Evans School of Public Affairs
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Agriculture-Environment Series:
Maize Systems At-A-Glance

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Table 1: Crop-Environment Interactions in Maize Production Systems in Sub-Saharan Africa (SSA) and South Asia (SA)

	Pre-Production	*Production*		*Post-Production*
Environmental Constraints	**LAND AVAILIBILITY:** Maize crop-land is expanding; in SSA the area doubled (15.5 to 30.9 Mha) from 1961-2010. Particularly in SSA, maize is often grown on shallow, nutrient-poor soils.	**SOIL FERTILITY:** Especially in SSA, low soil fertility is the most severe and widespread constraint to maize production. Soil erosion contributes to nutrient loss, while repeated harvests deplete soil nutrients.	**WATER CONSTRAINTS (WC) and BIOTIC FACTORS (BF):** Water availability and drought, along with crop damage from pests, weeds and diseases substantially compromise maize production in both SSA and SA.	**STORAGE LOSSES:** Post-harvest losses can be severe in the absence of adequate storage and transportation options.
Rank Importance	4	1	WC=2, BF=3	5
Adaptation Strategies	**EXPAND or INTENSIFY:** In SSA, area expansion converts non-agricultural land to crops. In SA there is limited scope to expand; inputs drive maize production.	**AGROCHEMICAL INPUT USE:** Fertilizer use dramatically increases maize yield, but remains low in SSA. **INTERCROPPING AND ROTATION:** Intercropping/rotation with legumes improves soil nitrogen content.	**IMPROVED MANAGEMENT:** Intercropped maize plots have fewer pests; planting trees/shrubs in crop plots reduces erosion, increases soil organic matter and water retention, and accesses nutrients from soil depths. Where possible, irrigation can also help overcome water deficits.	**SECURE STORAGE:** Using traditional and improved storage methods can reduce losses, as can reducing storage time via improvements in grain marketing and transport.
Environmental Impacts	**LAND & HABITAT/BIODIVERSITY DEGRADATION:** More than 50% of agricultural expansion in Africa from 1975-2000 arose through tropical deforestation. Estimated annual monetary losses from land degradation in Ethiopia range from 2-6.8% of GDP.	**FERTILIZER RUNOFF AND GHGs:** Fertilizer contamination of rivers, lakes and groundwater is severe in SA. Runoff is only a localized issue in SSA (where underuse is predominant), but may grow as systems intensify. Overuse of synthetic N is a major source of greenhouse gas emissions.	**(+) BENEFICIAL ENVIRONMENTAL FEEDBACK:** Intercropping and crop diversification strategies both have positive environmental feedbacks - increased soil fertility and reduced losses from pests on intercropped plots could reduce the need for agricultural expansion or chemical input use.	**WASTED EFFORT:** Lost harvest wastes environmental resources. Reducing post-harvest losses decreases pressures driving expansion of agricultural land or agrochemical use.
Best Practices	**INTENSIFICATION:** Use of fertilizers, better water management, improved fallowing (including planted fallows) and intercropping can raise productivity and reduce threats to marginal land.	**REDUCED TILLAGE:** Reduced-tillage and residue retention raise yield, reduce GHGs and support soil fertility. **DIVERSIFICATION AND FERTILIZER:** Maize-legume crop rotations and intercrops, along with organic manures and well-targeted small amounts of NP fertilizer all greatly raise yields.	**DROUGHT AND PEST RESISTANT SEED:** Improved varieties/seeds provide increased yields in drought-prone areas (but also permit maize land expansion, and may displace traditional crops). Maize with resistance to diseases and pests shows promise in reducing the severity of biotic constraints.	**IMPROVED STORAGE:** Use of air-tight metal silos and grain bags has dramatically reduced grain storage losses in some areas of SSA and SA. Reduced mycotoxins may also improve both human and animal health.

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Brief Contents

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Introduction

This review is one in a series that examines crop-environment interactions drawing on both the academic literature and the field expertise of crop scientists. In this brief we examine the environmental constraints to, and impacts of, smallholder maize production systems in Sub-Saharan Africa (SSA) and South Asia (SA), noting where findings apply to only one of these regions. We highlight crop-environment interactions at three stages of the maize value chain: pre-production (e.g., land clearing), production (e.g., fertilizer, water, and other input use), and post-production (e.g., waste disposal and crop storage). At each stage we emphasize environmental constraints on maize production (such as poor soil quality, water scarcity, or crop pests) and also environmental impacts of maize production (such as soil erosion, water depletion, or chemical contamination). We then highlight best or good practices for overcoming environmental constraints and minimizing environmental impacts in smallholder maize production systems.

Maize has expanded through the 20th and into the 21st century to become the principle staple food crop produced and consumed by smallholder farm households in SSA (Shiferaw *et al.*, 2011). The crop is most dominant in southern and eastern Africa, where it typically represents 20 to 50% of daily household consumption (FAOSTAT, 2010), and in recent decades has spread substantially in western and central Africa (Shiferaw *et al.*, 2011). Maize production has also expanded in SA farming systems. In many areas of northern and central India (where rice is the primary staple food crop), farmers have a long tradition of growing maize during the monsoon season as a supplementary source of human food and income (Joshi *et al.*, 2005). During recent decades, it has become increasingly common for farmers in SA to grow maize as a high-input cash crop during the cool dry season, especially to produce feed for poultry industries that continue to expand in the region (Joshi *et al.*, 2005; Ali *et al.*, 2009).

Maize is favored by many farmers worldwide because of its capacity to give high yields relative to other staple grains, in the presence of adequate water and organic and synthetic nutrients. Maize has also benefited from decades of public and private sector research and development resulting in multiple improved varieties and a wealth of knowledge on effective production practices. However, maize production has also resulted in environmental damage, both in extensive systems (e.g., habitat loss and land degradation in SSA) and more intensive systems (e.g., nutrient mining and pesticide contamination in SA).

Evidence on environmental constraints and impacts in smallholder maize production is uneven. Many environmental concerns such as biodiversity loss are commonly demonstrated more broadly for the agroecology or farming systems in which maize is grown, rather than specifically for the maize crop. And more research is available on the environmental impacts of agrochemical-based intensive cereal farming in Asia (where high-input maize is a common component) than on the low-input subsistence-scale maize cultivation more typical of SSA. Decisive constraint and impact estimates are further complicated by the fact that many crop-environment interactions in maize and other crops are a matter of both cause and effect (e.g., poor soils decrease maize yields, while repeated maize harvests degrade soils). Fully understanding maize-environment interactions thus requires recognizing instances where short-term adaptations to environmental constraints might be exacerbating other medium- or long-term environmental problems.

Conclusions on the strength of published findings on crop-environment interactions in maize systems further depend on one's weighting of economic versus ecological perspectives, physical science versus social science, academic versus grey literature, and quantity versus quality of methods and findings. We have tried to offer a comprehensive and balanced assessment incorporating many of these criteria.

Table 1 summarizes the key environmental constraints and environmental impacts associated with maize production in

SSA and in SA. The last row summarizes best or good smallholder practices currently identified in the literature. However, often farmers can make choices between several types of response or intervention, each with variable costs and benefits. The appropriate strategy in a given situation will vary widely based on contextual factors, such as local environmental conditions, market access, local knowledge, cultural preferences, availability of inputs, existing production practices and the policy environment.

Maize Production Systems

Smallholder maize cropping systems in SSA and SA show marked differences, though in both regions the crop is of major significance to food security and livelihoods of the poor (Hyman *et al.*, 2008). Major smallholder production systems in SSA incorporating maize to varying degrees include: cereal-root crop mixed; maize mixed; root crop; agro-pastoral millet/sorghum; and highland temperate mixed. In SA key systems often incorporating maize include rice-wheat, rainfed mixed, and highland mixed (see Dixon *et al*., 2001).

In the African systems farmers grow a mixture of traditional varieties (landraces), improved open-pollinated varieties (OPVs) and, increasingly, hybrid maize (although use of farm-saved seed rather than new seed remains high, even when hybrid seed is used). Cultivation occurs primarily on small, rain-fed plots in areas of uncertain rainfall, frequently on poor soils, and generally with little use of synthetic inputs. Intercropping or rotation with legumes and other food and cash crops is common. Maize is produced primarily for human consumption within rural households, with surplus production marketed to urban areas. The only major areas of high-input commercial maize in SSA are found in South Africa, with smaller amounts in neighboring countries such as Zimbabwe.

In South Asia, maize production is more varied in terms of seasonality, input use and enduses for the crop. In the more traditional maize areas of central and northern India and hill areas in Nepal farmers often grow maize using old landraces, newer OPVs and composite varieties bred in the field. Farmers in these areas now commonly grow commercial maize hybrids as well, mostly as a rainfed crop during the monsoon season with modest amounts of fertilizers (Joshi *et al.*, 2005). Elsewhere, as in the intensive small-plot farming systems of Bangladesh and northeastern India, hybrid maize is typically grown as an irrigated winter crop (often replacing wheat) with new seed and high inputs, as part of a two crop annual rotation with monsoon rice (Joshi *et al*., 2005; Ali *et al.*, 2009). Increasingly, farmers in SA will grow both monsoon-season maize for household food and sale, and winter maize primarily for sale. Such intensifying systems, incorporating maize into multi-crop rotations, will likely be of increasing future importance as a means to raise production in the face of decreased opportunity for land expansion (Timsina *et al.*, 2010; 2011).

The following sections describe environmental interactions in both extensive and more-intensive maize production systems throughout the production cycle (pre-production, production and post-production), with a focus on smallholder systems in SSA and SA.

Pre-Production of Maize

<u>Land Constraints</u>

One of the most binding constraints on any crop system is the availability of sufficient and suitable land to cultivate. In SSA, large areas of land cropped with maize are located in marginal mid-elevation plateau sub-humid and semi-arid areas (e.g., Dixon *et al.,* 2001) with shallow, eroded soils depleted of soil nutrients (Sanchez, 2002). In SA, there are large (but increasingly insufficient) areas with fertile soils and developed riverine irrigation systems where maize is grown, as well as more marginal rainfed and degraded (usually upland) maize production areas (Timsina *et al.*, 2010; Joshi *et al*., 2005).

Globally, maize area harvested increased 53% between 1961 and 2010, from 105 Mha to 161 Mha (FAOSTAT, 2012). This growth in area stems from a combination of: (i) existing cropland converted from other crops to maize; (ii) maize intensification through multiple harvests from a single plot; and (iii) non-agricultural land converted to agriculture.

Adaptation to Land Constraints

Agricultural adaptations to land constraints vary by region. In areas where land suitable for agricultural production is relatively abundant, as in much of SSA (UNEP/Grid, 2012; Bruinsma, 2009), the dominant response is to convert forests, grasslands and other non-agricultural land to cropland (Gibbs *et al.*, 2010). Agricultural expansion at the extensive margin (i.e., land-clearing) is most common where possibilities for intensification through irrigation and fertilizer use are limited (Barbier, 2004).[1] Maize is also a frequent first crop after slash and burn land clearing in SSA, since farmers value its ability to utilize the nutrients released through burning to produce high yields (see e.g., Binam *et al.*, 2004 for Cameroon). According to FAOSTAT (2012), the maize area harvested in Sub-Saharan Africa rose from 14.3 Mha in 1961 to 33.5 Mha in 2011 – an increase of 133%. A further 88 Mha of land suitable for maize is still considered available for cultivation in the

[1] Some intensification is occurring in SSA in more developed and climatologically favorable areas; see e.g., Ariga & Jayne, 2010.

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region (Shiferaw *et al.*, 2011) though this estimate has been challenged by some authors as optimistic.[2]

In South Asia, where land is now relatively scarce, farmers have responded to land constraints through gradual intensification in both irrigated and (to the extent possible) in rainfed/partially irrigated areas. Even though total maize area harvested in SA grew by 66% percent during 1961-2011, from 6.0 Mha to 9.9 Mha (FAO, 2012), much of this growth reflects a switch from existing crops such as rice, wheat, or dryland cereals (rather than new land clearing). Farmers in Bangladesh and in parts of India with good access to irrigation have also intensified production by using maize in double or triple annual crop rotational sequences on existing cropland (Timsina *et al.*, 2010).[3] Such intensification has historically been accompanied by adopting modern and/or hybrid seed varieties, as well as increasing irrigation, organic and synthetic fertilizer, and pesticide use (Pingali & Rosegrant, 1994; Pingali, 1992; Otsuka *et al.,* 1990).

Environmental Impacts of Land Use

Both agricultural expansion and agricultural intensification have environmental implications. Impacts of either practice broadly include:

- *Erosion and land degradation*: Over-cultivation of degraded and marginal lands damages soil structure and worsens wind and water erosion, particularly on sloped plots (Collins *et al.*, 2004). In extreme cases this can lead to desertification (Vlek *et al.*, 2010; Glantz, 1992). Maize-specific data on land degradation are only beginning to become available for SSA (Cobo *et al.*, 2010). More generally, in Ethiopia, farming on slopes leads to an estimated loss of 1.5 billion metric tons of topsoil from the highlands annually (Tadessi, 2001), and annual losses due to land degradation in Ethiopia are estimated to be between 2% and 6.75% of agricultural gross domestic product (Yesuf *et al.*, 2005). For India, Dregne (1992) reported widespread soil degradation, with 57% of cropland in need of soil conservation measures, although the type of erosion varied by region. Singh *et al.* (1992) estimated annual water erosion of soil in India averaged 5 t/ha/year; with the most severe erosion (>20 t/ha/year) primarily on sloped lands.

- *Forest and habitat loss*: Agricultural expansion also destroys natural habitat and therefore can reduce wild biodiversity. In a study of agricultural land use using remote sensing, Brink & Eva (2009) found that from 1975 to 2000 the total land area under crop cultivation in SSA increased by 140 Mha. During the same period, natural forest and non-forest vegetation decreased by a combined 131 Mha, at an annual average rate of about 5 Mha per year. Gibbs *et al.* (2010) find more than 55% of new agricultural land in SSA since 1975 arose through clearing of previously intact tropical forests. More recent estimates by Phalan *et al*. (2013) emphasize ongoing land clearing specifically for maize in SSA concentrated in Nigeria, Ethiopia and Sudan. In SA, there is less conversion of new land to agricultural production and much of the increased area of maize is the result of it replacing other crops (Ali *et al.*, 2009; Joshi *et al.*, 2005).

Additional environmental impacts from expanding or intensifying agriculture include:

- *Loss of wild and on-farm biodiversity*: Cropland expansion, cropping intensification and repeated plantings can negatively affect wild biodiversity directly (e.g., pesticides killing non-target organisms), and indirectly (e.g., land uses disrupting breeding cycles and destroying habitats of sensitive species) (Altieri & Nicholls, 2004; Saunders et. al., 1991). Shifts to intensive farming may also reduce the number of plant and animal species in agro-ecosystems and may inhibit provision of ecosystem services such as pollination and erosion control (Scherr & McNeely, 2008).

- *Loss of crop genetic diversity*: Replacing multiple locally-adapted and genetically diverse crop varieties (including diverse varieties of maize and also other traditional crops like certain millets in SSA) with a smaller number of modern maize varieties can reduce local and regional agro-biodiversity (Bellon *et al*., 1996).

Reduced biodiversity can increase maize vulnerability to abiotic stresses (e.g., heat or drought, compounded by loss of forest cover) and biotic stressors (e.g., crop pests such as maize stem borers and diseases) which can multiply dramatically on repeatedly-cropped land (Hajjar *et al.*, 2008; Altieri, 1999; Thrupp, 1998). Such biodiversity-related production consequences are compounded by the intrinsic loss of value when local crop landraces disappear or wild plant and animal species are destroyed or inhibited from performing ecological functions.

No estimates of wild plant and animal biodiversity loss specifically attributable to maize are available at the writing of this brief. Low levels of maize genetic diversity have gained some attention – in Kenya in 2010, for example, 48%

[2] Some authors argue that estimates of large arable land reserves in SSA ignore that much of the land not currently under cultivation may be of poor quality (e.g. shallow soils, in hilly areas, oxisols, sandy soils, arid zones, wet valley bottoms) and not suitable for long-term agricultural production (e.g., Young, 1999; Cassman *et al.*, 2003).

[3] The introduction of earlier maturity rice varieties (under development) and small-scale power tillers,-seeders and reapers to prepare land, plant and harvest more quickly may allow farmers even more time to grow crops like maize during the year (Timsina *et al.*, 2010; Ali *et al.*, 2009).

of maize area was planted with seed of a single variety derived from one released in 1986 (Smale *et al.*, 2011). However, recent trends towards the expanded import, distribution and use of maize breeding materials and new varieties from the Americas and elsewhere could mean that overall maize genetic diversity available in SA and SSA has actually *risen* in recent decades.

A final environmental impact associated with maize pre-production is climate change:

➢ *Climate change*: Greenhouse gas (GHG) emissions from maize-related land use may increase when stored carbon is released with forest and grassland conversions (Fargione *et al.,* 2008, Tinker *et al.,* 1996).

However, the net effect of expanding maize production on climate change is unclear, because adoption of relatively high-yield maize might *decrease* the need for agricultural expansion when compared to more-traditional cereal production systems such as those involving sorghum or millet. Growing maize for grain is arguably one of the most land and water efficient ways of producing carbohydrate food for humans.

Best Practices for Pre-Production Land Use

Several best practices for maize land use simultaneously improve soils, better manage water resources, reduce chemical runoff and may help reduce climate change. Broadly, best practices for maize pre-production consist of the following (Shiferaw *et al*., 2011; Pretty *et al.,* 2006; Smale *et al.,* 2006):

➢ *Select sites suitable for maize cultivation*: Sloped land and ecologically important land (in terms of ecosystem services) such as tropical rainforest and semi-arid areas may be unsuitable for maize when soil, climate and biodiversity impacts are considered. Related to this, there may be ways to help farmers with decisions on long-term fallowing and eco-rehabilitation of exhausted and nonproductive maize cropland, which might allow for the return of some wild plant and animal species.

➢ *Diversify crops and retain indigenous biodiversity*: Rotations and intercrops, retaining pockets of indigenous trees and shrubs on crop fields and borders, maintaining ponds and streams (including for irrigation/fishing), and implementing agroforestry systems across SSA can further maintain and partially protect on-farm and wild biodiversity (Phalan *et al*., 2011; Hajjar *et al.,* 2008), and in many cases can result in sustained or even improved maize yields (Scherr & McNeely, 2008; Pretty *et al.*, 2006). Retaining and using biodiversity on maize fields can raise maize productivity, as shown by *Faidherbia albidia* systems across SSA (where indigenous leguminous trees are retained in cropfields), or by more specific local practices such as the indigenous legume fallows in Zimbabwe (where retaining leguminous weed species on cropland increases soil nutrients and maize yields) (Mapfumo *et al*., 2005).

➢ *Improve land management and preparation:* Various soil management practices are available to manage or reduce soil erosion, nutrient depletion and water loss. These practices include land leveling, terracing, field border management, conservation agriculture (zero or reduced tillage techniques combined with crop residue retention and rotation), and planting methods that minimize soil disturbance (see Erenstein *et al*., 2012; Hobbs *et al*., 2008, for several regions; Fowler & Rockström, 2001, for SSA; Gupta & Sayre, 2007, for SA). Though many of the techniques available are not specific to maize (especially in SA where much of the emphasis has been on wheat) they often can be used with maize systems.

In SSA, despite decades of research and promoting various techniques there is little indication of significant sustained adoption of conservation agriculture technologies in smallholder farming (see Erenstein *et al*., 2012; Giller *et al*., 2009; Kassam *et al*., 2009). Nevertheless, in practice some smallholder maize farmers employ techniques that reduce soil disturbance such as the use of soil ridges or hoe planting into un-ploughed soil, and there has been some use of reduced tillage techniques such as animal-drawn ripper tine tillage with partial retention of crop residues.

Among the more widely promoted soil conservation techniques in SA are various types of tractor-drawn zero till seed and fertilizer drills used on the western and central Gangetic plain in India (see Hobbs *et al*., 2008; Gupta & Sayre, 2007) and power-tiller-operated reduced till seeders suited to the smaller field sizes found in Bangladesh (see Ali *et al*., 2009). Quick and widespread adoption of zero till methods (again, largely for wheat) has already occurred on the western Gangetic plain in India and Pakistan (see Erenstein *et al*., 2012; Kassam *et al*., 2009; Hobbs *et al*., 2008). Much of the conservation agriculture and zero-till adoption appears driven by prospects of cost saving and monetary gain rather than soil or water conservation goals (Erenstein *et al.,* 2008).

➢ *Improve maize productivity*: Intensifying maize production maize through improved seeds, judicious fertilizer use and water management (see detailed later sections) also reduces the need for land expansion and its associated negative environmental impacts, thus offering net environmental gains provided the new methods do not introduce environmental costs greater than the practices they replace.

Production of Maize

Soil Nutrient Constraints

Soil infertility and nutrient shortages comprise the most severe and widespread constraint to maize production in SSA (Mueller *et al.*, 2012; Cobo *et al.*, 2010; Sanchez, 2002). In a study of expert opinion by Gibbon *et al.* (2007), the combination of various soil nutrient constraints in SSA (including the lack of use of fertilizers) was considered to reduce maize yields by as much as 60%. In South Asia, soil nutrient deficiencies were also a significant, though less severe, barrier to yields, reducing maize output by an estimated 14% (*ibid*).

Widespread, large negative nutrient balances ("nutrient mining") have been a concern for some time in SSA maize-based farming systems (see Bationo *et al*., 1998; Nandwa & Bekunda, 1998; Stoorvogel *et al*., 1993). Nutrient mining occurs where nutrients extracted from the soil from crop and weed uptake, leaching, nutrient runoff/soil erosion, and volatilization exceed inputs from soil mineralization, rainfall, fixation, fertilizer/manure application, and crop residue decomposition. A recent review of studies in Africa (Cobo *et al.*, 2010) shows overall negative nutrient balances, especially of nitrogen (N) and potassium (K), but also wide differences across environments and management systems. Lal (2009) reported annual depletion of N, phosphorous (P) and K from African cultivated soils averaging 22 kg, 2.5 kg and 15 kg per hectare, respectively, since 1975 – an amount equivalent to roughly US$ 4 billion in synthetic fertilizer per year (Sanchez & Swaminathan, 2005).

In India, Lal (2009) reported combined depletion of soil N, P and K to be as much as 80 kg/ha annually, though it is far less in many areas due to alluvial soil replenishment in floods and high input of fertilizers. Overall, it appears nutrient mining is a significant, though incompletely studied, impact of maize production, particularly when multiple crops (of maize and other crops) are harvested each year and when nutrient additions are inadequate (Morris *et al*., 2007, Sanchez 2002).

Adaptations to Soil Infertility

Adaptations to soil fertility constraints in SSA (where synthetic fertilizer use remains uncommon) and SA (where fertilizers are widely used) summarily include:

- *Application of synthetic fertilizers:* Mineral or synthetic fertilizer use is the most direct method of improving soil fertility, and with adequate moisture and weed management N fertilizer almost always raises maize grain yields (Heisey & Mwangi, 1996). But synthetic fertilizer use may often not be feasible for smallholder farmers without economic or risk mitigation incentives, and fertilizer application may not be effective or desirable on marginal lands where nutrient leaching is a concern (Solomon *et al.*, 2000). In SSA, most smallholder farmers use little or no synthetic fertilizer (Morris *et al.*, 2007); however, of all synthetic fertilizer that is used, 40% is devoted to maize (Smale *et al.*, 2011). When fertilizer is applied in SSA it is often at low rates: throughout Africa, the average fertilizer application rate is only 17 kg/ha, compared to 100 kg/ha in developing countries overall and 270 kg/ha in developed countries (*ibid*). In contrast, in India and Bangladesh maize is widely grown as a high-input crop featuring large - commonly 100-200 kg N/ha - amounts of fertilizer and irrigation water, along with hybrid seeds (see Timsina *et al.*, 2010; Ali *et al.*, 2009 and Joshi *et al.*, 2005).

- *Application of organic soil amendments:* Applying animal manure and incorporating crop residues will frequently increase maize yields, and these are common practices in many smallholder farming situations, although the effects vary across trials and farm fields (Snapp *et al.*, 1998; Bekunda *et al.*, 1997). Despite widespread recognition of the role of organic inputs in maintaining soil fertility, farmers in both SSA and SA often use organic materials for important alternative purposes. In Ethiopia, for example, manures are generally not used for crop cultivation, but instead as fuel for households (Admasu, 2009). Cow dung is similarly used widely as a domestic fuel in SA. Crop residues, another potential source of nutrients, are often burned as biofuels or used as animal fodder in both Africa and South Asia (Yevich & Logan, 2003).

- *Intercropping, rotations and fallowing:* Non-fertilizer approaches to soil fertility management include fallowing and legume intercropping, or rotations with various grain legume/pulse species. These techniques are widely used in both SSA and SA. Traditionally in SSA, farmers have employed slash-and-burn shifting agriculture where land is abandoned when exhausted and allowed to return to long-term bush fallow while new land is opened up (Barbier, 2004). As sedentary crop agriculture has expanded in SSA, intercropping frequently appeared in wetter sub-humid areas, and rotations became more common in drier, less populated zones. In SA, cereal-legume sequences and rotations are widespread, particularly in areas that grow cereals during the rains, with legumes grown under irrigation or on residual moisture, or as a short "catch-crop" (a quickly growing crop planted between two regular crops). Some rotations with annual grain legumes, such as maize-groundnut, can provide large improvements in maize yields (doubling is common) although effects tend to decline in less fertile conditions (e.g., Waddington *et al*., 2007a).

- *Agroforestry*: Agroforestry consists of integrating trees and shrubs into annual crop production in the form of wind breaks, live fences, dispersed trees in fields, and/or more intensive shrub and tree intercropping, rotations or improved fallows. Combinations of agroforestry technologies can simultaneously reduce wind and water erosion, increase soil organic matter and N input, and recover nutrients from soil depths below crop rooting zones (Matlon & Spencer, 1984). Recent research strongly supports the intercropping/rotation of maize with planted non-food-producing leguminous tree and shrub species to increase long-term soil fertility and yields (Ajayi *et al.*, 2011). In a meta-analysis of three types of woody legume fallowing systems in SSA, Sileshi *et al.* (2008) reported average yield increases of between 0.8-1.6 tonnes/ha compared to unfertilized continuously mono-cropped maize, and a substantial number of studies reported doubled or even tripled maize yields, especially in low-to-medium fertility conditions. Adapting traditional agroforestry systems such as cereal cropping below *Faidherbia albida* trees in the Sahel (e.g., Kho *et al.*, 2001) have shown considerable promise to add N and P and raise cereal yields.

Interactions between nutrient management strategies are also important considerations. Studies in SSA and SA alike suggest that limited use of organic inputs and fallowing also influences the effectiveness of synthetic fertilizer inputs, since initial soil fertility has an impact on yield returns to fertilizer use. In other words, combined use of organic and synthetic fertilizer can result in higher maize yields than either input used separately (Chivenge *et al.*, 2011). In Côte d'Ivoire, for example, Vanlauwe *et al.* (2001) found maize yields were 1.6-3.7 t/ha higher on fields treated with both urea and organic material than for either of these inputs used alone. In a 26-year study on maize-wheat-cowpea cropping systems in India, Kanchikerimath & Singh (2001) reported that the paired use of synthetic and organic fertilizers had a similar effect. Additionally, since gradients of soil fertility have often built up on smallholder farms through farmer practices over time, fertilizer inputs and management improvements will often lead to greater yield increases on the more-fertile inner fields than the same practices on less fertile outfields (see Tittonell *et al.*, 2007; Wopereis *et al.*, 2006; Giller *et al.*, 2006).

Environmental Impacts of Soil Fertility Management

Literature specific to the environmental impacts of soil fertility management in maize production in SSA and SA is thin. Major agricultural impacts of widespread adaptations to soil fertility constraints include:

- *Fertilizer runoff:* Where synthetic fertilizer use is widespread, runoff into water bodies can lead to eutrophication (resulting in algal blooms) and contamination of drinking water. These impacts have been documented in the irrigated rice-wheat/maize production systems of South and East Asia (Sankararamakrishan *et al.*, 2008; Zhu & Chen, 2002). In SSA, however, the environmental impacts of fertilizer runoff have been limited to date since little is used in most areas.

- *Greenhouse gas emissions:* Both organic and synthetic fertilizers also increase greenhouse gas emissions from agriculture in the form of increasing nitrous oxide emissions from cropland (Reay *et al.*, 2012), as well as in the GHG-intensive production of N fertilizer itself.

The degree to which plants are able to assimilate nutrients also significantly influences environmental impacts. Recent estimates suggest fertilizers are often not efficiently used in agriculture, with 50% or more of applied nitrogen fertilizer not assimilated by plants (Foulkes *et al.*, 2009). However, regional rates of fertilizer use largely determine the severity of runoff. Fertilizer use in Africa is generally very low (Mwangi, 1996; Morris *et al.*, 2007) – in 2010, Africa represented only 3% of total nitrogen fertilizer consumption (FAOSTAT, 2012). Fertilizer runoff and leaching is therefore not currently a significant environmental concern in most areas of Africa - indeed, in the many areas where fertilizer is rarely used, increasing its use, even substantially, should significantly increase maize yields at relatively low costs to the local environment (in the form of N pollution) but potentially large overall environmental benefits (in the form of reduced pressure to bring new land into agricultural use). However, in areas where fertilizer use is already more prevalent, including many places in SA and small areas of Africa, fertilizer pollution is or will likely become a greater concern. For example, together with atmospheric deposition, agricultural runoff accounts for 90% of P and 94% of N inputs into Lake Victoria (Odada *et al.*, 2004). And in South Africa, fertilizer runoff was estimated to contribute 50% of N and P pollution in streams (Nkwonta & Ochieng, 2009).

Expanded use of synthetic fertilizers is also potentially associated with negative environmental feedback loops: a recent World Bank study in Ethiopia reported that repeated synthetic fertilizer use reduced soil organic matter content and led to increased erosion and nutrient runoff (Adamsu, 2009). Nevertheless, overall, with the low levels of fertilizer currently used, in most cases in SSA the short-to-medium term effect of increasing synthetic fertilizer use will likely be increased food production with relatively few negative environmental impacts.

Best Practices for Soil Fertility Management

Effectively addressing poor soil fertility while minimizing negative environmental impacts requires site-specific knowledge of soil conditions and farmer economic constraints and opportunities. Overall best practices include:

➢ *Utilize synthetic and organic fertilizers*: Most of the deficiencies of plant nutrients in the intensifying SSA and SA maize systems can only be met through appropriate use of synthetic and organic fertilizers – more efficient cycling of existing nutrients alone will be beneficial but not enough to substantially raise yields. Farm communities and households can raise the effectiveness with which they use organic inputs through improved refuse/waste recycling, crop residue composting, and use of animal manures. In SA, there may be scope to reduce the large amounts of fertilizer used in maize production through better types of fertilizer, and timing and placement techniques more suited to high rainfall and irrigated conditions. As well as improving use-efficiencies and overall maize yields, good fertilizer use practices reduce losses of nutrients through leaching, volatilization, and contamination of water bodies (Twomlow *et al.*, 2010).

In all cases the appropriate nutrient types should be targeted to where deficiencies (e.g., in P, K, S, or Mg) are clear and where general soil fertility is good or economic returns are most assured (Morris *et al.*, 2007). Other general principles for rainfed maize include early application of N after crop emergence, point placement and cover with soil for N and P, and split application of N with a second dressing conditional on good rainfall. Many of the basic principles for efficient use of synthetic fertilizer with maize in SSA and SA were developed in the 1940s-1970s and then adapted to smallholder farming conditions in various SSA countries during the 1980s-1990s. "Best practices" require adjusting to local circumstances of fertilizer availability, prices, soil types, types of maize, rainfall regimes, practical field management/labor availability, and weed interactions (Waddington *et al.*, 2004).[4] Recent work suggests the application of very small amounts of N (in the range of 15-25 kg N/ha) provides the highest nitrogen use efficiencies and such "microdosing" techniques appear to be highly suited to smallholder maize production in semi-arid zones in SSA (Twomlow *et al.*, 2010).

➢ *Adopt intercropping, rotation and mixed approaches:* Intercropping and rotation with legume species can also reduce some soil fertility constraints, especially if combined with organic or synthetic fertilizer application (Snapp *et al.*, 2010; 1998). Principles for what has become known as 'integrated soil fertility management' in SSA maize systems, including the combination of synthetic and organic inputs with appropriate crop varieties and improved land management based on local knowledge and agronomic principles, have been described by Vanlauwe *et al.* (2010). Mixed approaches to soil fertility management may also reduce GHG emissions associated with soils: a 10-year study in India found that using a combination of organic and synthetic fertilizers on maize-pea-cowpea crop rotation systems increased the amount of soil-sequestered carbon compared to other fertilizer applications (Purakaysatha *et al.*, 2008).

➢ *Practice agroforestry:* As indicated earlier, improved fallowing (in which leguminous perennial shrubs or trees are inter-planted with maize, and the shrubs are then allowed to grow through the dry season) can often provide two or three-fold increases in maize yields in various parts of Africa compared to current farming methods. Best results are achieved when agroforestry is combined with other improved practices such as use of synthetic fertilizer (Garrity *et al.*, 2010; Sanchez, 2002). Some of the simpler to manage and lower-cost systems like the low density planting of *Faidherbia albida* "fertilizer trees" in cropland may have the widest adoption potential while giving more modest but highly sustainable production benefits to maize and other crops (Akinnifesi *et al.*, 2011; Ajayi *et al.*, 2011). Recent initiatives in SSA to promote agroforestry involving perennial legumes, especially improved tree/shrub fallows and intercrops, have reported widespread success (see Ajayi *et al.*, 2011; Garrity *et al.*, 2010), although the degree of long-term adoption remains uncertain.[5]

Oftentimes mismatches between economic and environmental incentives arise in farmer intercropping and fallowing decisions: hence although numerous studies report yield and soil fertility benefits in legume-maize mixed cropping systems, some question their financial viability and practicality. For example, Waddington *et al.* (2007b) reported that although long-term maize yields in pigeonpea-maize intercrops in Zimbabwe were higher than for sole-cropped maize, limited opportunity to sell legume grain surpluses and the increased labor necessary for legume cultivation made sole maize cropping more financially viable on a large scale. Thierfelder *et al.* (2012) found a similar result in a study of maize rotations in Malawi, Mozambique, Zambia and Zimbabwe. While there are acceptance issues with increasing the use of annual legumes in maize cropping systems (e.g., Snapp *et al.*, 2002), in general, grain legumes

[4] For example, work that went into developing zone-specific fertilizer recommendations for hybrid maize in Malawi based on soil type and whether the maize was for home consumption or market sale is described in Benson (1998) and Waddington *et al.* (2004).

[5] Many agroforestry systems require substantial management by farmers, and woody legume fallowing systems do reduce the area available for planting maize and the number of maize plants grown per hectare (although traditional staggering of fallowing over several fields on a farm means maize can be grown each year). Thus productivity increases must be substantial to more than compensate for crops not grown if adoption is to be economically and socially feasible.

that provide food and income as well as help soil fertility in mixed cropping systems are the most attractive to farmers.

Water Constraints

The vast majority of the agricultural area in SSA is rainfed – You *et al.* (2011) estimated that only 13 Mha (6%) of agricultural land in Africa is currently irrigated. Maize in SSA is usually grown as a rainfed crop in sub-humid and semi-arid zones, characterized by short rainy seasons of variable lengths and with significant dry spells, and often on shallow sandy soils (e.g. Waddington *et al.*, 1995). An estimated 22% of mid-altitude or subtropical maize and 25% of lowland tropical maize in SSA is affected by drought (Cairns *et al.*, 2011). Gibbon *et al.* (2007) considered drought to be among the three most severe and widespread constraints for maize in the most important farming systems for maize in SSA.

In Asia, where irrigation is widespread, drought mainly affects maize in rainfed upland crop systems (that support 48 million rural poor and produce roughly 16 million metric tons of maize annually) (Gerpacio & Pingali, 2007). Overall, drought-related maize losses across irrigated and rainfed systems in SA are thought to be modest. However, *excess* water from flooding or heavy rainfall may lead to yield reductions as high as 17%, particularly in lowland rice-maize systems or in the pre-monsoon season (Ali *et al.,* 2009).

Although water is routinely identified by smallholders as a main limiting factor for agriculture, total annual rainfall is frequently sufficient to grow crops, even in dry regions (Rockstrom *et al.*, 2003). Despite being susceptible to drought, maize is water-efficient (it can produce a large amount of grain per unit of water used by the crop) relative to other major crops. In Bangladesh for example, maize needs only around 850 l water per kg grain produced (with 2-4 irrigations) compared with 1,000 l/kg for wheat grain (1-3 irrigations) and over 3,000 l/kg for rice (with 20-35 irrigations) (Ali *et al.*, 2009).

Improved soil and water management, including rainwater capture and irrigation, can provide additional water to address maize water constraints where economically and ecologically practicable.

Adaptations to Water Constraints

Strategies for water management in maize systems include:

- *Irrigation:* Two studies on maize cultivation using rainwater harvesting in Tanzania estimated that irrigation increased maize yields by 120-152% (Hatibu *et al.*, 2006). Another study reported profits from irrigated maize farming were more than double relative to those from farms without rain catchment; greater crop water availability also raises the efficiency of other inputs, particularly fertilizers (Kayombo *et al.*, 2004). You *et al.* (2011) suggest that properly targeted investments in small- and large-scale irrigation might allow irrigated area in SSA to expand by as much as 24 Mha over the next 50 years, an increase of 177%. Opportunities and gains to expanding irrigation are less certain in Asia, where irrigation water is becoming increasingly scarce (IRRI, 2004).

- *Land management*: Soil management and water management are critically interrelated (Bossio *et al.*, 2010; Sanchez, 2002). Practices such as intercropping with legumes and trees (see earlier) increase soil water retention and soil nutrient content simultaneously. Similarly, soil residue retention strategies (as part of conservation agriculture) have also been shown to improve soil water infiltration and retention (e.g., Thierfelder & Wall, 2009; Rockström *et al*., 2009; Fowler & Rockström, 2001). Other land management systems were developed and promoted specifically for water capture and infiltration into maize fields, including tied-ridging (where soil is used to cross-tie the ridges over the furrows to better hold water for infiltration) and 'pot-holing' or micro-catchments (where periodically-spaced small basins are made on the soil surface to collect water before it can run off) (see e.g., Jensen *et al.*, 2003).

When improved water management/irrigation is not possible or rainfall is exceptionally variable, drought tolerant varieties may help lower yield gaps and reduce yield variability.

- *Drought tolerant varieties:* Drought tolerant maize is often advocated as a means of overcoming water constraints (e.g., La Rovere *et al.*, 2010). Maize varieties and hybrids have been developed to tolerate water deficits around flowering and have been widely tested and supplied to smallholder farmers in SSA over the last 10-15 years (Bänziger *et al.*, 2006). More recently, similar work has been undertaken in Asia. A 2011 report on field trials in eight eastern and southern African countries by the Drought Tolerant Maize for Africa (DTMA) initiative found drought tolerant maize varieties outperformed commonly grown local maize hybrids by 35% in areas of low agricultural productivity. The private sector is active in developing and promoting drought tolerant maize germplasm products (Edmeades, 2008). In SSA for example, CIMMYT drought tolerant maize varieties are produced and marketed by (often small) private seed companies. In SA, several big seed companies are breeding and marketing maize hybrids with drought tolerance for rainfed environments.

Environmental Impacts of Water Management

Environmental impacts of current water management efforts broadly include:

➢ *Water depletion*: In SSA, many countries have yet to fully exploit surface and underground water resources and there is some opportunity for expanding irrigation. But if water use increases, water depletion (extraction faster than recharge rates) may become a concern. In SA water depletion is already a more serious concern; groundwater depletion is widespread in India (Wada *et al.*, 2010). In many parts of SA, water availability is becoming an increasing problem due to increasing demand from urban areas and industry, and from agriculture (Barker *et al.*, 2010). Further expanding irrigation will likely be difficult given these competing demands (Rjisberman, 2006; Tuong *et al.*, 2004). Importantly, incorporating more water-efficient crops such as maize into rice-based farming systems may actually *raise* the overall efficiency of water use in these farming systems.

➢ *Crop substitution and agricultural expansion*: A long-term trend in SSA has been for maize to replace more drought-tolerant cereals like sorghum and millets. If more drought-tolerant varieties of maize become available, allowing more crop substitution from traditional crops to maize, farmers could potentially be more vulnerable when a severe drought occurs. Drought tolerant maize may also allow marginal lands to remain in cultivation, and could lead previously uncultivable land to come under production, contributing to deforestation and natural habitat destruction. However no estimates of specific environmental impacts associated with the adoption of drought tolerant maize are available at the time of preparing this brief.

Best Practices for Water Management

Best practices for overcoming water constraints in smallholder maize production include:

➢ *Practice conservation agriculture*: Various reduced and zero tillage (and associated soil surface residue retention) field management systems, referred to collectively as 'conservation agriculture,' may help water infiltration and retention in soil for crops (e.g., Rockström *et al*., 2009; Lal, 2009). Background on these types of intervention was provided in the earlier section on pre-production land use management practices.

➢ *Expand water harvesting and small-scale irrigation:* The FAO (1997) has long advocated for small-scale irrigation including river diversion, wells, manual pumps and rainwater catchment as potential methods to increase agricultural production. In principle there are still many opportunities to capture, store and distribute surface water onto maize crop land in seasonally arid and semi-arid zones. If exploited, such opportunities may help raise maize production by smallholder SSA farmers, though possibilities of additional irrigation in SA are fewer. In SSA, the costs of developing small scale irrigation will often be too large relative to potential yield gains for maize - but in some cases maize might be grown during the off-season for higher-value irrigated crops like rice or sugarcane.

➢ *Use drought tolerant varieties*: Continuing to develop and deploy drought tolerant maize has the potential to help raise maize yields and yield stability, especially in SSA. IFPRI estimated that adoption of drought tolerant maize seed could increase average yields across SSA by 12.6% (Cenacchi & Koo, 2011). La Rovere *et al.* (2010) estimated potential maize yield gains in SSA due to the adoption of drought tolerant maize at 22-25%, though actual benefits would vary depending on the local frequency, timing and severity of drought.

➢ *Incorporate maize into rice systems*: As previously discussed, intensive crop sequence/rotation systems are common in SA, with typical combinations including monsoon rice-irrigated dry season rice and monsoon rice-irrigated dry season wheat. In parts of the eastern Gangetic plain (especially Bangladesh), the increased use of groundwater accessed through tubewells for irrigating the dry season (*boro*) rice crop has contributed to high arsenic levels in irrigation water and rice, presenting a risk to human health (Meharg & Rahman, 2003). Thus, in the face of water constraints and negative environmental impacts of intensive rice production, maize is becoming an increasingly attractive option for sustainably meeting food needs and promoting greater resource use efficiency (Timsina *et al.*, 2011).

A recent IFPRI study by Cenacchi & Koo (2011) found that although both drought tolerant seeds and irrigation would have positive impacts on SSA maize yields, irrigation would have the larger relative impact. The disparity was even greater when temperature and rainfall assumptions were varied to account for climate change. Nevertheless, improved drought tolerant maize can provide modest benefits at little or no additional cost to the farmer (the seed might be slightly more expensive) while irrigation and water management interventions can give substantial benefits but do require major recurrent investment in infrastructure, fuel, labor and timely decision making — and, of course, the water may simply not be available.

Pests and Other Biotic Constraints

Biotic stressors such as weeds, pests and diseases are responsible for substantial losses in African and Asian maize farming systems (e.g., Gibbon *et al.*, 2007; Oerke & Dehne, 2004; Sanchez, 2002). In a global study on the impact of biotic stressors on crop production, Oerke (2006) estimated that weeds, pests and disease led to annual maize losses of 5-19%. The type of insect, disease and weed pests and the magnitude of their effect on maize production varies substantially depending on agro-ecological zone. A 2000 study found downy mildew caused yield losses of up to 80% in wetter lowland tropical regions, *Turcicum* blight can cause yield losses of 15-20%, and gray leaf spot can cause losses of 30% in Africa when infection is present upon maize crop flowering (Pingali & Pandey, 2000). In SA, farmers identified post-flowering stalk rot as the most severe constraint to maize production in a 2001 survey in the states of Uttar Pradesh, Madhya Pradesh, Rajasthan, and Bihar in India (Gerpacio & Pingali, 2007).

Other pests of significance include armyworms and stemborers, and the parasitic weed *Striga* can be devastating in parts of SSA. Damage from weeds is often severe in many smallholder maize systems, where much of the yield reduction derives from weed competition with maize for limited soil nutrients/fertilizer inputs and soil moisture (e.g., Dimes *et al.*, 2004). Improved weed control allows fertilizer and water to be used more efficiently (Bishop-Sanbrook, 2005; Dimes *et al.*, 2004).

Adaptations to Biotic Constraints

Adaptations to biotic constraints summarily include:

- *Pesticide and herbicide use:* In Africa, pesticide, herbicide and fungicide use is low. A United Nations Environment Program (2002) report found that SSA accounted for only 5% of global pesticide imports. Various supply, management and crop system barriers have all contributed to the negligible use of herbicides by smallholder farmers in SSA, despite numerous earlier attempts to promote them for maize. Pesticides, herbicides and fungicides are common methods of pest control in SA, but data specific to maize are not available.

- *Pest and disease resistant varieties:* Maize has been bred with tolerance to several pests and diseases, including stemborers (Gouse *et al.,* 2006), downy mildew, gray leaf spot and blight (Pingali & Pandey, 2000). Herbicide-tolerant (Imidazolinone resistant (IR)) maize varieties, in which maize seed is coated with Imazapyr herbicide that kills Striga seedlings and seeds, has been shown to control *Striga* in western Kenya and elsewhere in east Africa, but may not always be cost-effective for smallholder farmers (Mignouna *et al.*, 2010; Kanampiu *et al.*, 2003).

- *Crop diversification:* Crop diversification, including intercropping and rotation systems, are frequently reported to reduce the prevalence of weeds and insect pests. In an on-farm study in Kenya, Khan *et al.* (2011) described how using a "push-pull" system, involving intercropping maize with the legume species *Desmodium* and planting a border of napier grass around the plot border, reduced attacks by stemborers and the prevalence of the weed species *Striga hermonthica*. In a Uganda study, Sekamatte *et al.* (2003) noted a lower prevalence of termite attacks on maize-bean intercrops than on sole-cropped maize plots. Skovgård & Peeter (1997) found that stemborers were 15%-25% less prevalent on intercropped maize-cowpea plots in Kenya. Intercropping may also decrease weeds compared to mono-cropping (Pretty *et al.*, 2011). In another study in Kenya, Oswald *et al.* (2002) showed that intercropping maize with legumes reduced the prevalence of *Striga*, although the size of the effect differed based on cropping configuration and legume type. Shave *et al.* (2012) found weed density was reduced on maize-legume plots, with the magnitude of decrease depending on when the intercrop was planted.

- *Mechanical weed control:* Developing appropriate mechanization for complex small-scale agriculture in SSA remains a challenge. Despite regular labor shortages and/or rising incomes in many rural areas, most maize continues to be hand weeded with hoes, especially in SSA. Many farmers have old worn-out farming implements, thus programs to make and supply improved hoes with better quality blades and handles could raise labor efficiency. Various forms of small animal drawn weeders/ridgers could also reduce the weeding burden. Tractors have found a place in semi-commercial (as well as large-scale commercial) agriculture in some SSA countries, but require large fields, simple cropping patterns and access to financial support.

Environmental Impacts of Pest Management

The greatest environmental concern associated with pesticide use is contamination of the environment, which threatens biodiversity and human health.

- *Pesticide contamination:* Data on the environmental impacts of pesticide use specific to maize in SSA and SA are limited as of the writing of this brief. A more established body of evidence from SA suggests that the use of pesticides can lead to negative environmental outcomes including the destruction of beneficial insect species that control crop pests (Pimental *et al.*, 1992) and periodic examples of acute poisoning and other negative health impacts in communities where pesticides are not safely used (Gupta, 2012). With maize herbicides, one of the bigger problems for smallholders has been the risk of killing susceptible crop species intercropped (and sometimes rotated) with maize, including legumes (e.g., Kanampiu *et al.,* 2002).

- *Pesticide resistance*: Improper use of pesticides can also lead to pest resistance with implications for on-farm productivity and for neighboring farms, substantially increasing the cost of pest control (e.g., Powles, 2008; Whalon *et al.*, 2008). Even where pesticide use is uncommon among smallholders, excessive or improper use of pesticides by larger farms can lead to the emergence of pesticide-resistance with regional implications in the event of outbreaks. Pesticide resistance is also a threat to the potential of newly introduced genetically modified crop varieties: a review by Tabashnik *et al.* (2013) documents the emergence of resistance to the genetically engineered insecticidal trait in Bt crops (Bt maize and Bt cotton) across five continents over the past decade. In a trial in South Africa, researchers found more than 50% of insects were resistant to the pesticide trait in Bt maize.

➢ *Soil erosion:* Studies in Asia (China, Thailand, Laos) and Africa (Ethiopia, Tanzania) have reported that manual soil tillage for weed control can contribute to substantial soil erosion (Kimaro *et al.,* 2005; Zhang *et al.*, 2004; Nyssen *et al.*, 2000; Turkleboom *et al.*, 1999).

Best Practices for Pest Management

Best practices for pest management include:

➢ *Increase crop diversification:* Diversifying planting materials can manage the incidence of pests, weeds and diseases. Agro-ecologically complex systems including "push-pull" systems have offered cost-effective and environmentally beneficial stem borer pest and Striga weed management (De Groote *et al.*, 2010; Vanlauwe *et al.*, 2008). More than 2,000 farmers in western Kenya increased maize yields by 60-70% after adopting maize, grass-strip, and legume intercropping systems that suppress the growth of *Striga* and trap stem-borers (Pretty *et al.*, 2003). The technology has continued to spread in Africa (Khan *et al.*, 2011). Studies of maize intercropping in Latin America and Africa have found that mixed maize-legume plots exhibit significantly fewer pests compared to mono-cropped maize plots (De Groote *et al.*, 2010; Altieri & Nicholls, 2004; Sekamette *et al.*, 2003).

➢ *Use pest and disease resistant varieties:* The use of pest and disease resistant varieties offers promise for addressing pest constraints at low cost to farmers and the environment. A study in South Africa on smallholder maize farms reported that Bt maize averaged 32% higher yields than traditional maize varieties. The CIMMYT Insect Resistant Maize for Africa (IRMA) initiative estimated that Bt maize adoption in Kenya could produce US$208 million in economic benefits over 25 years (De Groote *et al.*, 2003). However, recent research in East Africa cautions the additional costs of improved varieties such as IR maize may not be justified by their increased production (De Groote *et al.*, 2010).

Post-Harvest of Maize

There are relatively few direct environmental impacts associated with maize post-production (apart from air pollution and greenhouse gas emissions from burning crop residues in some areas). Post-harvest losses, however, carry the cumulative burden of all resources consumed in creating the harvest that was lost.

<u>Post-Harvest Losses</u>

Post-harvest losses result from a combination of pests, molds and physical damage during grain storage, processing and transport. Recent studies have shed new light on the magnitude of losses. A study by the World Bank (2011) estimated post-harvest losses for maize in SSA were 10-20% of production. Similarly, the African Post Harvest Losses Information System (APHLIS, 2012) estimates post-harvest maize losses in SSA at roughly 17% of total production. Tefera (2012) estimated that post-harvest losses of maize in SSA represent 14-36% of total production, with the major losses associated with harvesting and drying and with on-farm storage. The expert opinion surveyed by Gibbon *et al.* (2007) estimated post-harvest losses comprised as much as 15% of the total maize yield gap in both SSA and SA.

In rice-maize-wheat cropping systems in Bangladesh, poor storage practices led to estimated post-harvest losses of 2.5% for maize, compared to only 1.5% for wheat. Post-harvest losses from all sources for maize were estimated at 3.6% (Bala *et al.*, 2010).

Major post-harvest losses come from pest infestation, often related to the duration of grain storage and storage conditions. A World Bank (2011) study reported the proportion of post-harvest losses due to pests among smallholders in Kenya, Uganda and Tanzania was 17%, 25% and 40% respectively. Additionally, poor storage practice can lead to mycotoxin contamination and poisoning (Tefera, 2012).

Best Practices for Post-Harvest Management

Post-harvest losses can be minimized through:

➢ *Improve drying:* Insufficiently dried maize is more apt to rot. Drying machines offer a means of increasing the amount of grain that is properly dried and reducing losses due to mold and rotting, and reducing contamination by mycotoxins (World Bank, 2011; Gatea, 2010). Raising awareness of farmers and providing training on sun-drying can reduce crop losses at lower costs.

➢ *Improve storage:* Hermetically-sealed air-tight enclosures that kill insect pests and reduce molds are required to minimize losses. Small metal silos and sealed grain bags effectively reduce damage and spoilage due to pests, and have recently been widely used in developing countries in the Americas, SA and SSA. In some areas, adopting these silos and bags has reduced post-harvest losses to almost zero (Tefera, 2012; Tefera *et al.*, 2011). Using chemical protectants is also increasing in some areas. Additionally, some progress is reported with breeding maize for resistance to certain storage pests, including weevils and grain borer (Tefera, 2012).

- *Expand market and road access:* Public goods investments in developing countries could also decrease post-harvest losses. Reliable market systems and roads allow farmers and farmer groups to better respond to the demand for agricultural products, reducing storage and transit times (Hodges *et al.*, 2011). Large scale central storage facilities represent an additional opportunity for improving postharvest management, potentially reducing post-harvest losses and improving rural agricultural marketing opportunities, but they can be less accessible to poorer or more isolated farmers (Coulter & Onumah, 2002).

Other Environmental Issues: Impacts of Climate Change

Climate change will likely exacerbate the seriousness of some biotic and abiotic constraints to maize production, including high temperature, drought and pests, and has attracted substantial research in recent years. Jones & Thornton (2003) estimated that climate change would reduce global maize yields by 10% by the year 2055. Climate change may also affect where maize can be grown. Schlenker & Lobell (2010) estimated that aggregate maize yields in Africa would decrease by 22% by 2050. Others make more uncertain predictions. For example, using IFPRI's IMPACT model, Nelson *et al.* (2009) estimated that climate change might either increase or decrease global maize yields in developing countries depending on scenario assumptions, but for all scenarios the effect was 3% or less.

The impacts of climate change are likely to be especially severe in the rainfed maize systems of SSA. A recent study by Lobell *et al.* (2011) reviewing over 20,000 maize trials in Africa concluded that each accumulated degree day above 30°C decreased maize yields by 1% under optimal rain-fed conditions, and by 1.7% under drought conditions. The study estimated that 65% of African rain-fed area and 100% of drought prone area would experience yield losses in the event of a one degree C increase in global average temperatures. Mitigation of climate change effects will require farmers to more effectively employ a range of the soil, water and weed management practices described earlier, and in extreme cases switch to improved types of more heat- and drought-tolerant cereal crops such as pearl millet or sorghum. However, some of the potential losses from climate change may be partially offset by high temperature tolerant maize varieties currently under development (see Cairns *et al.*, 2013).

Conclusions and Overall Best Practices

CIMMYT, other international maize research organizations and national partners have advocated for (and made some progress with) the development of drought tolerant, pest resistant and other improved maize varieties to address constraints to maize production. Such research is especially valuable as climate change will likely have a serious impact on maize yields, particularly in rain-fed areas, exacerbating current problems associated with drought and pests.

But at the same time many producers in both SSA and SA are not currently meeting their maize production potential given current seed availability and climate conditions (Licker *et al.*, 2010). This requires farmers' adoption of integrated sets of interventions and practices, many of which can be inherently complex and knowledge intensive. Alongside seed genetic improvements, improved farm-level soil management practices (including reduced tillage, crop residue retention, intercropping and crop rotation) in combination with fertilizer use and weed management, rainwater capture and irrigation water management, and integrated approaches to insect pest and disease management offer promise to address soil fertility constraints, mitigate drought and flood impacts, and reduce pest outbreaks. Improving storage practices can also increase maize productivity, although understanding the magnitude of gains will require more data on current post-harvest losses. Farmers are likely to be best supported with technologies and inputs provided jointly with information systems and training on how to use complex interventions effectively.

Lastly, though expandingthe land area devoted to maize offers an avenue of increasing output – particularly in Africa where land remains relatively abundant – increasing deforestation, biodiversity loss, and greenhouse gas emissions should be carefully monitored, with a view to minimizing them whenever possible.

Methodology:

This literature review was conducted using databases and search engines including University of Washington Library, Google Scholar and Scopus, as well as the following websites: CIMMYT, African Development Bank, World Bank, UNFAO, UNEP, Millennium Ecosystem Assessment and IPCC. Searches used combinations of the following terms: maize, developing world, Sub-Saharan Africa, South Asia, soil fertility, constraints, land, pollution, small-holder, environment, environmental impacts, biotic, drought, climate change, natural resources, yield gap. The methodology also included searching for sources that were identified as central works and examining relevant lists of work cited. This literature review draws upon around 160 cited sources, and relied in equal parts on peer-reviewed publications and data, and publications from major international organizations, especially FAO, CIMMYT, IFPRI, IRRI and the World Bank.

Please direct comments or questions about this research to Leigh Anderson, at eparx@u.washington.edu.

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NOTE: The findings and conclusions contained within this material are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

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