions in agricultural development initiatives.

These briefs aim to ensure that:

➢ Decision-makers (such as research planners, policy makers, funding agents) working with specific crops and crop systems will have a better understanding of regionally specific "red flags" in terms of the crop-environment interactions associated with production practices, and a better appreciation of best practices likely to mitigate their impacts

➢ Grant-makers and program managers (such as Gates Foundation Program Officers) will be more comfortable engaging in conversations about environmental considerations in the context of grant development dialogues and identifying areas where a proposed approach may offer new information about crop-environment interactions

➢ Economic and policy analysts will share a common foundation to discuss the interactions between crop value chains and the environment.

We begin this overview by describing our methodology for ranking crop-environment interactions, and follow by introducing the major smallholder farming systems in which the crops are grown in SSA and SA. We then highlight key environmental constraints and impacts of each crop through its value chain.

An in-depth account of these findings are available in the five EPAR crop-environment briefs listed above. Each of these detailed briefs include a summary table identifying key environmental constraints and environmental impacts of the selected food crop in farming systems in SSA and SA. These full briefs further summarize good practices identified in the literature to address environmental problems associated with the crops. While the detailed briefs are crop-focused, Part II of this overview presents relevant crop information broken out by region (SSA and SA), and a summary of the research by region.

Ranking Methodology

We evaluate the importance of crop-environment interactions by assessing the frequency with which an environmental constraint to crop production, or environmental impact from crop production, is mentioned in the peer-reviewed literature, and whether it is characterized in that literature as minor, moderate or severe. Recognizing that this accounting depends on the stock of literature, we report on the depth of the literature for each crop, to allow the reader to calibrate the results by the amount of research that has been conducted.

We use three criteria to summarize the empirical evidence currently available in peer-reviewed scholarship and to identify apparent gaps in research on crop-environment interactions:

I. Severity of Environmental Constraints Reported

The relative effects of major biotic and abiotic constraints on crop yields are increasingly available in the peer-reviewed literature, including recent and cross-cutting review articles evaluating constraints in relation to 'yield gaps' by crop and by farming system (see for example Waddington *et al.,* 2010; Dixon *et al.,* 2001). Some of these cross-cutting crop-level estimates of constraints and yield gaps are given in the individual crop-environment briefs. In this overview we summarize the relative significance of various environmental constraints on crop production for six general categories, based on a comprehensive review of published literature and consultation with crop experts. The categories are land availability, nutrient constraints, water constraints, biotic constraints, climate change, and post-harvest losses. These same categories are used in the summary table at the beginning of each detailed crop brief.

We categorize the severity of these environmental constraints for each crop as follows:

0. *No mentions of the environmental constraint in published literature or expert accounts on the crop*
1. *Rarely mentioned or a minor constraint*
2. *Sometimes mentioned as a moderate constraint*
3. *Consistently mentioned as a moderate constraint*
4. *Sometimes mentioned as a severe constraint*
5. *Consistently mentioned in published literature or expert accounts on the crop as a severe constraint*

Wherever possible at least two experts with expertise specific to each crop validated the categorizations; in any remaining cases the authors used their own judgment based on expert input and their own assessments of the available evidence. The resultant categorization indicates the relative importance, in very broad terms, of different environmental constraints on crop yields. Further details on each type of constraint can be found in the accompanying briefs on each crop.

II. Severity of Environmental Impacts Reported

Precise estimates of crop-specific environmental impacts are rarely available, however based on the published literature and expert opinion some assessments of the relative severity of different environmental impacts can also be made. Thirteen categories of environmental impact were identified from the detailed crop briefs: land degradation, wild biodiversity loss, agro-biodiversity loss, water depletion, water pollution, soil nutrient depletion, soil pollution, pest resistance, greenhouse gas (GHG) emissions (CH4), GHG emissions (N2O), air pollution (burning), storage chemicals and post-harvest losses.

We classify severity of crop environmental impacts as follows:

0. *No mentions of the environmental impact in published literature or expert accounts on the crop*
1. *Rarely mentioned or a minor impact*
2. *Sometimes mentioned as a moderate impact*
3. *Consistently mentioned as a moderate impact*
4. *Sometimes mentioned as a severe impact*
5. *Consistently mentioned in published literature or expert accounts on the crop as a severe impact*

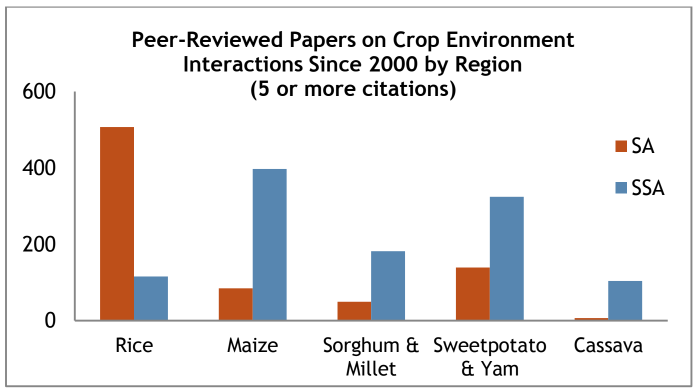
While 'percentage losses' and 'yield gaps' represent more-or-less universally accepted measures of the severity of environmental constraints on crop yields, there are no such established measures for evaluating the environmental impacts of crop production. Ultimately conclusions on the relative severity of crop-related environmental impacts depend on one's weighting of economic versus ecological perspectives, physical science versus social science, and academic versus grey literature (as reviewed in the individual crop briefs).

Nevertheless the rough categorization above provides some indication of the relative importance of different environmental impacts both within crops and across different crops as judged by the academic and expert communities to date. Further detail can be found in the accompanying briefs on each crop. To a large extent, however, assessments of the severity of crop-environment interactions also depends on how much we know about the issues, i.e., how much research has been completed on a particular problem. This leads to our third criterion.

III. Depth of Research on Crop-Environment Interactions

Without making normative judgments on the types, relevance or quality of research available we can nevertheless evaluate the quantity of peer-reviewed published research available on different crop-environmental interactions to date. The number of studies conducted on various aspects of crop-environment interactions is highly uneven across crops, across environmental impacts, and across regions and continents. The quality and depth of studies conducted also varies by crop.

Counts of peer-reviewed articles published on environmental interactions for different crops as reported in the academic database *Scopus* from 2000 to 2013 provide quantitative information on the degree to which environmental problems have received academic attention in scholarly debates. These counts are given for each crop for the 13 categories of environmental impact mentioned above, as well as summarized across crops in a final overview chart. In an attempt to ensure only quality papers were included in the counts, we eliminated all papers that Scopus reported had been cited fewer than five times.



Many large-scale environmental concerns are commonly demonstrated more broadly for the agroecology or farming systems in which certain food crops are grown, rather than specifically for individual crops. The loss of biodiversity associated with agricultural activity is a good example, with relatively more general publications available than crop-specific research. Meanwhile some environmental impacts such as climate change can be found globally, often well away from the origin of their causes. To the extent that only general studies (rather than crop-specific or region-specific studies) exist on a given environmental problem this limitation is also noted here.

Finally, while some environmental impacts of smallholder agricultural systems are consistently reported in the literature (indicating a relatively strong understanding and/or consensus on these impacts) others are not (perhaps indicating the need for more research, especially for more serious impacts). In other cases scientific consensus for a given environmental impact is high but much of the literature for a constraint with a crop or farming system is more than 10 years old, presumably reflecting earlier interest in the issue. One example may be the significant amounts of older work published on soil losses from agricultural systems. In such cases, the possibility that the existing scholarship may be outdated is also acknowledged here and in the ensuing crop-environment briefs.

Major Crop Systems in SSA and SA

The crops studied in the Agriculture-Environment Series are very important in at least four major farming systems in SSA (according to the farming systems descriptions in Dixon *et al.*, 2001). The Root Crop system extends from Sierra Leone to Côte d'Ivoire, Ghana, Togo, Benin, Nigeria, Cameroon and the Central African Republic, in the moist sub-humid and humid agro-ecological zones. There is a similar strip further south in Congo, DR Congo, and northern Angola. Food crops cultivated include yams, cassava and sweet potato, with sorghum, maize and rice in some areas. North of the Root Crop system, the Cereal-Root Crop Mixed system extends from Guinea through northern Côte d'Ivoire to Ghana, Togo, Benin and the mid-belt states of Nigeria to northern Cameroon, the Central African Republic, Chad and South Sudan. Of the food crops examined in the briefs, sorghum, millet, cassava, yams, sweet potato, maize and rice are all grown. The Maize Mixed system is the most important food production system in East and Southern Africa, extending across plateau and highland areas at elevations of 800 to 1600 meters above sea level, from Ethiopia, Uganda, Kenya and Tanzania to Angola, southern DR Congo, Zambia, Malawi, Mozambique, Zimbabwe, South Africa and Swaziland. Of the crops studied, maize is often dominant in this system, with some cassava, millets, sorghum and sweetpotato. Finally, the Agro-Pastoral (Millet/Sorghum) system is found in the semi-arid zone of West Africa from Senegal and Mali to Niger, Chad and Sudan, and across East and Southern Africa from Somalia, Ethiopia and Tanzania to Angola, Botswana, Zimbabwe, Namibia, Mozambique and South Africa. Sorghum and pearl millet are important crops in these areas, with some maize.

In addition to the four major SSA farming systems above, some of the root crops and maize are also found in other humid SSA systems such as the Humid Lowland Tree Crop system of West Africa, the Forest Based system in Central Africa and the Highland Perennial system in East Africa. Rice is increasingly important in the small but widely-distributed Irrigated system.

At least five other farming systems significantly incorporate these same crops in SA. The Highland Mixed system extends across the hills and valleys of the Himalayan range, from Afghanistan, Pakistan, India, Nepal to northeastern India, as well as in isolated areas of Kerala and central Sri Lanka. Among the crops in this study, rice and maize are very important in this system. The Rice system is concentrated in Bangladesh, West Bengal and Orissa, but smaller areas are found along India's eastern coast and into Tamil Nadu and Kerala states, as well as in southern Sri Lanka. In this system two-season rice (rainfed and irrigated) is important, with some maize, and some cassava in the south. The Rice-Wheat system forms a broad swath across northern Pakistan and India, from the Indus irrigation area in Sindh and Punjab, across the Gangetic plain to northwestern Bangladesh. This system provides the bulk of the marketed food grains that feed the cities of SA. Rainfed and irrigated rice and maize are important, with some sorghum. The Rainfed Mixed system occupies a very large area in central, south central and southern India. Rice, rainfed maize, sorghum and millets are all found. Finally the Dry Rainfed system is in the `rain shadow' area of the western Deccan in India. Sorghum and millets are important, with some other irrigated cereals.

Crop-Environment Interactions through the Value Chain

Pre-Production: Overcoming Land Constraints & Sustaining Biodiversity

For all crops, cropping decisions (including the choice of crop or variety to plant) are directly shaped by the availability and quality of land. In areas where land suitable for crop production remains relatively abundant – such as in much of Sub-Saharan Africa – the dominant response to land constraints continues to be conversion of forests, grasslands and other non-agricultural land to crops. In South Asia, where land is now relatively scarce, farmers have primarily responded to land constraints through a process of intensification over recent decades, involving multiple cropping, typically facilitated by the adoption of irrigation, organic and synthetic fertilizers, and pesticides. In both cases – whether expanding agricultural production onto new land, or intensifying agricultural production on existing cropland – cropping decisions have direct and often significant impacts on land cover, soil structure and soil nutrients, as well as implications for on-farm and off-farm biodiversity (Stevenson *et al.*, 2014).

Key environmental impacts from agricultural expansion and intensification broadly include:

- *Land degradation and erosion*: Land clearing exposes land to physical and chemical degradation, as well as contributing to air pollution. Over-cultivation and tillage of degraded and marginal lands damages soil structure, drives soil loss through erosion processes and reduces water retention capacity. Loss of vegetative cover also worsens wind and water erosion on sloping uplands (Bai *et al.*, 2008). Land clearing and tillage may also have environmental impacts in the form of fossil fuel use for machinery, or forage/feed production and GHG emissions associated with draft animals.

- *Loss of wild biodiversity both off-farm and on-farm*: Cropland expansion, cropping intensification and repeated plantings can negatively affect wild biodiversity directly (e.g., removal of tropical forests, habitat loss, or pesticides killing non-target organisms), as well as indirectly (by disrupting the breeding cycles and destroying habitats of sensitive species) (Phalan *et al.*, 2011).

- *Loss of food crop genetic diversity*: Shifts to more-intensive farming systems often reduce the number of crop species in agro-ecosystems. Replacement of multiple locally-adapted and genetically diverse crop landraces or varieties with a smaller number of modern varieties reduces local and regional agro-biodiversity; in some cases increasing vulnerability to drought, pest infestations and other abiotic or biotic threats (Snapp *et al.*, 2010; Altieri & Nicholls, 2004).

- *Climate change*: GHG emissions (such as carbon dioxide, methane and nitrous oxide) from crop fields tend to increase with increased cropping intensity, and with conversion of forests/grasslands to food cropping. Carbon dioxide emissions arise primarily from land conversion (releasing carbon stored in forests), soil tillage (releasing soil carbon) and post-harvest burning of crop residues. Other major GHG sources are crop-or system-specific: methane emissions are primarily associated with flooded rice fields, for example, and nitrous oxide emissions arise from nitrogen fertilizer application (Reay *et al.*, 2012).

The ultimate environmental and productivity-related impacts of land-use decisions are not only direct, but also systemic and cyclical in nature. For example, in addition to the intrinsic value of biodiversity loss on-farm and in the wild, biodiversity impacts stemming from land-use decisions may also inhibit provision of valuable ecosystem services such as pollination and pest control, with implications for future crop production. Similarly climate change, though less controllable by individual farmers, has impacts on both the global environment and on future crop production in some regions (Burke *et al.*, 2009). Consequently, interventions directed at minimizing or eliminating the environmental impacts of crops pre-production can have positive implications throughout current and future crop production cycles.

Production: Overcoming Input Constraints, Sustaining Renewable Resources, and Avoiding Pollution

Once crops have been selected and planted, various environmental factors including inadequate access to and use of soil nutrients, water availability and drought, and direct damage from pests, weeds and diseases can substantially compromise production in both SSA and SA. At the same time, common responses to these production constraints such as applying chemical fertilizers, water extraction and irrigation, and applying pesticides and herbicides can themselves pose significant environmental risks and costs for crops, wildlife and human populations.

Key environmental impacts from crop production practices include:

- *Soil nutrient depletion ("nutrient mining")*: Nutrient mining occurs when cropped soils experience negative nutrient balances, with extraction faster than the replacement of nutrients (Cobo *et al.*, 2010). Effects may be especially significant when food crops are integrated into intensive repeated rotations with inadequate nutrient management as in SA (Timsina *et al.*, 2010), or when socio-economic circumstances and limited effective technical options prevent adequate replenishment of nutrients on already depleted soils, as in much of SSA (Shiferaw *et al.*, 2011; Vanlauwe *et al.*, 2010).

- *Soil and water contamination*: Excessive applications of synthetic nutrients can aggregate in soils, and runoff nutrients can accumulate in rivers and lakes and leach into groundwater (Fageria, 2011). Already a severe problem in large parts of SA, contamination/accumulation is only a local issue in SSA (where fertilizer underuse is predominant) but will grow where systems intensify. Overuse of synthetic nitrogen (N) is also a major source of global GHG emissions (associated with its manufacture and use). In intensive systems, excessive use of fertilizer may lead to soil acidification, while overuse of pesticides may contaminate soil and water-bodies and can clearly be inefficient in terms of crop yields (Gupta, 2012).

- *Water depletion*: Drought and water shortages represent significant constraints to crop yields and cropping areas (Li et al., 2011; de Fraiture *et al.*, 2010). Introducing efficient irrigation technologies can address water constraints to a degree, however the shortage and depletion of surface water (especially in SSA where irrigation is poorly developed) and groundwater resources (mainly in SA where more advanced irrigation systems already exist) are growing problems (Wada et al., 2010; Ali et al., 2009).

- *Pest resistance, outbreaks and new pests and diseases*: Pests and diseases can be so devastating for some crops that they severely restrict cropping, as is the case with viral diseases of cassava in parts of East Africa. Application of pesticides and shifts towards pest- and disease-resistant crop varieties have gone hand-in-hand with the emergence of resistance in some pests, sometimes resulting in devastating outbreaks (Oerke, 2006). In other cases, efforts to address crop production constraints have inadvertently introduced new pest and disease problems – for example, the use of new early-maturing varieties of sorghum and millet to overcome drought constraints has exposed grains to fungi and molds that now devastate harvests in some regions.

The production constraints and impacts of greatest significance vary by crop and by farming system, but several general claims repeatedly appear in the literature on agriculture and the environment. Minimal tillage and the retention of crop residues can often reduce soil erosion, sometimes raise yields, reduce GHGs and support soil fertility. For many crops in SSA smallholder cropping systems, implementing rotations and intercrops, along with organic manures and targeted small amounts of synthetic fertilizer all frequently raise yields while also improving food system stability (reducing risks of total crop failure) and diversity of foods produced (e.g., Thierfelder *et al.*, 2012). Efforts to overcome water constraints on crop production in smallholder systems include irrigation and other water management practices or the use of diverse and drought resistant varieties, depending on local contexts (Li *et al.*, 2011). Finally, integrated pest management approaches to biotic constraints – including judicious use of pesticides but relying primarily on interventions supporting crop health and discouraging pest outbreaks (e.g., through intercropping and use of 'push-pull' systems to attract and trap pests) – have seen growing effectiveness and acceptance among farmers.

Advances in crop breeding also promise to alleviate some environmental constraints and reduce negative environmental impacts of crop production. Nevertheless, to date the effectiveness of modern varieties for advancing smallholder productivity has been mixed. For example, 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). And many of the advances with hybrid maize crops have focused on high-input systems typical of industrialized 'Western' agriculture rather than lower-input systems used by most farmers in SSA and by many in SA (although some improvements in tolerance to abiotic stresses such as drought have been made). At present there are still traditional varieties that, though lower-yielding under ideal conditions, out-perform many modern varieties in times of drought or input scarcity, making these varieties more attractive to risk-averse smallholders. Appropriate choice of crops and improved varieties combined with management options such as modified planting dates and fertilizer use offer substantial opportunities for smallholder farmers to mitigate the effects of climate change in SSA (e.g., Waha et al., 2013).

Post-Production: Improving Processing, Storage and Waste Management

Post-harvest losses of crops carry the burden of all resources consumed in creating the harvest that was lost. Reducing post-harvest losses from poor processing or storage pests therefore reduces the unit weight or unit area environmental impact of a given crop harvest each year. Improved small-scale on-farm storage methods involving air-tight plastic bags and metal or plastic drums are very effective for the cereals (e.g. Tefera, 2012), while better storage in the soil and improved processing methods are especially useful for root crops like cassava.

Other crop- or system-specific environmental impacts of post-production include:

- *Emissions from crop residue burning:* The burning of crop residues contributes to the emission of GHGs (Smith *et al.*, 2008; Lal, 2005; Andreae & Merlet, 2001) and also harms local air quality, contributing to respiratory ailments. It is also a source of lost organic C that could otherwise be used to stabilize soil structure and maintain soil fertility.

Caveats and Limitations to Crop-based Analyses

There are of course important caveats to these crop-based environmental reports. First, as emphasized in this initial overview, evidence on environmental problems in smallholder crop production systems is uneven across regions and ecologies – and hence the appropriateness or ultimate effectiveness of some best practices in some contexts is not yet known. Second, appropriate strategies to overcome constraints and minimize environmental impacts will vary widely based on contextual factors, such as local environmental conditions, market access, cultural preferences, production practices and public policies.

Finally, and perhaps most importantly, while these briefs adopt a crop-specific focus looking at rice, maize, sorghum/millets, sweetpotato/yams, and cassava independently, as we discussed earlier, in practice farmers grow these crops in diverse and sometimes complex farming systems. Thus the degree of interaction of crops with the environment varies widely across agro-ecological zones and across the many farming systems within SSA and SA. Combinations of crops are important in several farming systems, so that for those systems the environmental effects and impacts are a summation of contributions from several single crops, and there may sometimes be complex interactions between the multiple crops in the systems and the environment. Additionally, livestock are important in many of the systems and these also interact with the crops and environment.

These concerns vary depending on crop distribution in the systems. Some of the crops studied are widely found in many of the systems, although they dominate in few. For example, because of their diversity, millets are grown in most of the SSA farming systems, ranging from tef in the Highland Temperate mixed system in Ethiopia, through finger millet in the Maize mixed, to pearl millet in the Agropastoral system. Cassava and maize are important across many of the systems in SSA but dominate in one or two. In SA, maize is now widely grown across most of the SA farming systems described earlier.

The different crops may have contrasting roles in the farming system and different types and degrees of environmental interaction. For example in the Maize Mixed and Cereal-Root Crop Mixed systems in SSA, maize may often be found as an initial crop associated with land clearing and slash-and-burn agriculture, while cassava may be a last resort-crop on exhausted fields in those systems before the fields are returned to bush fallow. Intensive cultivation of rice in the Rice and Rice-Wheat systems of SA will have far greater impacts on soil nutrient depletion, and water and pesticide contamination than does sparse low input and output sorghum and millet production in the Agropastoral system of SSA.

Also, the types of environmental impacts may differ widely for the same crops in different systems. For example, while rice and maize are often associated with substantial soil erosion on hill slopes in the Highland Mixed system of SA, those same crops may be associated more with the buildup of pests and weeds on the intensively cultivated flatland in the SA Rice system.

In some of the systems, other food or cash crops that were not included in this series of briefs may also be very important and have significant environmental impacts – soil degradation through tillage for wheat for example in the Rice-Wheat system in SA. Various grain legumes/pulses are also often very important in many of the farming systems in both SA and SSA, and may have some positive environmental impacts such as through the fixation of N and conservation of soil.

We should also reemphasize that a large body of important research on relevant environmental issues has been conducted without reference to crops and cropping systems. Examples would include soil erosion (which is often assessed for a watershed, soil catena or soil type), the environmental impacts of pesticides (often associated with biodiversity or human health studies) and much of the work on climate change. Since it is not crop-specific, some of this broader work will not have been captured in the literature surveys reported here.

Developing Best Practices in the Crop-Environment Nexus

All agriculture inevitably changes the natural environment. However in many instances harm to natural ecological systems is either unnecessary (i.e., all or, more commonly, part of the ecosystem could be maintained without significant losses in food output) or outright undesirable (since a wholly or partially intact ecosystem could provide more benefits in terms of local or regional food production than another parcel of marginal cropland).

In virtually all crop systems, yield gains can be realized – and many environmental damages averted – through the relatively well-understood interventions of (i) improved water management, including proper soil preparation, crop selection and timing of planting to reduce runoff and utilize available water resources even in the absence of irrigation (Pretty *et al.*, 2011; Pretty *et al.*, 2006); (ii) improved soil fertility management, including ensuring farmers do not over-use fertilizers, the use of crop rotation (where feasible), intercropping with leguminous species, and incorporating agricultural residues (Fageria, 2011;Vanlauwe *et al.*, 2010; Singh *et al.*, 2009), and (iii) improved pest (plus disease and weed) management through integrated pest management (IPM) techniques, including judicious pesticide use (Williamson et al., 2008). Pre-production decisions (sparing marginal lands and ecologically important areas from cropping) as well as efforts to reduce post-harvest losses through improved storage methods and facilities (World Bank, 2011) are additional general considerations to mitigate environmental impacts that apply across all crops and regions.

However most appropriate responses to environmental problems must be context-specific (Waddington et al., 2010), and lessons learned in one region may only be loosely applicable to the same crops being grown in a different region with a different ecological and social context (Pingali, 2012). Moreover "best" practices in a given place may change over time with changing crop systems and a changing climate (Lobell *et al*., 2011).

The ensuing pages – with their summaries of crops and literature surveys, and the expanded briefs that they serve to introduce – attempt to provide a framework for considering the potential environmental costs, environmental benefits, and social-environmental tradeoffs associated with alternative food crops and cropping practices in SSA and SA.

Rice Production Systems in SSA and SA: Summary of Crop-Environment Interactions

Rice is the most widely consumed food crop of the developing world, and includes two species (*Oryza sativa,* native to the Asian continent, and *Oryza glaberrima,* native to Africa) grown on over 155 million (M) ha worldwide. In both the dryland upland rice systems predominant in SSA and the irrigated rice systems of SA, the single most significant environmental constraint to rice production is water: rice is 2-10 times more water intensive than other major crops (Bouman *et al*., 2007). Other constraints include inadequate soil nutrients (Waddington *et al*., 2010; Witt *et al*., 2007), weeds (in non-flooded systems), insects, rodents and assorted other pests. Especially in SA, agricultural intensification including the adoption of improved irrigation, fertilizers, improved seeds, and pesticides has contributed to dramatic gains in rice yields since the 1960s (Dawe *et al.,* 2010). However, increasing evidence suggests intensive rice systems, if not properly managed, can cause serious environmental harm by reducing soil fertility, polluting soil and water, depleting groundwater, using large amounts of fossil fuels for water pumping, and contributing to climate change. Many of these issues are especially acute for high-yield intensive irrigated winter season rice, which has become very important in parts of SA in recent decades. Flooded rice fields are also associated with an increase in malaria transmission among farmers, workers, and communities adjacent to flooded rice-producing areas in both Africa and Asia.

Crop-Environment Interactions in SSA Rice Systems

Most smallholder rice production in SSA is rainfed and low-input (and also low-yield) upland rice. Major environmental constraints in the region include water constraints, making up as much as 10-31% of the rice yield gap in SSA, nutrient constraints (15-30% of the yield gap) and weeds, especially where flooding is not an option for weed control (Waddington et al., 2010; Dobermann & Fairhurst, 2000). The overall rice area remains relatively modest in SSA, but recent trends in area expansion for rice have been dramatic: with the rice area harvested more than doubling between 1980 and 2010, from 4.7M to 9.3M ha (FAO, 2012). Some of this expansion is due to intensification (shifts from one to two crops per year) made possible by irrigation and the introduction of Asian *sativa* varieties into lowland and wetland areas of SSA (Larson et al., 2010). But for most smallholders, rainfed rice-fallow production (one crop per year) remains common (Dawe *et al*., 2010).

Relative Severity of Environmental Impacts

Africa's largely dryland rice systems are relatively insignificant contributors to environmental impacts typical of more intensive rice systems, such as water resource depletion, methane emissions or chemical runoff (Yan *et al.,* 2009). The key environmental threats from extensive low-productivity rice in SSA take the form of degradation of fragile and erosion-prone uplands (Bai *et al*., 2008), or expansion of new *sativa* flooded rice production into ecologically important lowland/wetland ecosystems. The relatively recent introduction of irrigation into rice production in SSA has been linked to dramatic increases in rice productivity — in 2009 only 14% of rice area in the region was irrigated, but this area made up 33% of total rice produced (Africa Rice Center, 2009). Intensification also entails impacts such as chemical runoff and greenhouse gas (GHG) emissions.

Research on Environmental Interactions and Areas of Debate

Research on environmental impacts of rice is limited in SSA. No estimates of impacts such as land conversion or biodiversity loss attributable to upland rice are available, though some research is underway (Phalan *et al*., 2011). Research on environmental impacts in new irrigation-based rice systems in SSAlags behind research on production, and since there is very limited local information, current reviews of SSA rice environmental impacts largely draw on the Asian experience with rice intensification (Larson *et al*., 2010). Site-specific (and somewhat more contested) studies on improved soil and water management in SSA such as the System of Rice Intensification (SRI) suggest significant opportunities for increasing yields, water efficiency and pest management in SSA.

Crop-Environment Interactions in SA Rice Systems

Smallholder rice production in SA is principally under rainfed conditions during the monsoon season, but increasingly also under irrigation pre-monsoon. Almost all farmers use synthetic fertilizers (often at high rates) and pesticides. Water constraints remain a problem, accounting for 23% of rice crop losses in irrigated SA rice and rice-wheat systems (Li *et al.,* 2011). Shortages of soil nutrients are also constraints, particularly nitrogen (N), phosphorus (P) and potassium (K) (Waddington *et al*., 2010; Witt *et al.,* 2007). Pests, including insects, rodents and disease also significantly reduce rice yields (Singleton *et al.,* 2010; Mejia, 2004).

Relative Severity of Environmental Impacts

Rice production in SA has many known environmental impacts, with water depletion, water contamination, pest resistance and GHG emissions among the most severe. Irrigation is a key driver of water depletion in SA, with 50% of all irrigation used for rice (Wada *et al.,* 2010). Meanwhile overuse of synthetic fertilizer and other chemicals has been linked to runoff and even poisonings, partly owing to input use beyond prescribed levels (Peng *et al.,* 2006). Historically, overuse of insecticides for rice has also reduced populations of pests' natural enemies, leading to outbreaks (Heong & Schoenly, 1998). More recently, rice systems are believed to constitute 10% or more of global methane emissions annually, with GHG emissions concentrated in the flooded rice fields of India and China (Yusuf *et al.,* 2012).

Research on Environmental Interactions and Areas of Debate

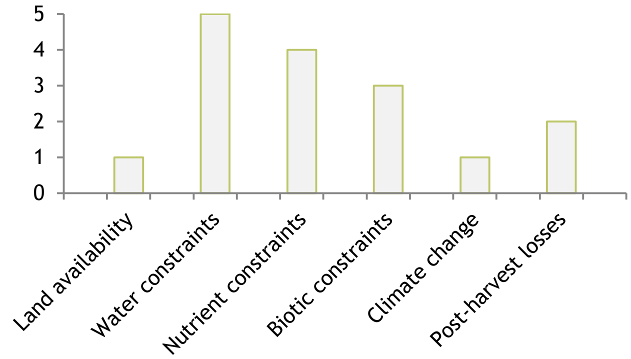
There is a wealth of published research on the environmental impacts of rice production in SA, including recent reviews (Pandey *et al.*, 2010). Rice pre-production (land clearing) is relatively under-studied but also fairly low-impact: as most potential arable land in SA has already been converted to agriculture, the new biodiversity and habitat impacts of rice are presumed minimal. However, continued blanket rice cropping means there is little possibility for the return of some land to 'natural' agro-ecosystems. Meanwhile the effects of rice farming on soils and chemical runoff rates vary by system and by crops planted between rice harvests, though there is rising consensus on the non-sustainability of intensive pre-monsoon/winter irrigated rice systems. There is also increasing consensus on the role of irrigated rice in methane emissions. High financial (as well as environmental) costs of irrigated winter rice production are already encouraging farmers on the Gangetic plain to scale back on this production system. Myriad improved land and crop management practices, including direct seeding, improved fertilization and effective weed control can improve crop yield while minimizing environmental impacts (Tuong *et al.*, 2005).

Rice Production Systems in SSA and SA: Overview of Current Knowledge

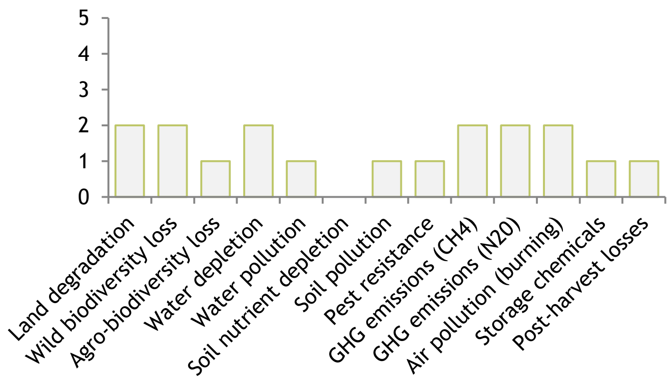
Far more published research is available for environmental impacts of Asian rice production systems as compared to African rice systems. Moreover the environmental impacts of rice production in South Asia are generally more severe and commonly found due to the relatively chemical-intensive and irrigation-based production practices typical of widespread double-crop South Asian rice production (including for smallholders).

Crop-Environment Interactions in SSA Rice Systems

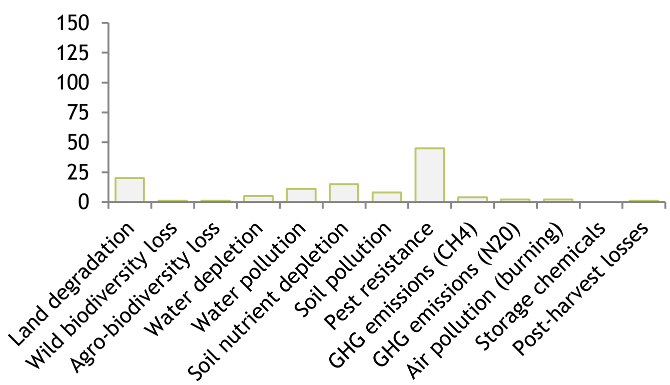
Relative Severity of Rice Environmental *Constraints* (SSA)



Relative Severity of Rice Environmental *Impacts* (SSA)

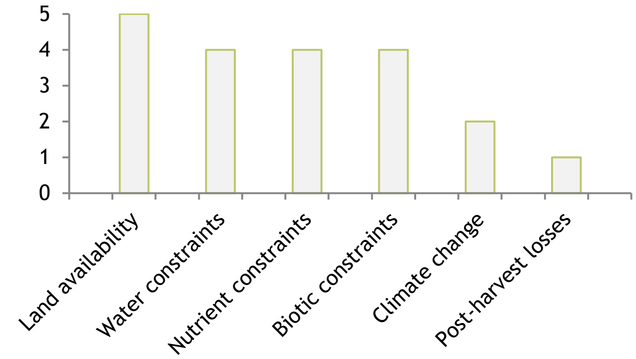


Research on Rice-Environmental Interactions in SSA

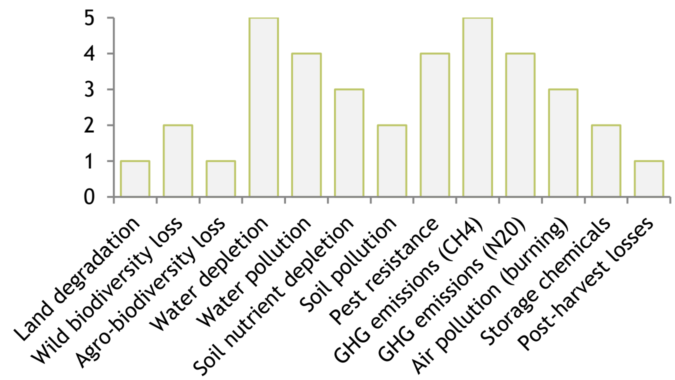


Crop-Environment Interactions in SA Rice Systems

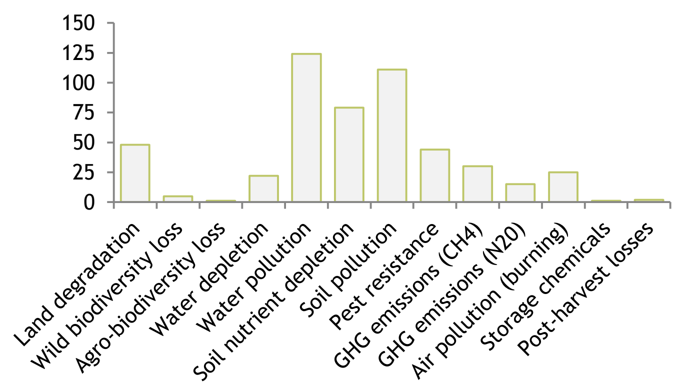
Relative Severity of Rice Environmental *Constraints* (SA)



Relative Severity of Rice Environmental *Impacts* (SA)



Research on Rice-Environmental Interactions in SA



Maize Production Systems in SSA and SA: Summary of Crop-Environment Interactions

Globally, maize is an extremely important food crop. The maize area harvested worldwide increased 53% between 1961 and 2010, from 105 Mha to 161 Mha (FAOSTAT, 2012), accompanied by trends towards the intensification of maize systems. Maize expanded during the 20th and 21st centuries in SSA to become the principle food crop produced and consumed by smallholder farm households (Shiferaw *et al.*, 2011) and is an increasingly important smallholder food and cash crop in SA. This growth stems from a combination of existing cropland converted from other crops to higher-yielding maize, maize intensification through double-harvests each year from fertilized plots, and non-agricultural land converted to agriculture. Maize is favored by farmers worldwide because of its high yields relative to other staple grains, in the presence of adequate water and organic and synthetic nutrients. However declines in soil fertility, water scarcity and biotic stressors such as weeds, pests and diseases cause substantial losses in both SSA and SA maize systems (Gibbon *et al.*, 2007; Oerke & Dehne, 2004). Maize production has also led to environmental damage, both in extensive systems (such as habitat loss, soil degradation and GHG emissions from deforestation in SSA) and intensive systems (via nutrient mining and pesticide contamination in SA). The relatively widespread and growing use of synthetic fertilizers in maize systems also releases GHGs, both during manufacture of the fertilizer and in its use. Good practices to manage the environmental impacts of maize include improved soil conservation (Hobbs *et al.*, 2008) and nutrient management (Timsina *et al.*, 2010; Vanlauwe *et al.*, 2010), as well as retaining and using biodiversity on maize fields. Many maize systems maintain high crop productivity while reducing environmental impacts, as in the traditional systems across SSA where leguminous trees or weed residues are incorporated into croplands (Ajayi *et al.*, 2011; Mapfumo *et al.*, 2005). Future climate change will likely exacerbate the severity of biotic and abiotic constraints to maize yields, including high temperature, drought and pests, and reduce the areas where maize can be grown.

Crop-Environment Interactions in SSA Maize Systems

In SSA the area dedicated to maize doubled (15.5 to 30.9 Mha) from 1961 to 2010. Maize in SSA is dominant in southern and eastern Africa where it makes up 20 to 50% of food consumption (FAOSTAT, 2010). In recent decades maize has spread in western and central SSA (Shiferaw *et al.*, 2011). Cultivation occurs primarily on small rain-fed plots, often with uncertain rainfall and poor soils, and almost always with few or no synthetic inputs.

Soil infertility and nutrient shortages represent the most severe and widespread constraints to maize yields in SSA (Mueller *et al.*, 2012). Drought is also a constraint (Gibbon *et al.,* 2007), with small changes in rainfall or temperature leading to major yield losses (Lobell *et al.*, 2011). Pests such as downy mildew, gray leaf spot, armyworm, stemborers, and the parasitic weed *Striga* also hamper maize production (Pingali & Pandey, 2000). Pests also cause post-harvest losses: the World Bank (2011) estimates post-harvest losses in SSA to be 10-20% of maize production, representing a significant waste of resources.

Relative Severity of Environmental Impacts

Land degradation, soil erosion and nutrient depletion are key environmental impacts of maize in SSA. Maize is a common first crop after slash and burn clearing since farmers value its ability to utilize nutrients released by burning to boost yields (Binam *et al.*, 2004). Deforestation destroys habitat and releases GHGs (Fargione *et al.,* 2008), with maize-related clearing in Nigeria, Ethiopia and Sudan (Phalan *et al.*, 2013). Erosion and fertility loss are also linked to maize in SSA. Efforts to improve soil management (reduced tillage, residue retention, intercropping) can reduce erosion and nutrient losses, but the adoption of conservation agriculture techniques in SSA remains limited (Erenstein *et al.*, 2012; Bossio *et al.*, 2010). Other impacts such as chemical contamination are only localized in SSA; in most areas underuse of fertilizers and pesticides is predominant.

Research on Environmental Interactions and Areas of Debate

Continuous maize production with few fertilizer inputs is a known contributor to soil nutrient depletion, but maize-specific data on land degradation in SSA are only now emerging (Cobo *et al.*, 2010). The net effects of maize on land and climate are also unclear since higher-yield maize might *decrease* land clearing compared to lower-yield traditional cereals. There is consensus that climate change impacts will be severe for rainfed maize in SSA (Schlenker & Lobell, 2010).

Crop-Environment Interactions in SA Maize Systems

Total maize area harvested in SA grew by 66% percent from 1961-2011, from 6.0 Mha to 9.9 Mha (FAO, 2012). Much of the growth in SA reflects a switch from crops such as rice, wheat, or dryland cereals to maize (Ali *et al.*, 2009). In India, farmers traditionally grow rainfed maize in the monsoon season as a supplemental source of food and income. Increasingly high-input maize is also grown during the monsoon and irrigated winter seasons to produce feed for large poultry industries (Joshi *et al.*, 2005). There are now vast (but increasingly insufficient) areas with fertile soils and developed irrigation systems growing maize in SA, in addition to the more marginal rainfed (usually upland) maize (Timsina *et al.*, 2010).

Constraints to maize in SA vary by sub-region — a 2001 survey of farmers in India found post-flowering stalk rot to be the most severe constraint to maize (Gerpacio & Pingali, 2007). Soil nutrient deficiencies are also a yield barrier (though less severe than in SSA) reducing maize output across SA by up to 14% (Gibbon *et al.*, 2007). Losses related to drought are relatively modest and mainly a concern in rainfed upland maize systems (but these key systems support some 48 million rural poor). Post-harvest losses (2-15% of production) are also significant.

Relative Severity of Environmental Impacts

In SA maize is often a high-input crop produced using hybrid seeds, irrigation, fertilizer (up to 100-200kg N/ha), pesticides and herbicides (Ali *et al.*, 2009; Joshi *et al.*, 2005). As with many intensive systems, repeated cultivation and overuse of synthetic inputs can degrade soils and contaminate soil and water. Pesticides can also destroy beneficial species that control pests; poisoning and other human health impacts have also been seen in SA (Gupta, 2012). With herbicide use, another problem has been the risk of killing crops intercropped or rotated with maize, including beneficial legumes once common in both SSA and SA maize systems (Kanampiu *et al.,* 2002).

Research on Environmental Interactions and Areas of Debate

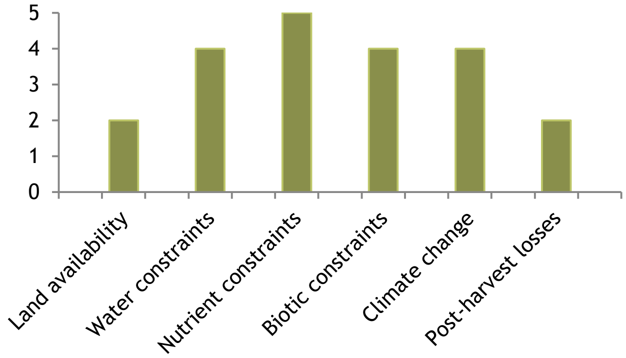
Environmental research specific to maize is very thin in SA. Maize has long been a traditional low-input crop in some areas, but is a recent arrival in intensive cropping systems. Like in SSA, the net environmental impacts of maize in SA are also ambiguous: in the face of water constraints and severe impacts from intensive rice farming, maize is seen as a relatively high-yield, water-efficient alternative crop for promoting both food production and resource use efficiency (Timsina *et al.*, 2011).

Maize Production Systems in SSA and SA: Overview of Current Knowledge

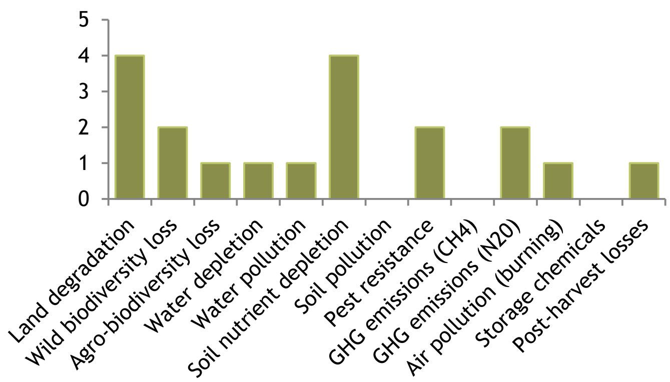
Maize production systems and environmental impacts differ across regions. In SSA maize is typically grown as the primary food crop, in rainfed systems, often on marginal soils and/or newly cleared land, and with few inputs. Thus in SSA environmental impacts of maize largely relate to land clearing and soil degradation. In SA maize is also a traditional rainfed crop in some areas, but in many others it is grown as an irrigated, high-input crop for market sale in rotation with other crops. This makes soil degradation, nutrient depletion and chemical pollution key concerns, though maize-specific data are lacking in intensive multi-crop systems.

Crop-Environment Interactions in SSA Maize Systems

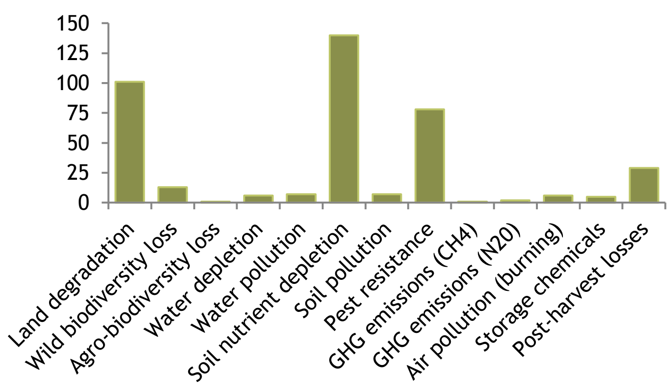
Relative Severity of Maize Environmental *Constraints* (SSA)



Relative Severity of Maize Environmental *Impacts* (SSA)

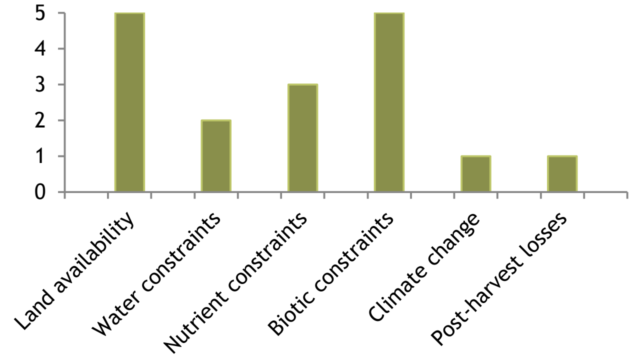


Research on Maize-Environmental Interactions in SSA

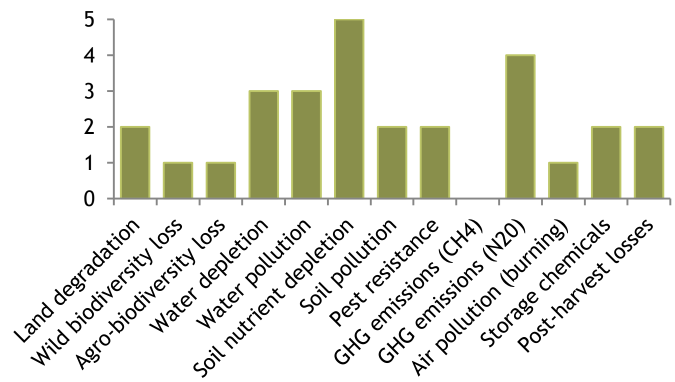


Crop-Environment Interactions in SA Maize Systems

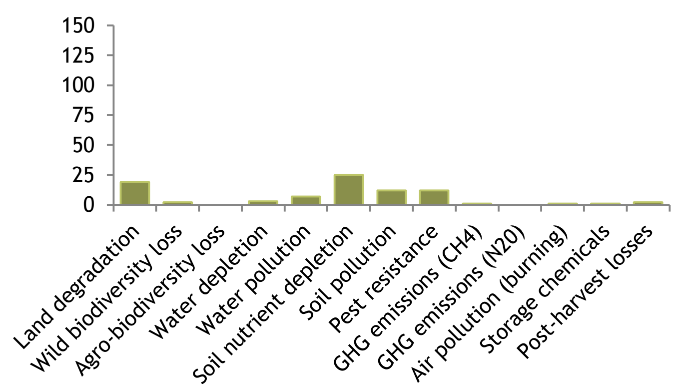
Relative Severity of Maize Environmental *Constraints* (SA)



Relative Severity of Maize Environmental *Impacts* (SA)



Research on Maize-Environmental Interactions in SA



Sorghum/Millet Production Systems in SSA and SA: Summary of Crop-Environment Interactions

Sorghum and millets (which are not a single species but rather a diverse group of small-grained annual cereal grasses including pearl millet, foxtail millet, finger millet and many others) are particularly important for smallholder farmers on drought-prone marginal lands. Sorghum and many of the millets are tolerant of low soil fertility and drought in comparison to other cereals, and are widely grown in areas with unreliable rainfall and few inputs in both SSA and SA (Waddington *et al.*, 2010; Gari, 2002). Though relatively drought-tolerant, sorghum and millets still have greatly reduced yields under drought conditions (Mutava *et al.*, 2011; Waddington *et al.*, 2010). Moreover, since the rainfall season is frequently short and intense in sorghum and millet growing regions and soil cover sparse, problems such as waterlogging, water runoff and soil erosion represent major yield constraints (Murty *et al.,* 2007; Witcombe & Beckerman, 1986). Low temperatures, low soil P, iron toxicity, acid soils, and wind damage (blown sand) also hinder crop yields, while downy mildew, insect pests, and weeds such as *Striga* cause serious losses (Tari *et al.*, 2013; Estep *et al.*, 2011; Singh *et al.*, 2009; Clay, 2004; Jeger *et al.*, 1998; Michels *et al.*, 1993). The overall environmental impacts of sorghum and millet cultivation are generally considered less severe than the effects of other major crops owing to the low-input nature of production. However the crops' adaptability to marginal soils may lead to planting on nutrient-depleted soils and sloped and erosion-prone plots that would otherwise be left undisturbed, contributing to a loss of biodiversity. Moreover, the use of sorghum and millet residues for fodder, fuel and construction has become widespread; this residue removal further exposes soils to wind and water erosion, and depletes soil nutrients for future crops. In such contexts, increasing judicious use of agricultural inputs may *reduce* environmental impacts by increasing the productivity of grain and stover, and slowing the damaging expansion of agricultural land.

Crop-Environment Interactions in SSA Sorghum/Millet Systems

In 2011 sorghum and millets accounted for 42% of cereal area and 25% of cereal production in SSA (FAOSTAT, 2012). Sorghum area increased by 76% from 1980 to 2010 in SSA, with the former Sudan and Nigeria making up much of the new area (FAOSTAT, 2012). Millets represent 10% of the area harvested for all crops in SSA and are particularly important for smallholder farmers on drought-prone marginal lands. Sorghum and millets are often low yielding (<500 kg/ha) due to genetic and environmental factors, and yield far less than the common alternative of maize in many sub-humid smallholder systems in SSA (Rurinda *et al.,* 2014). But locally adapted varieties remain very important for food security: millets including pearl millet, finger millet and "minor millets" like *fonio* or *tef* are often planted on the most marginal lands where maize and even sorghum fail (Mohammed *et al.,* 2002). In the future sorghum and millet cultivation is expected to expand in SSA as an adaptation to climate change (Cooper *et al.*, 2008).

Relative Severity of Environmental Impacts

Because sorghum and many millets are drought-tolerant and grow with few inputs, they are often produced on marginal land that is ecologically fragile (Tari et al., 2013). Shortened fallows and expansion onto marginal lands with minimal use of fertilizer has led to declining soil fertility and yields on sorghum/millet plots (Clay, 2004). Loss of on-farm biodiversity is also a concern – while historically smallholders planted multiple local varieties with different agronomic and nutritional attributes, pearl millet now makes up 90% of the millet grown in SSA (FAOSTAT, 2012). Integrating crop residues into soils is widely recommended for increasing soil fertility and moisture retention on sorghum or millet plots, and reducing CO_2 emissions (Valbuena *et al.*, 2012). But this deprives farmers of valuable fodder, fuel, and incomes from stover.

Research on Environmental Interactions and Areas of Debate

Overall literature on environmental impacts of sorghum and millets in SSA is thin. The impacts of sorghum/millets on soils in SSA have only recently begun to be studied (Fageria, 2011; Subbarao et al., 2000) while less is known about climate change, weeds, and pests with these crops. Research is also minimal on disease, post-harvest losses, biodiversity loss, and GHG emissions. Research and discussion may be hindered in part by the many species classified as millets, and by the range of (often harsh) sorghum and millet growing environments.

Crop-Environment Interactions in SA Sorghum/Millet Systems

In 2011, sorghum and millets accounted for 13% of the cereal area harvested and 5% of cereal production in SA (FAOSTAT, 2012). The area of planted with sorghum and millet in SA has declined steeply since 1980, but average yields have remained steady or increased over time owing to the adoption of improved varieties and more-intensive cultivation practices (Basavaraj et al., 2010). Sorghum and millets in SA are typically grown for grain and fodder as dryland non-irrigated crops, often in rotation with pulses or 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. In parts of SA sorghum and pearl millet are sometimes irrigated, especially to increase fodder production (Basavaraj et al., 2010).

Relative Severity of Environmental Impacts

With recent trends to intensify sorghum/millet production (Pray & Nagarajan, 2009) sorghum and millet systems in SA exhibit some of the adverse environmental impacts of other intensive crop systems, such as soil degradation, nutrient mining and water depletion. Irrigation of sorghum and pearl millet threatens already-scarce water resources in SA (Garia-Ponce *et al.*, 2012). The emergence of new pest and disease strains is another major concern in SA: early-flowering varieties of pearl millet (bred to overcome drought constraints) also expose the developing grain to wet conditions in which grain molds now thrive (Williams *et al.*, 1981).

Research on Environmental Interactions and Areas of Debate

Sorghum and millet production impacts in SA are rarely studied alone, but rather are treated in the literature on the multi-crop systems of which they are a part. The volume of research on the environmental impacts of sorghum is only slightly more than that of millets in SA. Water constraints and drought, and soil nutrient limitations are considered to be important with sorghum and millets in SA, but the roles of climate change, weeds, and pests are less clear. There appears to be very little published on diseases, post-harvest impacts, biodiversity loss, and GHG emissions in sorghum and millet smallholder cropping.

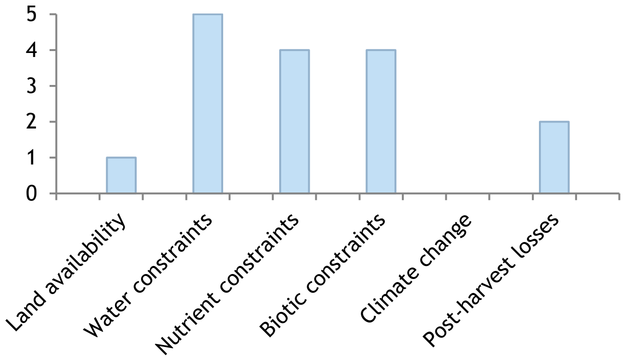
Long considered to be minimally damaging to the environment, more recent research emphasizes the contribution of intensively cultivated sorghum and millets to broader and important soil and water problems threatening intensive SA food cropping systems.

Sorghum/Millet Production Systems in SSA and SA: Overview of Current Knowledge

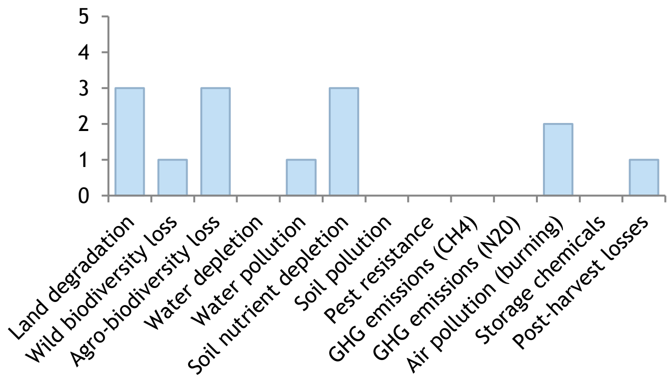
Sorghum and millet production systems and environmental impacts differ vastly across regions. In SSA sorghum and a wide variety of millets (though increasingly pearl millet is predominant) are typically grown as the primary food crop in rainfed systems on extremely poor marginal soils with no synthetic inputs. In stark contrast, in SA most sorghum and millet cultivation is irrigated and high-input, grown for market sale in rotation with other crops. Consequently in SSA the environmental impacts of sorghum and millets largely relate to land clearing and degradation on marginal soils, while in SA soil nutrient depletion and agro-chemical runoff are greater concerns. In both SSA and SA, sorghum and especially millets have suffered from a dearth of empirical research, both on environmental constraints and environmental impacts.

Crop-Environment Interactions in SSA Sorghum/Millet

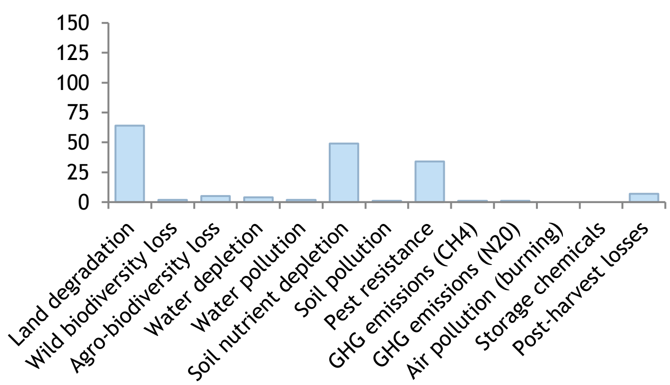
Relative Severity of Sorghum/Millet *Constraints* (SSA)



Relative Severity of Sorghum/Millet *Impacts* (SSA)

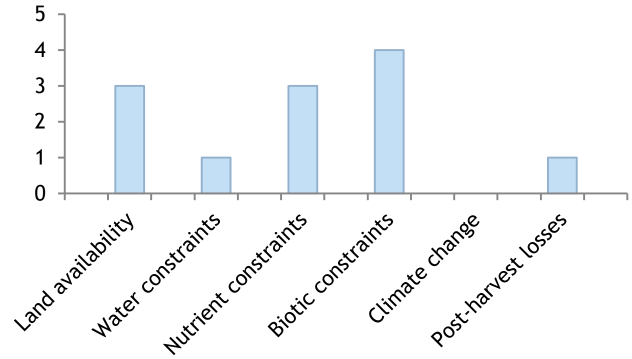


Research on Sorghum/Millet-Environmental Interactions (SSA)

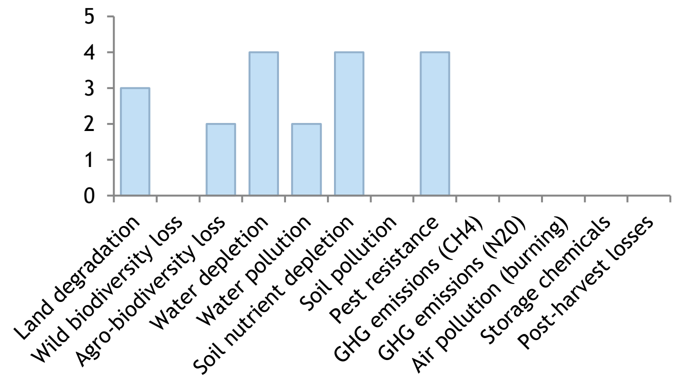


Crop-Environment Interactions in SA Sorghum/Millet

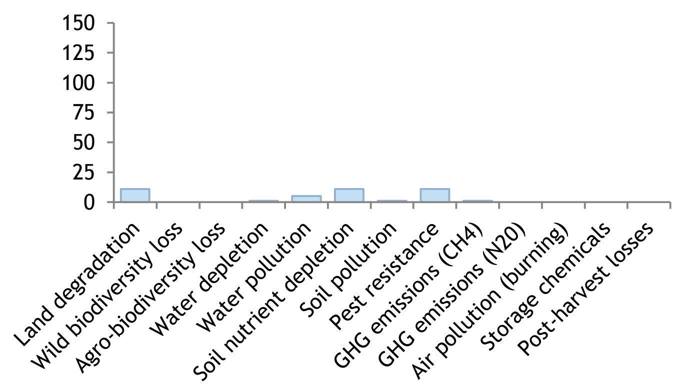
Relative Severity of Sorghum/Millet *Constraints* (SA)



Relative Severity of Sorghum/Millet *Impacts* (SA)



Research on Sorghum/Millet-Environmental Interactions (SA)



Sweetpotato and Yam Production Systems in SSA and SA: Summary of Crop-Environment Interactions

Root and tuber crops including sweetpotato, yams, and cassava represent (after cereals) the second-most cultivated food crops in tropical countries (FAOSTAT, 2012). Yam is almost exclusively grown in SSA rather than in SA, while sweetpotato is favored in both regions because of its low labor needs, low input costs and relatively low production risk (Low *et al*., 2009). Sweetpotato is also tolerant of a range of growing conditions (Edison *et al*., 2009), providing good yields even under poor soil conditions, extreme temperatures and prolonged dry seasons (Thornton, 2012; Bagambda *et al*., 2012; Kyamanywa *et al*., 2011; Claessens *et al*., 2010; Paeth *et al*., 2008). When grown with traditional methods sweetpotato and yam are considered environmentally friendly relative to most cereal crops. Both plants are easily intercropped (or grown in mounds for home gardens), and their fast growth and dense foliage help reduce soil erosion (ASARECA, 2005). Sweetpotato and yam are also low-input crops – and often grown as no-input crops (Andrade *et al*., 2009) – although some chemical pesticides are increasingly used to address major pests and diseases such as the sweetpotato weevil and the insect-borne yam mosaic virus. Recommended best practices for sweetpotato and yam production include manure application and mulching to increase soil nutrients and moisture (Bridge *et al*., 2005), as well as crop rotation, intercropping and site cleaning (burning infected plant material) to reduce pest and disease risks (Stathers *et al*., 2005). The use of disease-free growing material and judicious chemical use (e.g., dipping vines in insecticide prior to planting to delay infestations) is also recommended to mitigate potentially heavy losses from disease (Lebot, 2009). Finally, while climate change has the potential to lower the yields of many crops across SSA and SA (Srivastava *et al*., 2012), some research suggests sweetpotato and yam may be relatively resilient to climate change, and could help fill gaps left by declining production in other crops.

Crop-Environment Interactions in SSA Sweetpotato & Yam Systems

Sweetpotato and yam in SSA are largely secondary crops grown by female smallholders in polyculture systems on small plots (<0.5 ha) and often marginal lands (Ewell, 2011; Low *et al*., 2009; Andrade et al., 2009). East and West Africa account for 93% of African sweetpotato area, with intensive production around Lake Victoria (CIP, 2010). For yam, West Africa accounts for 90% of <u>global</u> area for yam production and 90% of global harvests (CIP, 2010). In addition to cropping systems, sweetpotato and yam are also widely found on small areas of mounded/ridged land in homesteads or gardens.

Yield constraints for sweetpotato and yam in SSA include drought, disease, and soil infertility. In a survey of farmers in East Africa drought was the largest production constraint to sweetpotato (Fuglie, 2007). Sweetpotato is also susceptible to viral infections, with over 15 known viruses reported (Valverde *et al*., 2007), and pest damage and vegetative propagation using contaminated vine cuttings exacerbating disease risks.

For yam, the infertility of soils is the key constraint in intensive yam-producing areas of West Africa (Lebot, 2009). Experiments in Nigeria saw yam yields decrease by 50% from 1995 and 2000 because of declining soil fertility (Agbaje *et al*., 2005). Yam is more drought tolerant than sweetpotato (Lebot, 2009), but insects and disease seriously reduce yam yields. The yam tuber beetle, scale insects and termites are major pests (Lebot, 2009); nematodes (Agbaje *et al*., 2005) and mealybugs are also threats (Peters, 2000). Anthracnose and yam mosaic virus are significant yam diseases (Amusa *et al*., 2003; Peters, 2000).

Relative Severity of Environmental Impacts

Sweetpotato and yam are considered relatively low-impact crops. Both may contribute to agricultural expansion and land degradation on marginal cropland where they are regularly grown. Use of agrochemicals for sweetpotato/yam remains rare in most of SSA (with the notable exception of Nigeria). However use of pesticides is growing in some areas (including Uganda).

Research on Environmental Interactions and Areas of Debate

Pest resistance has attracted major attention with sweetpotato; the environmental implications of this are not altogether clear, but may be quite minor. Some research suggests sweetpotato and yam may be relatively resilient to climate change, but others including Ringler *et al*. (2010) and Srivastava *et al*. (2012) suggest sweetpotato and yam yields will decrease by 14% or more, depending on soil type and scenario.

Crop-Environment Interactions in SA Sweetpotato Systems

South Asia is not a significant producer of sweetpotato compared to SSA and produces almost no yam (FAOSTAT, 2012). Due to the relative lack of land for agricultural expansion, sweetpotato production in SA is often a component of more intensive uses of existing cropland, particularly multi-crop rotations with major grains or legumes. In contrast to the low-input sweetpotato/yam systems typical of SSA, in SA both biological and chemical inputs are widely used in sweetpotato cultivation.

Key yield constraints on sweetpotato in SA include soil depletion/soil infertility, water unavailability and crop pests. Soil fertility is considered a serious constraint for sweetpotato in SA (Edison *et al.*, 2009) though estimates of the yield gap are not available. Estimates of water constraints are similarly unavailable or outdated — in an early study in Tamil Nadu, for example, Goswami *et al.* (1995) found that irrigating three times during the growing season increased sweetpotato yields by 24% over non-irrigated sweetpotato crops. More recent field trials in Orissa, India have shown intercropping sweetpotato with pigeonpea can increase soil quality, water retention and tuber yields under rainfed conditions (Nedunchezhiyan, 2011). Regional pest control research is focused on weevil damage (Lebot, 2009). Irrigation and the flooding of fields, which keeps the earth from cracking thus reducing weevil habitat, also reduced weevil in some parts of Asia (Stathers *et al.*, 2005).

Relative Severity of Environmental Impacts

Though on its own sweetpotato is considered environmentally friendly relative to cereal crops, repeated cropping of sweetpotato as part of intensive multi-crop rotations in SA threatens to degrade soils and deplete soil nutrients.

Research on Environmental Interactions and Areas of Debate

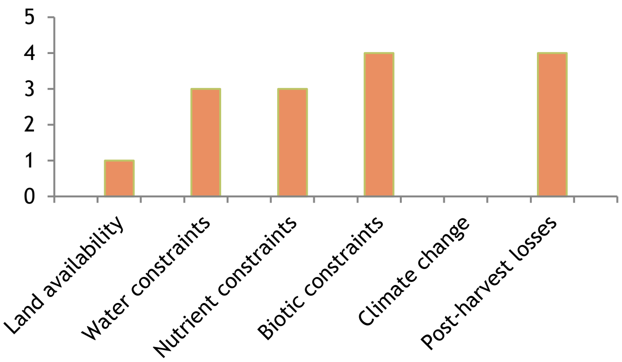
Research on both environmental constraints and environmental impacts of sweetpotato production is extremely limited in SA. Even less information is available on yam (which remains very uncommon in SA).

Sweetpotato/Yam Production Systems in SSA and SA: Overview of Current Knowledge

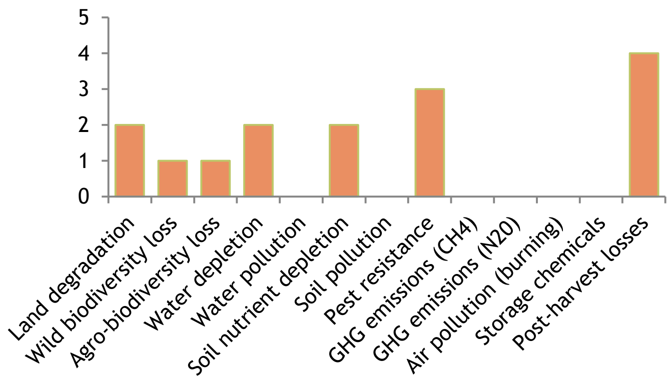
More research is available for environmental impacts of African sweetpotato/yam production systems as compared to South Asian systems, however some environmental impacts of sweetpotato/yam production in SA may be more severe owing to the relatively chemical-intensive production practices typical of South Asian systems (though not necessarily at the smallholder level). Others, like the loss of biodiversity, are relatively greater in SSA, associated with the large area in parts of the region.

Crop-Environment Interactions in SSA Sweetpotato/Yam

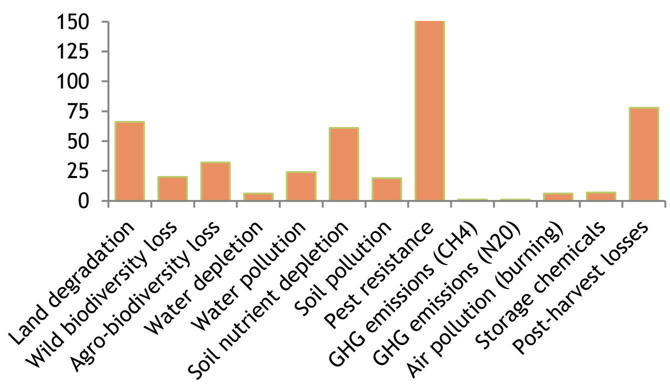
Relative Severity of Sweetpotato/Yam *Constraints* (SSA)



Relative Severity of Sweetpotato/Yam *Impacts* (SSA)

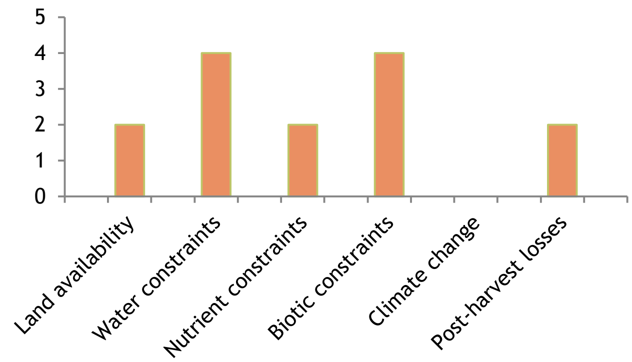


Research on Sweetpotato/Yam –Enviro. Interactions (SSA)

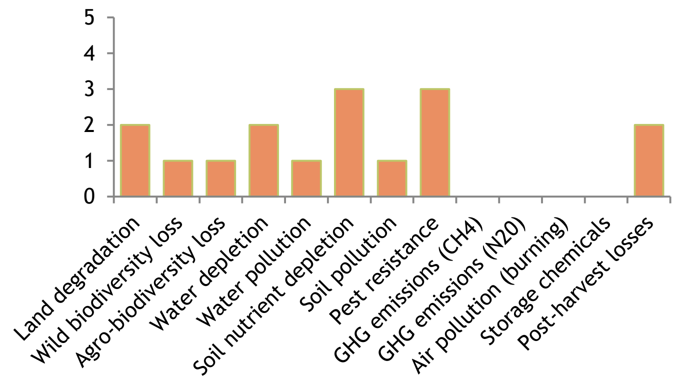


Crop-Environment Interactions in SA Sweetpotato/Yam

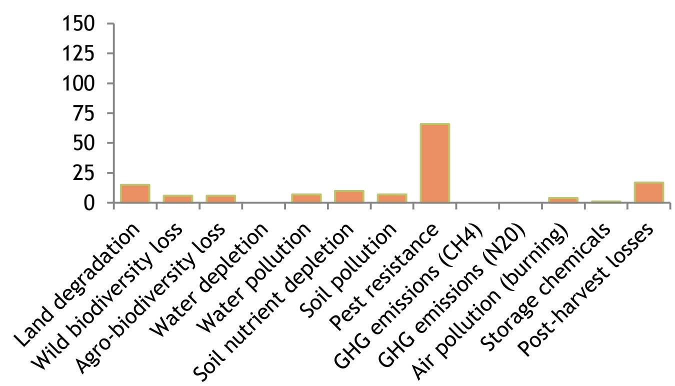
Relative Severity of Sweetpotato/Yam *Constraints* (SA)



Relative Severity of Sweetpotato/Yam *Impacts* (SA)



Research on Sweetpotato/Yam –Enviro. Interactions (SA)



Cassava Production Systems in SSA and SA: Summary of Crop-Environment Interactions

Cassava (*Manihot esculenta*) is a widely-grown staple food in the tropical and subtropical regions of Africa, Asia, and Latin America. Globally, the harvested area of cassava more than doubled between 1961 and 2010, from 9.6 Mha to 19.6 Mha. Africa produced 122 M t of cassava in 2010, or 53% of global production, followed by Asia at 33% (FAOSTAT, 2013). Traditional smallholder cassava systems are environmentally friendly in comparison to cereal crops: cassava does not require total clearing of forest for planting, it is easily intercropped, and (like other root crops) cassava can tolerate water stress better than many grain staples (Fermont, 2009a). Cassava is also grown with few inputs – minimizing environmental impacts from chemicals – although the crop tends to be grown on marginal nutrient-depleted soils and soil disturbance for root harvesting can lead to soil erosion. Biotic environmental constraints also impact cassava, particularly pests (mites, mealybugs, whiteflies (Bellotti, 2002)) and associated viral diseases (cassava mosaic disease, cassava brown streak disease (Legg *et al.*, 2006, 2011; FAO, 2010)), as well as competition from weeds. Additionally, harvested cassava roots deteriorate more rapidly than other root/tuber crops such as yam or sweetpotato, increasing the indirect environmental impacts of cassava through wasted effort in production. Best practices to manage environmental impacts of cassava include intercropping (already widely practiced) and the incorporation of crop residues into soils after harvest to maintain soil fertility (Howeler, 2002b). The use of clean planting material is key to managing diseases, while improved harvest and storage practices can reduce post-harvest losses. In the future, largely because of its tolerance to drought and high temperatures, cassava is expected to be more resilient to climate change than maize, rice, sorghum, and even millet (Jarvis *et al.*, 2012; Paavola, 2008).

Crop-Environment Interactions in SSA Cassava Systems

SSA has seen most of the worldwide increase in cassava production over the past 30 years, largely due to increased area planted rather than yield gains (Fermont, 2009b). The crop is widely grown in humid and sub-humid root crop-maize farming systems across SSA (Waddington *et al.*, 2010).

Cassava area harvested in SSA increased from 5.6 Mha in 1961 to 13.0 Mha in 2011 (FAOSTAT, 2013); thus many environmental impacts of cassava in SSA are land-use related. Cassava often occupies hillsides, drought-prone areas and acidic soils where other crops cannot be grown or only with high inputs (Hershey & Howeler, 2000). In West and East Africa, farmers frequently plant cassava on otherwise exhausted fields (e.g. Adjei-Nsiah *et al.*, 2007; Fermont *et al.*, 2008). Despite the crop's adaptability to poor soil conditions, depletion of soil fertility is an increasing challenge for cassava in many areas of SSA (Fermont, 2009b).

Viral diseases (spread by the whitefly vector) are also major concerns in SSA, especially cassava mosaic and cassava brown streak virus disease (Legg *et al*. 2011, 2014; FAO, 2010) which have devastated cassava production in East and Central Africa, sometimes leading to total losses of harvests. Meanwhile pests, including mites and mealybugs, can reduce yields as much as 80% in SSA (Bellotti, 2002), while uncontrolled weed growth can reduce yields by 95% (Melifonwu, 1994), although widely used hand-weed management substantially reduces actual losses.

Relative Severity of Environmental Impacts

Cassava in SSA is often grown in or near forested agro-ecologies so its area expansion can drive forest loss. Crop losses due to poor soil fertility are also severe in cassava systems in SSA (Waddington et al., 2010), with continuous cassava farming driving soil fertility declines (Fermont *et al.*, 2008). There is little synthetic fertilizer use for cassava in SSA, with fertilizers not available, too costly, or reserved for other (grain) crops (Fermont, 2009b; FAO, 2001). Similarly pesticides or herbicides have only local environmental impacts in SSA cassava systems since they are rarely used. However hand weeding contributes to soil erosion (Melifonwu, 1994) causing significant soil losses.

Research on Environmental Impacts and Areas of Debate

Once regarded as an environmentally benign crop, the expansion of cassava into forested and marginal lands in SSA has increased forest loss, soil degradation and erosion over time. However, despite cassava being such a widely grown and important crop in SSA, the research base on its interaction with the environment is generally thin. There is a clear need for broad-based work studying environmental impacts with cassava.

Crop-Environment Interactions in SA Cassava Systems

Although widely grown in Asia, cassava is a crop of secondary importance in South Asia. The area of cassava harvested in SA increased from 0.31 Mha in 1961 to 0.55 Mha in 1975, but has actually fallen to 0.25 Mha in 2011, in part due to yield gains through intensification and due to emerging preferences for other food crops. India is the principle cassava producer in SA, producing 8 M t in 2011 (FAOSTAT, 2013), but the crop is mainly grown only in the southern states of Kerala and Tamil Nadu, with some production in Andhra Pradesh and the northeast (Patil & Fauquet, 2009; Onwueme, 2002).

The 2011 average yield for cassava in India was 36.4 t/ha, compared to only 10.8 t/ha for SSA (FAOSTAT, 2013). Higher yields in India are attributed to fewer pests and disease and more intensive crop management, including irrigation and use of fertilizer, especially in Tamil Nadu (FAO, 2001). Production practices vary by sub-region, with about 70% of cassava in India grown as a monoculture, and 30% intercropped, especially with groundnut, vegetables and coconut (Hershey & Howeler, 2000; Onwueme, 2002). Supplemental irrigation is practiced only in the commercial cassava fields of Tamil Nadu (Howeler, 2000).

Relative Severity of Environmental Impacts

Environmental impacts of cassava production in SA include effects on soil and water attributable to the relatively intensive agricultural production practices. In the most intensive commercial cassava systems in SA, soil preparation with heavy machinery increases soil density and creates hard pans, further degrading soils (El-Sharkawy, 2006; FAO 2001), while synthetic fertilizer and pesticide application, along with intensive irrigation, can contaminate soils and water sources or deplete surface and groundwater supplies.

Research on Environmental Impacts and Areas of Debate

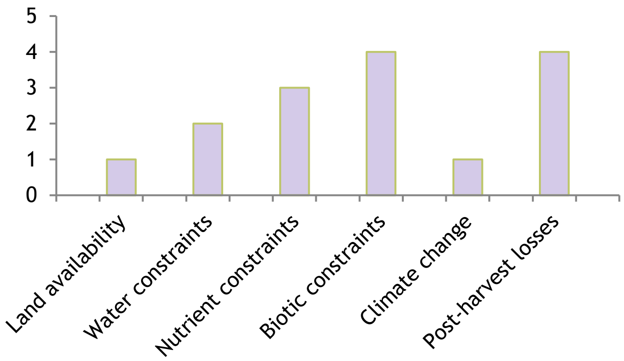
Unlike in SSA, issues with agricultural expansion seem irrelevant in SA since the cassava area is contracting. Agricultural intensification, however, can have negative environmental impacts — although such potential impacts remain under-studied in SA cassava systems. Like SSA, cassava in SA depletes soil nutrients, and it is possible the widespread use of fertilizers in SA may improve nutrient management. But as fertilizer use has become widespread in SA cassava farming systems (both directly for cassava and on intercrops) the potential for this exacerbating other environmental problems has also increased.

Cassava Production Systems in SSA and SA: Overview of Current Knowledge

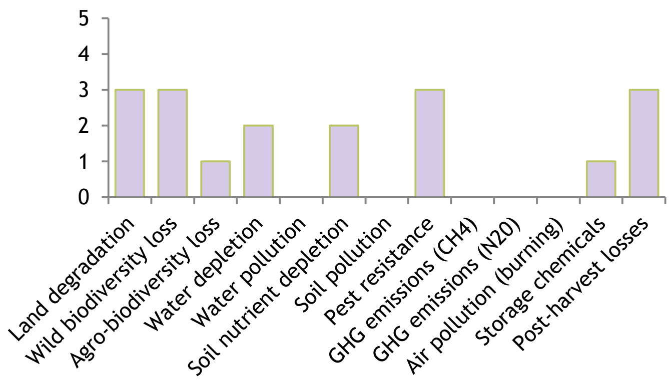
More research is available for environmental impacts of African cassava production systems as compared to South Asian systems. However some environmental impacts of cassava production in SA may be more severe owing to the relatively chemical-intensive production practices typical of South Asian systems (though not necessarily at the smallholder level). Others, like the loss of biodiversity, are relatively greater in SSA, associated with the extremely large area of cassava in the region and the important role of the crop in many areas undergoing widespread deforestation for agricultural expansion.

Crop-Environment Interactions in SSA Cassava Systems

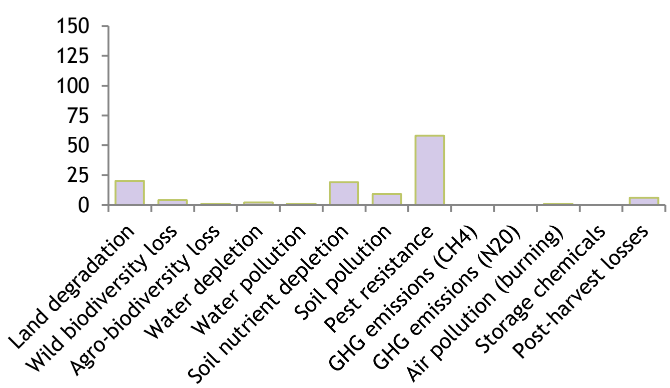
Relative Severity of Cassava Environmental Constraints (SSA)



Relative Severity of Cassava Environmental Impacts (SSA)

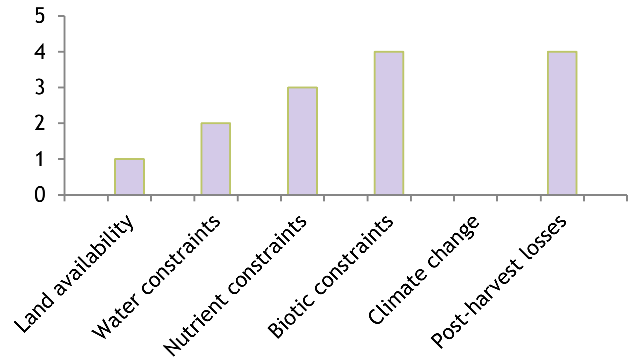


Research on Cassava-Environment Interactions (SSA)

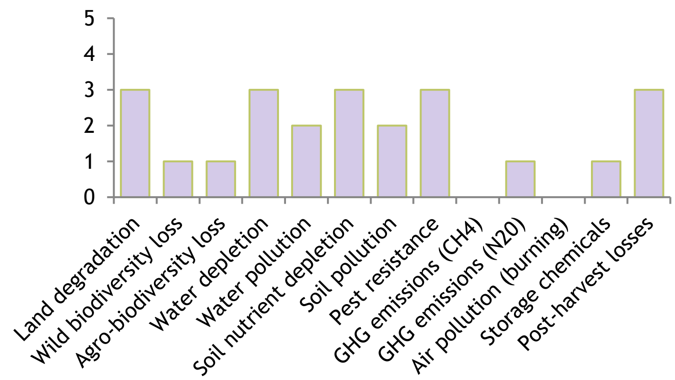


Crop-Environment Interactions in SA Cassava Systems

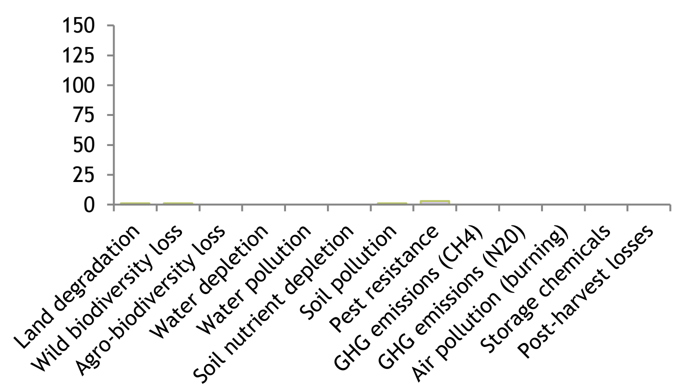
Relative Severity of Cassava Environmental Constraints (SA)



Relative Severity of Cassava Environmental Impacts (SA)



Research on Cassava-Environment Interactions (SA)



Appendix 1: Summary of Research on Crop-Environmental Interactions across Regions and Crops

Relative Severity of Crop-Environment Constraints

Although many different types of production constraint affect all food crops in SSA and SA, the relative importance of different categories of constraint varies by crop. In general, biotic constraints such as diseases and pests are frequently considered more severe for root crops than the cereals, which are affected more by various abiotic constraints, particularly those related to water and soil nutrients.

Water constraints were assessed as severe for rice in both regions, but especially in SSA (with a relative severity of 5). Land constraints were felt to be among the most severe constraints to rice in SA (rated 5), but barely featured in SSA. Nutrient constraints were felt severely in both SSA and SA (rated 4), with biotic constraints perhaps slightly less so.

For maize many different types of constraint were considered important, especially in SSA. Among these, nutrient constraints were especially severe (with a relative severity of 5) in SSA, as were land availability and biotic constraints (both rated 5) in SA. Water constraints, biotic constraints and (interestingly) climate change were all rated 4 in SSA.

With sorghum/millets, water constraints were considered extremely severe (relative severity 5) in SSA, but far less so in SA. Biotic constraints were felt to be severe, with a relative severity of 4 in both SSA and SA, as were nutrient constraints (severity of 3-4). Land availability was also considered an issue for sorghum/millets in SA.

Biotic constraints (relative severity 4) were considered the most severe type of constraint for sweetpotato/yam in both SSA and SA, while water constraints also featured highly, especially in SA (relative severity 4). Post-harvest losses (also 4) and nutrient constraints were considered important in SSA.

With cassava the pattern of importance among constraint categories was viewed very similarly for both SSA and SA. Those related to biotic constraints and post-harvest losses were felt to be the most severe (relative severity 4), followed by nutrient constraints and then water constraints.

Relative Severity of Crop-Environment Impacts

There are some notable patterns in the treatment of crop-environment interactions in the published literature to date as evidenced by a *Scopus* literature search from 2000 to 2013.

In SSA, several categories of environmental impact across the crops are well represented, especially those covering land degradation, soil nutrient depletion and pest resistance. There has been particular emphasis on the land degradation and soil nutrient depletion impacts of maize and to some extent sorghum/millets, and major attention given to pest resistance and post-harvest loss issues with sweetpotato/yam.

Other impacts, especially agro-biodiversity loss (with the curious exception of sweetpotato/yam), water depletion, air pollution, GHG emissions, and storage chemicals barely feature in the literature for our study crops in SSA. For areas such as biodiversity, air pollution and storage chemicals, one reason for this may be because much of the research in these areas is likely to be non-specific to our focus crops and so missed in our Scopus searches.

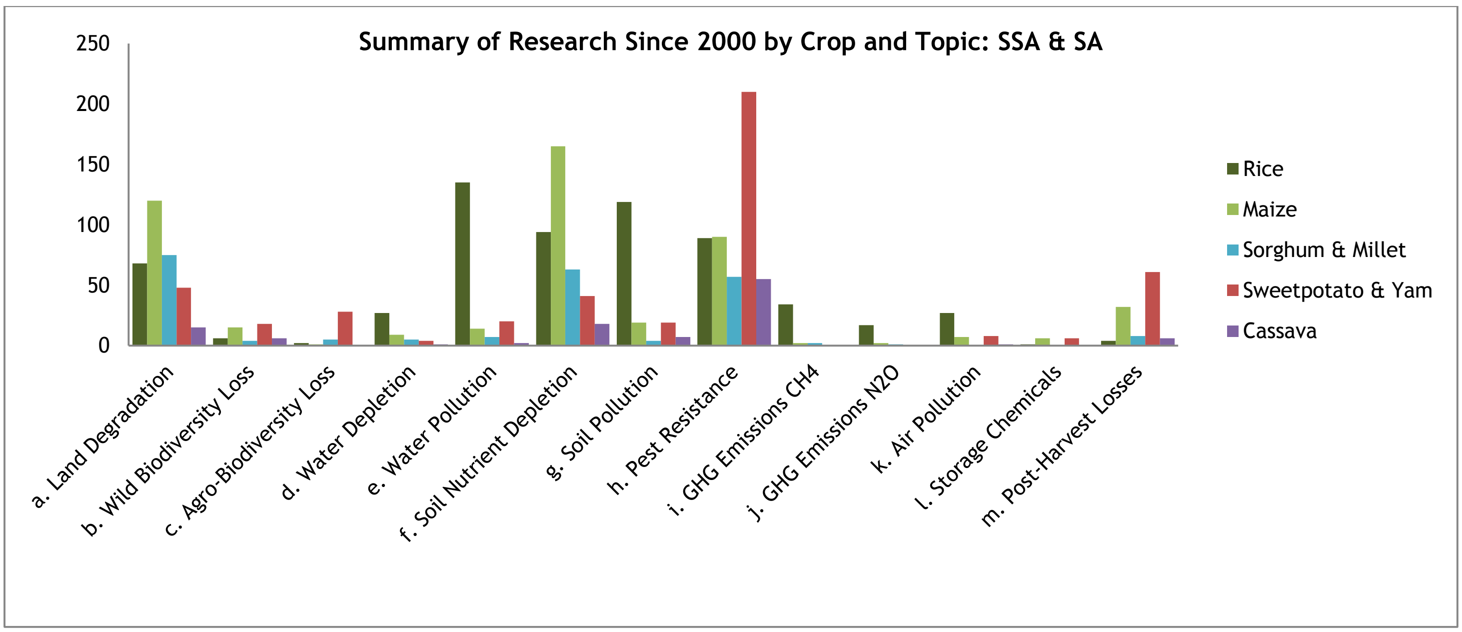
There have been some interesting changes in the amount of reported work on the topics over the period 2000-2013. The emphasis on publications that address soil nutrient depletion for maize systems in SSA was especially strong in the 2000s but appears to have declined somewhat in recent years. Several publications on soil pollution with maize have appeared during the last few years, unlike the early 2000s when there were none. In contrast to increasing research with all the other crops, there has been a decline in the number of sorghum/millet publications for several environmental issues, including those on soil nutrient depletion, pest resistance and post-harvest issues. However, interest in wild biodiversity loss has risen somewhat, as was also noted for the other cereals. With sweetpotato/yam in SSA, some of the issues that received considerable attention in the early 2000s appear to have further increased their popularity since then, including pest resistance, post-harvest losses, and land degradation.

Given the rising concern about water depletion in agriculture in SSA, the under-representation of work on this area was surprising (much of this work would be crop-related and so feature in the count) and may merit increased future support. Perhaps biodiversity loss for crops such as maize and cassava, and GHG emissions and air pollution more generally, merit more attention in SSA. Despite cassava being such an important food crop in SSA, there is surprisingly little published literature available for most potential environmental impacts. Environmental interactions may merit significant additional attention with this crop.

In SA the relative attention to different crops and different environmental factors is in clear contrast to SSA. Most of the crop-environment literature we found for SA is for rice, followed by sweetpotato/yam (which was somewhat surprising given the secondary importance of those crops in the region). As for SSA, in SA there was substantial representation of work on soil degradation, pest resistance and soil nutrient depletion in the literature. Additionally there was an emphasis (much greater than with SSA) on water pollution, soil pollution and to a lesser extent air pollution, with all three issues dominated by research for rice. Few publications were found for biodiversity and storage chemicals, while numbers of publications on water depletion and GHG emissions were intermediate but again almost exclusively reported for rice.

Looking at changes in publications over time in SA, with rice there has been a recent trend to an increased frequency of publications on soil and water pollution, and on land degradation. Only in recent years have a few papers been published on biodiversity loss in rice systems in SA. There has also been a trend to more publications on soil nutrient depletion with maize in SA over the period, while almost all those on water depletion, water pollution and soil pollution for maize started to appear only after 2005.

Cassava is a crop of some importance in parts of southern SA, but apart from a little work on pest resistance there is almost no work on environmental issues related to the crop. Some new work may be justified on subject areas that directly impact production of the crop such as soil nutrient depletion and water depletion. As maize becomes more important in SA rice systems, it is likely that it will feature more in environmental impact work that currently appears to have been almost exclusively for rice. There may be a role for additional support of research on water depletion for maize and sorghum/millets, and on ways to address biodiversity issues for the cereal systems in SA.



Works Cited

Ali, M.Y., Waddington, S.R., Timsina, J., Hodson, D. & Dixon, J. (2009). Maize-rice cropping systems in Bangladesh: Status and research needs. *Journal of Agricultural Science and Technology USA*, 3(6): 35-53.

Altieri, M.A., & Nicholls, C.I. (2004). *Biodiversity and Pest Management in Agroecosystems*. 2nd Edition. Food Products Press, Binghamton, NY.

Andreae, M.O., & Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, 15(4): 955-966.

Bai, Z.G., Dent, D.L., Olsson, L., & Schaepman, M.E. (2008). Proxy global assessment of land degradation. *Soil Use and Management*, 24(3): 223–234.

Barker, R., Meinzen-Dick, R., Shah, T., Tuong, T.P., & Levine, G. (2010). Managing irrigation in an environment of water scarcity. In *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security* (p. 333). 2.6: International Rice Research Institute (IRRI), Manila, Philippines.

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.

Cobo, J.G., Dercon, G., & Cadisch, G. (2010). Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agriculture, Ecosystems & Environment*, 136(1): 1-15.

Dixon J., Gulliver A., & Gibbon D. (2001). *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World*. FAO and World Bank, Rome and Washington DC.

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

de Fraiture, C., Molden, D., & Wichelnsa, D. (2010). Investing in water for food, ecosystems, and livelihoods: an overview of the comprehensive assessment of water management in agriculture. *Agricultural Water Management*, 97: 495–501.

Gupta, A. (2012). Pesticide use in South and South-East Asia: environmental public health and legal concerns. *American Journal of Environmental Sciences*, 8(2): 152-157.

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, 31(4): 575-584.

Li, X., Waddington, S.R., Dixon, J., Joshi, A.K., & de Vicente, M.C. (2011). The relative importance of drought and other water related constraints for major food crops in South Asian farming systems. *Food Security*, 3(1): 19–33.

Lobell, D.B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, 333(6042): 616-620.

Oerke, E.C. (2006). Crop losses to pests. *Journal of Agricultural Science*, 144(01): 31-43.

Phalan, P., Onial, M., Balmford, A., & Green, R.E. (2011). Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science*, 333(6047): 1289-1291.

Pingali, P L. (2012). Green Revolution: Impacts, limits, and the path ahead. *Proceedings of the National Academy of Sciences*, 109(31): 12302-12308.

Pretty, J., Toulmin, C., & Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, 9(1): 5-24.

Pretty, J.N., Noble, A.D., Bossio, D., Dixon, J., Hine, R.E., Penning de Vries, F.W.T., & Morison, J.I.L. (2006). Resource-conserving agriculture increases yields in developing countries. *Environmental Science & Technology*, 40(4): 1114-1119.

Reay, D.S., Davidson, E.A., Smith, K.A., Smith, P., Melillo, J.M., Dentener, F., & Crutzen, P.J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, (6): 410-416.

Schlenker, W., & Lobell, D.B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1): 014010.

Shiferaw, B., Prasanna, B.M., Hellin, J. & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security*, 3(3): 307-327.

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, UK: CAB International Publishing.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Pushpam, K., McCarl, B., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492): 789-813.

Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., & Kanyama-Phiri, G.Y. (2010). Biodiversity can support a greener revolution in Africa. *Proceedings of the National Academy of Sciences*, 107: 20840-20845.

Tefera, T. (2012). Post-harvest losses in African maize in the face of increasing food shortage. *Food Security*, 4(2): 267-277.

Thierfelder, C., Cheesman, S., & Rusinamhodzi, L. (2012). A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Research*, 137: 327–250.

Timsina, J., Jat, M.L., & Majumdar, K. (2010). Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. *Plant & Soil*, 335(1-2): 65-82.

Vanlauwe, B., Bationo, A., Chianu, J. Giller, K.E., Merckx, R. Mokwunye, U., Ohiokpehai, O. Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., & Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, 39(1): 17-24.

Wada, Y., van Beek, L.P., van Kempen, C.M., Reckman, J.W., Vasak, S., & Bierkens, M.F. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, 37(20): L20402.

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.

Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J. & Lotze-Campen, H. (2013). Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. *Global Environmental Change*, 23(1): 130-143.

Williamson, S., Ball, A., & Pretty, J. (2008). Trends in pesticide use and drivers for safer pest management in four African countries. *Crop Protection*, 27(10): 1327-1334.

World Bank. (2011). *Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa*. Retrieved from http://siteresources.worldbank.org/INTARD/Resources/MissingFoods10_web.pdf

Note: References quoted in the crop summaries below are provided at the end of this document. Please see the full briefs for additional references for each crop.

Works Cited Appendices

Rice-Environment Citations	*p. 18*	*Maize-Environment Citations*	*p. 19*
Sorghum/Millet-Environment Citations	*p. 20*		
Sweetpotato/Yam-Environment Citations	*p. 21*		
Cassava-Environment Citations	*p. 22*		

Rice-Environment Citations

Africa Rice Center. (2010). Africa Rice Center (AfricaRice) Annual Report 2009: *Increasing Investment in Africa's Rice Sector*. Cotonou, Benin.

Bai, Z.G., Dent, D.L., Olsson, L., & Schaepman, M.E. (2008). Proxy global assessment of land degradation. *Soil Use and Management*, 24(3): 223–234.

Bouman, B.A.M., Humphreys, E., Tuong, T.P., & Barker, R. (2007). Rice and water. *Advances in Agronomy*, 92: 187-237.

Dawe, D., Pandey, S. & Nelson, A. (2010). Emerging trends and spatial patterns of rice production. In S. Pandey, D. Byerlee, D. Dawe, A. Dobermann, M. Samarendu, S. Rozelle, & B. Hardy (Eds.), *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security* (p. 333). 2.6: International Rice Research Institute (IRRI). Manila, Philippines.

Dobermann, A., & Fairhurst, T. (2000). *Rice: Nutrient Disorders & Nutrient Management*. IRRI, the Philippines, PPI, USA., and PPIC, Canada.

FAO. (2012). FAOSTAT. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://faostat.fao.org

Heong, K.L., & Schoenly, K.G. (1998). Impact of insecticides on herbivore-natural enemy communities in tropical rice ecosystems. In: Haskell P.T., McEwen P., eds. *Ecotoxicology: Pesticides and Beneficial Organisms.* (pp. 381-403). London, UK: Chapman and Hall.

IRRI. (2004). IRRI's Environmental Agenda: an approach toward sustainable development. International Rice Research Institute (IRRI). Manila, Philippines.

Larson, D.F., Otsuka, K., Kajisa, K., Estudillo, J., & Diagne, A. (2010). *Can Africa replicate Asia's green revolution in rice?.* World Bank, Development Research Group, Agriculture and Rural Development Team. Washington DC.

Li, X., Waddington, S.R., Dixon, J., Joshi, A.K., & Carmen de Vicente, M. (2011). The relative importance of drought and other water related constraints for major food crops in South Asian farming systems. *Food Security*, 3(1): 19–33.

Mejia, D. (2004). *Rice-post harvest system: An efficient approach*. FAO, Rome.

Nguyen, N., & Ferrero, A. (2006). Meeting the challenges of global rice production. *Paddy and Water Environment,* 4(1): 1-9.

Norton, G., Heong, K.L., Johnson, D., & Savary, S.(2010). Rice pest management: issues and opportunities. In S. Pandey, D. Byerlee, D. Dawe, A. Dobermann, M. Samarendu, S. Rozelle, & B. Hardy (Eds.), *Rice in the Global Economy: Strategic Research and Policy Issues for Food Security* (p. 333). IRRI. Manila, Philippines.

Pampolino, M.F., Manguiat, I.J., Ramanathan, S., Gines, H. C., Tan, P.S., Chi, T.T.N., & Buresh, R.J. (2007). Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems. *Agricultural Systems,* 93(1): 1-24.

Peng, S., Buresh, R.J., Huang, J., Yang, J., Zou, Y., Zhong, X., & Wang, G. (2006). Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crops Research*, 96(1): 37-47.

Phalan, P., Onial, M., Balmford, A., & Green, R.E. (2011). Reconciling food production and biodiversity conservation: land sharing and land sparing compared. *Science*, 333(6047): 1289-1291.

Pingali, P.L. (1995). Impact of pesticides on farmer health and the rice environment: an overview of results from a multidisciplinary study in the Philippines. In *Impact of Pesticides on Farmer Health and the Rice Environment*. (pp. 3-21). Springer, Dordrecht, The Netherlands.

Singleton, G. (2003). *Impact of Rodents on Rice Production in Asia. IRRI Discussion Papers*. International Rice Research Institute (IRRI), Manila, Philippines.

Tuong, T.P., Bouman, B.A.M., & Mortimer, M. (2005). More rice, less water—integrated approaches for increasing water productivity in irrigated rice-based systems in Asia. *Plant Production Science,* 8:231-40.

Wada, Y., Beek, L., Kempen, C., Reckman, W. T., Vasak, S., & Bierkens, M. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, 37(20): L20402.

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.

Witt, C., Buresh, R.J., Peng, S., Balsubramanian, V., & Doberman, A. (2007). Nutrient Management. In *Rice: A Practical Guide to Nutrient Management*. Eds. Fairhurst, T., Witt, C., Buresh, R., Doberman, A. International Rice Research Institute (IRRI), Manila, Philippines.

Yan, X., Akiyama, H., Yagi, K., & Akimoto, H. (2009). Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. *Global Biogeochemical Cycles*, 23: GB2002.

Yusuf, R.O., Noor, Z.Z., Abba, A.H., Hassan, M.A.A., & Din, M.F.M. (2012). Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. *Renewable and Sustainable Energy Reviews*, 16(7): 5059-5070.

Maize-Environment Citations

Ali, M.Y., Waddington, S.R., Timsina, J., Hodson, D. & Dixon, J. (2009). Maize-rice cropping systems in Bangladesh: Status and research needs. *Journal of Agricultural Science and Technology USA*, 3(6): 35-53.

Binam, J.N., Tonye, J., Nyambi, G., & Akoa, M. (2004). Factors affecting the technical efficiency among smallholder farmers in the slash and burn agriculture zone of Cameroon. *Food Policy*, 29(5): 531-545.

Bossio, D., Geheb, K., & Critchley, W. (2010). Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods. *Agricultural Water Management*, 97(4): 536-542.

Cassman, K.G., Dobermann, A., Walters, D.T., & Yang, H. (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*, 28(1): 315-358.

Cobo, J.G., Dercon, G., & Cadisch, G. (2010). Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agriculture, Ecosystems & Environment*, 136(1): 1-15.

Erenstein, O., Sayre, K., Wall, P., Hellin, J., & Dixon, J. (2012). Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: Lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. *Journal of Sustainable Agriculture*, 32(2): 180-206.

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, 319(5867): 1235-1238.

FAO. (2012, 2010). FAOSTAT. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://faostat.fao.org

Gerpacio, R., & Pingali, P. (2007). *Tropical and Subtropical Maize in Asia*. CIMMYT, Mexico. Retrieved from http://repository.cimmyt.org/xmlui/bitstream/handle/10883/800/90044.pdf?sequence=1

Gibbon, D., Dixon, J., & Flores, D. (2007). *Beyond Drought Tolerant Maize: Study of Additional Priorities in Maize*. Report to CGIAR Generation Challenge Program. CIMMYT Impacts, Targeting and Assessment Unit, CIMMYT. México DF, México.

Gupta, A. (2012). Pesticide use in South and South-East Asia: Environmental, public health and legal concerns. *American Journal of Environmental Science*, 8: 152-157.

Joshi, P.K., Singh, N.P., Singh, N.N., Gerpacio, R.V. & Pingali, P.L. (2005). *Maize in India: Production Systems, Constraints, and Research Priorities*. México, D.F., CIMMYT.

Kanampiu, F., Ransom, J., Gressel, J., Jewell, D., Friesen, D., Grimanelli, D., & Hoisington, D. (2002). Appropriateness of biotechnology to African agriculture: Striga and maize as paradigms. *Plant Cell, Tissue and Organ Culture*, 69(2): 105-110.

Lobell, D.B., Bänziger, M., Magorokosho, C., & Vivek, B. (2011). Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change*, 1(1): 42-45.

Mapfumo, P., Mtambanengwe, F., Giller, K.E., & Mpepereki, S. (2005). Tapping indigenous herbaceous legumes for soil fertility management by resource-poor farmers in Zimbabwe. *Agriculture, Ecosystems & Environment*, 109 (3-4): 221-233.

Mueller, N.D., Gerber, J.S., & Johnston, M. (2012). Closing yield gaps through nutrient and water management. *Nature*, 490: 254-257.

Oerke, E.C., & Dehne, H.W. (2004). Safeguarding production—losses in major crops and the role of crop protection. *Crop Protection*, 23(4): 275-285.

Phalan, B., Bertzky, M., Butchart, S. H., Donald, P. F., Scharlemann, J. P., Stattersfield, A. J., & Balmford, A. (2013). Crop expansion and conservation priorities in tropical countries. *PloS One*, 8(1): e51759.

Pingali, P.L., & Pandey, S. (2000). Meeting World Maize Needs: Technological Opportunities and Priorities for the Public Sector. CIMMYT, Mexico. Retrieved from http://apps.cimmyt.
org/Research/Economics/map/facts_trends/maizeft9900/pdfs/maizeft9900_Part1a.pdf

Schlenker, W., & Lobell, D.B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1): 014010.

Shiferaw, B., Prasanna, B.M., Hellin, J. & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. *Food Security,* 3(3): 307-327.

Timsina, J., Jat, M.L., & Majumdar, K. (2010). Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. *Plant & Soil*, 335(1-2): 65-82.

Timsina, J., Buresh, R.J., Dobermann, A., & Dixon, J. (2011). *Rice-maize Systems in Asia: Current Situation and Potential*. IRRI, Manila, The Philippines.

Waddington, S.R., Edmeades, G.O., Chapman, S.C. and Barreto, H.J. (1995). *Where to with agricultural research for drought-prone maize environments?* In: Maize Research for Stress Environments (Jewell, D.C., Waddington, S.R., Ransom, J.K. and Pixley, K.V., eds.), Proceedings of the Fourth Eastern and Southern Africa Regional Maize Conference, Harare, Zimbabwe. (pp. 129-152). CIMMYT, Mexico, D.F., Mexico.

World Bank. (2011). *Missing Food: The Case of Postharvest Grain Losses in Sub-Saharan Africa*. Retrieved from http://siteresources.worldbank.org/INTARD/Resources/MissingFoods10_web.pdf

Sorghum/Millet-Environment Citations

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.

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

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

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.

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.

FAO. (2012). FAOSTAT. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://faostat.fao.org

García-Ponce, E., Gómez-Macpherson, H., Diallo, O., Djibril, M., Baba, C., Porcel, O., Mathieu, B., Comas, J., Mateos, L., & Connor, D.J. (2013). Contribution of sorghum to productivity of small-holder irrigation schemes: On-farm research in the Senegal River Valley, Mauritania. *Agricultural Systems*, 115: 72-82.

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.

Jeger, M.J., Gilijamse, E., Bock, C.H., & 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.

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.

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, Andhra Pradesh, India.

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.

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. In Ed. E. Lichtfouse, Sustainable Agriculture Reviews Volume 2. *Climate Change, Intercropping, Pest Control and Beneficial Microorganisms*, (pp. 339-372). Springer, Dordrecht, The Netherlands.

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

Rurinda, J., Mapfumo, P., van Wijk, M.T., Mtambanengwe, F., Rufino, M.C., Chikowo, R., & Giller, K.E. (2014). Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *European Journal of Agronomy*, 55:29-41.

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, UK: CAB International Publishing.

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.

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.

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.

Williams, R.J., & Rao, K.N. (1981). A review of sorghum grain molds. *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*.

Sweetpotato/Yam-Environment Citations

Agbaje, G.O., Ogunsumi, L.O., Oluokun, J.A., & Akinlosotu, T.A. (2005). Survey of yam production system and the impact of government policies in southwestern Nigeria. *Journal of Food, Agriculture & Environment*, 3(2): 222–229.

Ames de Icochea, T., & Ames, T. (1997). *Sweetpotato: Major Pests, Diseases, and Nutritional Disorders*. International Potato Center (CIP), Lima, Peru.

Amusa, N.A., Adegbite, A., Muhammed, S., & Baiyewu, R.A. (2003). Yam diseases and its management in Nigeria. *African Journal of Biotechnology*, 2(12): 297–502.

Andrade, M., Barker, I., Cole, D., Dapaah, H., Elliott, H., Fuentes, S., Grüneberg, W., Kapinga, R., Kroschel, J., Labarta, R., Lemaga, B., Loechl, C., Low, J., Lynam, J., Mwanga, R., Ortiz, O., Oswald, A., & Thiele, G. (2009). *Unleashing the Potential of Sweetpotato in Sub-Saharan Africa: Current Challenges and Way Forward*. International Potato Center (CIP), Lima, Peru. Working Paper 2009-1.

ASARECA. (2005). *Potato and Sweetpotato*. Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA).

Bagamba, F., Bashaasha, B., Claessens, I., & Antle, J. (2012). Assessing climate change impacts and adaptation strategies for smallholder agricultural systems in Uganda. *African Crop Science Journal*, 20(2): 303-316.

Bridge, J., Coyne, D. & Kwoseh, C.K. (2005). Nematode Parasites of Tropical Root and Tuber Crops. In: *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture*. Revised 2nd Edition. Luc, M., Sikora, R. and Bridge, J. (Eds), (pp. 221-258). CAB International, Wallingford, UK.

CIP. (2010). *Facts and Figures about Sweetpotato*. International Potato Center, Lima, Peru.

Claessens, L., Antle, J., Stoorvogel, J.J., Thornton, P.K., & Herrero, M. (2010). *Assessing Climate Change Adaptation Strategies for Small Scale, Semi-subsistence Farming*. Retrieved from: http://www.researchgate.net/publication/

Edison, S., Hegde, V., Makeshkumar, T., Srinivas T., Suja, G., & Padmaja, G. (2009). Sweetpotato in the Indian Sub-Continent. In *The Sweetpotato*, Loebenstein, G. & Thottappilly, G., Eds., (pp. 391–414). Springer, Dordrecht, The Netherlands.

Ewell, P. (2011). *Sweetpotato Production in Sub-Saharan Africa: Patterns and Key Issues.* Nairobi, Kenya.

FAO. (2012). FAOSTAT. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://faostat.fao.org

Fuglie, K.O. (2007). Priorities for sweetpotato research in developing countries: Results of a survey. *HortScience*, 42(5): 1200–1206.

Geist, H.J., & Lambin, E.F. (2004). Dynamic causal patterns of desertification. *Bioscience*, 54(9): 817-829.

Goswami, S.B., Sen, H., & Jana, P.K. (1995). Tuberization and yield potential of sweetpotato cultivars as influenced by water management practices. *Journal of Root Crops*, 21: 77–81.

Kyamanywa, S., Kashaija, I.N., Getu, E., Amata, R., Senkesha, N., & Kullaya, A. (2011). Enhancing food security through improved seed systems of appropriate varieties of cassava, potato and sweetpotato resilient to climate change in Eastern Africa. Retrieved from http://cgspace.cgiar.org/bitstream/handle/10568/10817/Project2_Cassava.pdf?sequence=6

Lebot, V. (2009). Tropical Root and Tuber Crops: Cassava, Sweetpotato, Yam and Aroids. *Crop Production Science in Horticulture* No, 17. CABI Publishing, Wallingford, UK.

Low, J., Lynam, J., Lemaga, B., Crissman, C., Barker, I., Thiele, G., Namanda, S., et al. (2009). Sweetpotato in Sub-Saharan Africa. In *The Sweetpotato*, Loebenstein, G. & Thottappilly, G., Eds., (pp. 359-390). Springer, Dordrecht, The Netherlands.

Nedunchezhiyan, M. (2011). Evaluation of sweet potato (*Ipomoea batatas*) based strip intercropping systems for yield, competition indices and nutrient uptake. *Indian Journal of Agronomy*, 56(2): 98-103.

Paeth, H., Capo-Chichi, A., & Endlicher, W. (2008). Climate change and food security in tropical West Africa—a dynamic-statistical modelling approach. *Erdkunde, 62*: 101-115.

Peters, J. (2000). *Control of Yam Diseases in Forest Margin Farming Systems in Ghana.* Final Technical Report. DFID. Available at: http://www.dfid.gov.uk/r4d/PDF/Outputs/CropProtection/R6691_FTR.pdf

Ringler, C., Zhu, T., Cai, X., Koo, J., & Wang, D. (2010). *Climate change impacts on food security in Sub-Saharan Africa*. IFPRI Discussion Paper. Retrieved from http://www.parcc-web.org/parcc-project/documents/2012/12/climate-change-impacts-on-food-security-in-sub-saharan-africa.pdf

Srivastava, A.K., Gaiser, T., Paeth, H., & Ewert, F. (2012). The impact of climate change on Yam (Dioscorea alata) yield in the savanna zone of West Africa. *Agriculture, Ecosystems & Environment*, 153: 57-64.

Stathers, T.E., Rees, D., Kabi, S., Mbilinyi, L., Smit, N., Kiozya, H., & Jeffries, D. (2003). Sweetpotato infestation by Cylas spp. in East Africa I. Cultivar differences in field infestation and the role of plant factors. *International Journal of Pest Management*, 49(2): 131-140.

Thornton, P. (2012). Recalibrating food production in the developing world: Global warming will change more than just the climate. CGIAR. Retrieved from http://cgspace.cgiar.org/bitstream/handle/10568/24696/CCAFS_PB06-Recalibrating%20Food%20Production.pdf"

Valverde, R.A., Clark, C.A., & Valkonen, J.P. (2007). Viruses and virus disease complexes of sweetpotato. *Plant Viruses,* 1(1): 116-126.

Cassava-Environment Citations

Alves, A.A.C. (2002). Cassava botany and physiology. In *Cassava: Biology, Production and Utilization*, Eds R.J. Hillocks, J.M. Thresh & A. Bellotti, (pp. 67-89). CABI Publishing, Wallingford, UK.

Adjei-Nsiah, S., Kuyper, T.W., Leeuwis, C., Abekoe, M.K. & Giller, K.E. (2007). Evaluating sustainable and profitable cropping sequences with cassava and four legume crops: Effects on soil fertility and maize yields in the forest/savannah transitional agroecological zone of Ghana. *Field Crops Research*, 103: 87-97.

Bellotti, A.C. (2002). Arthropod pests. In *Cassava: Biology, Production and Utilization*. Eds R.J. Hillocks, J.M. Thresh & A. Bellotti, (pp. 209-235). CABI Publishing, Wallingford, UK.

El-Sharkawy, M.A. (2006). International research on cassava photosynthesis, productivity, eco-physiology, and responses to environmental stresses in the tropics. *Photosynthetica*, 44(4), 481-512.

FAO (2001). Proceedings of the Validation Forum on the Global Cassava Development Strategy '00: Strategic environmental assessment, *an assessment of the impact of cassava production and processing on the environment and biodiversity*. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://www.fao.org/docrep/007/y2413e/y2413e00.htm

FAO (2010). *Cassava diseases in Africa: a major threat to food security*. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://www.fao.org/fileadmin/templates/fcc/documents/CaCESA_EN.pdf

FAO. (2013). FAOSTAT. Food and Agricultural Organization of the United Nations (FAO), Rome. Retrieved from http://faostat.fao.org

Fermont, A.M., Van Asten, P.J.A., & Giller, K.E. (2008). Increasing land pressure in East Africa: The changing role of cassava and consequences for sustainability of farming systems. *Agriculture, Ecosystems & Environment*, 128(4): 239-250.

Fermont, A.M. (2009). *Cassava and soil fertility in intensifying smallholder farming systems of East Africa*. PhD thesis, Wageningen University, The Netherlands.

Fermont, A.M., Van Asten, P.J.A., Tittonell, P., Van Wijk, M.T., & Giller, K.E. (2009). Closing the cassava yield gap: an analysis from smallholder farms in East Africa. *Field Crops Research*, 112(1): 24-36.

Hershey, C.H., & Howeler, R.H. (2000). Cassava in Asia: Designing crop research for competitive markets. In *Cassava's Potential in Asia in the 21st Century: Present Situation and Future Research and Development Needs*. Proceedings 6th Regional Workshop, held in Ho Chi Minh City, Vietnam, pp. 110-146.

Howeler, R.H. (2000). Cassava agronomy research in Asia: Has it benefited cassava farmers? In *Cassava's Potential in Asia in the 21st Century: Present Situation and Future Research and Development Needs.* Proceedings 6th Regional Workshop, held in Ho Chi Minh City, Vietnam, pp. 345-382.

Howeler, R.H. (2002). Cassava mineral nutrition and fertilization. In *Cassava: Biology, Production and Utilization*, Eds R.J. Hillocks, J.M. Thresh & A. Bellotti, (pp. 115-147). CABI Publishing, Wallingford, UK.

Jarvis, A., Ramirez-Villegas, J., Campo, B.V.H., & Navarro-Racines, C. (2012). Is cassava the answer to African climate change adaptation? *Tropical Plant Biology*, 5(1): 9-29.

Legg, J.P., Owor, B., Sseruwagi, P., & Ndunguru, J. (2006). Cassava mosaic virus disease in East and Central Africa: epidemiology and management of a regional pandemic. *Advances in Virus Research*, 67: 355-418.

Legg, J.P., Jeremiah, S.C., Obiero, H.M., Maruthi, M.N., Ndyetabula, I., Okao-Okuja, G., Lava Kumar, P. (2011). Comparing the regional epidemiology of the cassava mosaic and cassava brown streak virus pandemics in Africa. *Virus Research*, 159(2): 161-170.

Melifonwu, A.A. (1994). Weeds and their control in cassava. *African Crop Science Journal*, 2(4): 519-530.

Oluwole, O., & Cheke, R.A. (2009). Health and environmental impacts of pesticide use practices: a case study of farmers in Ekiti State, Nigeria. *International Journal of Agricultural Sustainability*, 7(3): 153-163.

Omonona, B.T., & Akinpelu, A.O. (2012). Water, environment and health: Implications on cassava production. *Continental Journal of Agricultural Science*, 4: 29-37.

Onwueme, I.C. (2002). Cassava in Asia and the Pacific. In *Cassava: Biology, Production and Utilization*. Eds R.J. Hillocks, J.M. Thresh & A. Bellotti, (pp. 55-65). CABI Publishing, Wallingford, UK.

Paavola, J. (2008). Livelihoods, vulnerability and adaptation to climate change in Morogoro, Tanzania. *Environmental Science & Policy*, 11(7): 642-654.

Patil, B.L., & Fauquet, C.M. (2009). Cassava mosaic geminiviruses: actual knowledge and perspectives. *Molecular Plant Pathology*, 10(5): 685-701.

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