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Agriculture-Environment Series:
Wheat Systems At-A-Glance

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

	Pre-Production	*Production*		*Post-Production*
Environmental Constraints	**LAND AVAILABILITY:** While globally wheat area harvested has decreased, in SSA it has increased from about 8 million ha in 1980 to 9.5 million ha in 2010.	**HEAT STRESS:** Heat stress is noted as the greatest constraint to wheat in India with a linear decline in yield after optimal planting date. **SOIL FERTILITY:** stagnating or declining yields in SA have been tied to lack of K, N, C, Zn, and P.	**WATER CONSTRAINTS:** About 30% of yield losses in India are estimated to be due to water-related constraints. Water constraints exacerbate heat stress. **BIOTIC FACTORS:** Rusts, weeds, and pests lead to reduced yields.	**STORAGE LOSSES:** Temperature and moisture conditions allow fungal growth and insect infestation. Storage losses accounted for only 1.5% in Bangladesh.
Adaptation Strategies	**LAND INTENSIFICATION OR EXPANXION:** In SA, rice and wheat are grown on the same land, alternating seasons.	**AVOID LATE PLANTING:** Wheat can be planted only after rice is harvested in rice-wheat production system. **AGROCHEMICAL INPUT USE:**	**IRRIGATION:** About 80% of wheat grown in India is irrigated. **PESTICIDE, HERBICIDE, FUNGACIDE USE:**	**SECURE STORAGE:** iron silos or seal steel hoppers, alternative low-cost storage such as using bed nets or modifying gases of storage environment.
Environmental Impacts	**LAND DEGRADATION:** gradual degradation of soil over time from planting rice and wheat on the same land, twice a year.	**CREATE NEW LAND CONSTRAINTS:** if new varieties are introduced, new lands may be converted to grow wheat. **AGROCHEMICAL RUNOFF:** Pollution of waterways and greenhouse gas emissions.	**WATER DEPLETION AND CONTAMINATION:** Soil salinization, depleted aquifers, alterations of watershed by changing stream and river flows. Water supplies in India are dwindling. South Africa is largest importer of pesticides in Africa and they have been detected in endangered avian species.	**GREENHOUSE GAS EMISSIONS:** On-field crop residue burning, and transportation great distances from farm to market.
Best Practices	**INCREASE YIELD:** improved management techniques will reduce the need to clear more land.	**CROP ROTATION, FALLOWING, INTERCROPPING, ZERO TILLAGE:**	**ZERO OR REDUCED TILLAGE AND PERMANENT BEDS:** to retain soil moisture.	**UTILIZE WASTES:** Integration of crop residues reduces CO2 emissions and improves soils without adversely affecting yields.

Agriculture-Environment Series: Wheat Systems

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Introduction

This literature review examines the environmental constraints to, and impacts of, wheat production systems in South Asia (SA) and Sub-Saharan Africa (SSA). The review highlights crop-environment interactions at three stages of the wheat value chain: pre-production (e.g., land availability), production (e.g., heat, water, and soil), and post-production (e.g. storage, crop residues, and transport). At each stage we emphasize environmental constraints on production (e.g., poor soil quality, water scarcity, crop pests, etc.) and also environmental impacts of crop production (e.g., soil degradation, water depletion and pollution, greenhouse gas emissions, etc.). We then highlight published best practices for overcoming environmental constraints and minimizing environmental impacts in wheat production systems.

Table 1 summarizes the key environmental constraints and environmental impacts associated with wheat production in SA and in SSA. In reality many crop-environmental interactions are a matter of both cause and effect. For example, water scarcity is both an environmental constraint on wheat production (e.g., drought) and an environmental impact of wheat production (e.g., aquifer depletion due to irrigation).

Responses to environmental constraints on crop production must therefore take into account environmental tradeoffs associated with different practices, and also recognize when short-term adaptations might be exacerbating medium- or long-term environmental constraints.

Production systems

Globally, wheat production systems show a great deal of regional variation, both in terms of climate and farm production practices(Braun *et al.,* 1996). However, wheat is most widely grown in dry, temperate climates. There is usually one growing season per year, as opposed to other crops that have multiple (Clay, 2004). In 2010, SA produced an estimated 124,609,303 tons, or 19% of world production (FAO, 2012). Much of SA wheat is grown in the mixed rice-wheat system of the Indo-gangetic plains, with rice grown during hot, monsoon summer months and wheat grown during cooler, drier winter months under irrigation. Rice-wheat crop systems are located in a broad swathe from Northern Pakistan, through Eastern and Northern India, to Northwest Bangladesh. In a report for the FAO, Sayre(2002) identified this zone as the most important developing-world wheat producing area, accounting for roughly 90% of irrigated wheat production among developing world countries.

Wheat production is far less prevalent in Africa, accounting for only 3% of global wheat production in 2010(FAO, 2012). However, it is important in a number of Africa countries, In SSA, wheat is often grown at higher altitudes, in areas with moderate temperatures and relatively high rainfall (Sayres, 2002). In 2010, the top wheat producing countries in SSA were Ethiopia (%), South Africa (%), and Kenya (%) (FAO, 2012). In Ethiopia, the largest producer, wheat is typically grown by smallholder farmers under rain-fed conditions without the use of agricultural inputs (White *et al.*, 2001).

Pre-Production of Wheat

Land Constraints

One of the most binding constraints on any crop system is the availability of sufficient and suitable land to cultivate. Although globally the area harvested for wheat has decreased in the past several decades, it increased moderately in Africa from 8,118,473 ha in 1980 to 9,528,801 ha in 2010 and in Southern Asia from 37,889,681 ha to 48,087,659 ha (FAOstat 2010). Land is not currently seen as a major constraint to wheat production (Joshi 2007; Hobbs 1998). However, as the climate changes, areas under wheat production may become unsuitable due to rising temperatures. If new wheat varieties are developed, wheat production could expand into new ranges and create pressure to convert non-agricultural lands to wheat production (Hobbs 1998). Habitat conversion to agricultural use may result in loss of biodiversity and changes in drainage and hydrology (Clay 2004).

Adaptation to Land Constraints

- *Intensification:* In South Asia, where land is relatively scarce, farmers have primarily responded to land constraints through intensification with the rice-wheat cropping system.
- *Expansion:* In Ethiopia, Gebreselassie (2006) attributed increased agricultural production to land expansion rather than technology adoption because from 1990-2004

grain production increased by 74%, area cultivated increased 51%, but yields only increased 18%.

Taffesse (2011) concurs that in the last decade yield improvements for cereals in Ethiopia have primarily come from land expansion. However, there is little suitable land available for further expansion of crop cultivation, especially in the highlands. Future cereal production will need to come from yield improvements.

Environmental Impacts of Land Use Strategies

Both agricultural intensification and agricultural expansion have potential negative environmental impacts. Impacts of either practice broadly include:

- *Erosion and land degradation*: Over-cultivation of degraded and marginal lands damages soil structure and reduces water retention capacity. Loss of vegetative cover with land clearing also worsens wind and water erosion, particularly on sloped and drought-prone plots;
- *Soil nutrient mining*: Repeated wheat harvests deplete soil nutrients, including key micronutrients;
- *Climate change*: Greenhouse gas emissions from wheat-related land clearing increase when soil carbon is released due to over-cultivation and when stored carbon in forests and grasslands is released through conversion to wheat cropland; and
- *Loss of wheat genetic diversity*: Production systems favoring multiple annual crops (rather than alternating crops or fallowing) and employing a small number of modern varieties (rather than multiple local varieties) may reduce crop resilience to stressors (Smale et al., 2008).

The consequences of greenhouse gas emissions on climate change are in part attributable to general farming practices rather than individual farmer land use decisions. The consequences of soil erosion and nutrient mining, on the other hand, can be vividly observed at the farm level. Globally, 24% of land experienced degradation from 1995-2008 as measured by declining ecosystem function and productivity, particularly along sloped lands in Africa and Southeast Asia (Bai *et al.,* 2008). In India, decades of twice-annual harvests through an intensive rice-wheat system have led to chronic land degradation and stagnating yields. Lal (2009) reported combined depletion of nitrogen, phosphorous and potassium in thirteen provinces in India to be as much as 80kg/ha annually, while other research suggests yield barriers in part driven by micro-nutrient deficiencies including zinc, boron, and sulfur (Gupta & Seth, 2007). Though wheat-specific data on land degradation are unavailable for Africa, Lal (2009) reported overall annual depletion of nitrogen, phosphorous and potassium on African cultivated lands had averaged 22kg, 2.5kg and 15kg per hectare respectively since 1975 – an amount equivalent to roughly $4 billion dollars in fertilizer per year (Sanchez & Swaminathan, 2005).

Best Practices for Pre-Production Land Use

- *Increase yield:* greater yield on the same land through improved management techniques will reduce the need to clear more land.
- *Maintaining genetic diversity of wheat varieties:* mitigates risk on marginalized lands as an effective strategy for enhancing productivity in the highlands of Ethiopia (Di Falco 2007).
- *Selecting sites suitable for wheat cultivation*: Ecologically beneficial lands (in terms of ecosystem services and habitat) may be unsuitable for wheat when soil, climate and biodiversity impacts are considered (Gupta & Seth, 2007).

Production of Wheat

<u>Heat Stress Constraints</u>

Wheat is sensitive to heat stress because as temperature increases, photosynthesis time shortens, grain-filling time shortens, and mass per grain and overall yields decline (Lawlor & Mitchell 2000). One study on spring wheat found that each degree Celsius of temperature increase during the growing season was linked to a 6% decline in grain yield (Bender et al., 1999). There is a linear decline in yield after the optimal planting date in Indian Gangetic Plains (Hobbs 1998).

Wheat growing regions are defined as heat stressed when the highest average temperature in the coolest month is above 17.5 degrees C. Heat stress can be caused by the climate or late planting of the wheat crop (Waddington 2010; Duveiller 2007). The optimum temperature range for growing wheat is 20-25 C, but temperatures up to 35 C are possible (Porter & Gawith, 1999, Table 3).

Kosina et al. (2007) discussed major constraints to wheat production as perceived by wheat growers in 19 developing counties, including India, Bangladesh, Ethiopia, Sudan, and Zimbabwe. Of respondents surveyed, 57% said they were constrained by heat.

Adaptation to Heat Constraints

- *Avoid late planting:* Much of the wheat grown in India is sown after the ideal planting time window because the wheat fields are only sown after the rice has been harvested.
- *Wheat varieties with natural heat resistance:* Wheat varieties have differing abilities to withstand heat stress. Researchers have identified sources of alleles for heat tolerance, and have introduced them into breeding populations through both conventional methods and biotechnology (Ortiz et al., 2008).

Field experiments have shown that each day of sowing delay leads to roughly 0.8-1.5% yield loss, mostly due to excessive heat near the end of the season (Lobell et al., 2012). Many researchers advocate zero-till management of wheat, which allows wheat to be sown as much as two to three weeks earlier than traditional methods. Adoption of this technique by some farmers, as well as technologies such as earlier maturing rice, led to wheat in India being sown an average of one week earlier in 2010 than in 2000 (Lobell et al., 2012).

Environmental Impacts of Adapting to Heat

- *Additional land constraints:* If new heat-resistant seed varieties are adopted that can grow in areas that were previously unsuitable for traditional varieties, this may create new land constraints to convert land to wheat cultivation.

Best practices for Alleviating Heat Constraints

- *Optimal planting time:* improving management of planting in the rice-wheat crop system will allow for optimal timing of wheat planting (Lobell et al., 2012; Duveiller 2007).
- *Improve heat resistant wheat varieties:* There is a call for new wheat varieties that are heat stress resistant, or that mature earlier with no yield penalties (Waddington 2010).

There is limited literature available that discusses heat constraints specific to SSA.

<u>Water Constraints</u>

Limited water availability, unpredictable rainfall, and drought are constraints to wheat production in both rain-fed and irrigated wheat systems (Waddington 2009). Irrigation is responsible for 87% of the world's consumptive use of water and agriculture is in competition with urban and manufacturing needs (Passioura & Angus 2010).

Water supplies in India are dwindling (Joshi 2007). Li et al (2011) surveyed over 300 informants in India who estimated yield losses to drought at around 10%, but that other water-related constraints such as access and cost of irrigation or flooding of low-lying fields to be around 30%.

Water constraints on wheat are exacerbated by high temperatures due to increased transpiration (Passioura & Angus 2010). Water stress further leads to soil borne pathogen susceptibility (Duveiller 2007).

Adaptation to Water Constraints

- *Irrigation:* Irrigation has been a common adaptation to water constraints in SA. 80% of wheat in India is grown under irrigation. Of that, about a third is full irrigation and the remainder is partial.
- *Manage soil moisture retention:* In Ethiopia where soil moisture is a constraint, two studies found that permanent raised beds reduced runoff, retained soil, and improved wheat yields (Araya et al. 2011; Gebreegziabher et al. 2009). Zero tillage in wheat-rice cropping systems in SA can also be used to retain moisture content (Joshi 2007).

In Ethiopia the *terwah* planting system consisting of traditional plowing followed by making every 1.5–2 m contour furrows, and permanent raised beds with contour furrows at 60–70 cm interval treatments were both shown to increase water utilization and soil conservation by reducing runoff with permanent beds performing better than *terwah*, which performed better than conventional plowing (Gebreegziabher et al 2009).

Reeves et al. (2000) recommends that using zero-tillage on one ha of land in the rice-wheat cropping system of the Indo-Gangetic Plains can save one million liters of irrigation water and 98 liters of diesel fuel, as well as reducing carbon dioxide emissions by 0.25 tons.

Even where water is available through irrigation, drought can still a challenge because the cost of diesel to run the tubewell irrigation systems. For example, In India a significant gap exists between irrigation availability and use (EPAR brief No. 202).

Environmental Impacts of Water Use Strategies

- *Soil salinization:* Irrigation causes soil salinization, which in the long run make soil unfit. It also makes less water available for nonagricultural uses, depletes aquifers, and alters watersheds by changing streams and rivers (Clay 2004).
- *Groundwater depletion:* In SSA, many countries have yet to exploit groundwater resources and there is opportunity for irrigation expansion. However, if water use increases, groundwater depletion (extraction faster than the recharge rate of groundwater) may become a concern. In SA, groundwater depletion is already rampant in India (Wada *et al.*, 2010), and expanding irrigation will likely be difficult given water demand (Tuong *et al.* 2004, Rjbersman 2006).

Best Practices for Water Management

- *Improve soil water retention:* Implement zero tillage, permanent raised beds (including *terwah* system), or fallowing to increase residual water accumulation.
- *Avoid late plating*: In the context of the crop systems in India, Li et al. (2011) recommends sowing wheat earlier and when there is adequate moisture content in the soil.

<u>Soil Fertility Constraints</u>

In rice-wheat systems there has been a gradual degradation of soil fertility over the past several decades from planting rice and wheat on the same land, twice a year every year. Stagnating or declining yields in long-term experiments in South Asia have been tied to declining soil nutrient content, particularly potassium (K) but also including nitrogen (N), carbon (C), zinc (Zn), and phosphorus (P) (Ladha et al., 2003).

Loss of nutrients through erosion is cited as a constraint in Ethiopia due to the hilliness of the terrain (Aune et al. 2006). In fact, Ethiopia has one of the highest rates of soil nutrient depletion in SSA and more than half of the area in the Tigray highlands region is highly degraded (Di Falco et al. 2007).

Adaptations to Soil Fertility Constraints

- *Return nutrients to the soil:* Fertilizer use is low in SSA, with the exception of South Africa, which single-handedly accounts for 38 percent of the fertilizer used in the region. Fertilizer use is significantly higher in SA. Wheat accounts for 20.5% (3.44 million metric tons) of total fertilizer use in India. Using manure as organic fertilizer is beneficial because it gradually releases nutrients back into the soil.
- *Retain soil nutrients:* Zero tillage in wheat-rice cropping systems has been shown to retain nutrient content in the soil (Chatrath 2007). Crop rotation and fallowing can increase future wheat yields because it improves soil fertility and physical properties (Hobbs 1998).

- *Intercropping*: Intercropping with nitrogen fixing legumes can be beneficial to soil fertility (Clay 2004, Hobbs 1998, IRRI 2009).

Numerous studies have been conducted to test the relationship between fertilizer levels and wheat yields. In an experiment in Bangladesh, Hossain et al. (2006) found that 50, 100, and 150 kg of nitrogen resulted in yields of 2.98, 3.47, and 3.70 MT/ha, respectively.

Fertilizer use in India on irrigated wheat (144.9 kg/ha), which accounts for the majority of wheat production, is almost double that of rainfed wheat (75.9 kg/ha) (FAO 2005). India uses over 50 percent of its theoretical maximum (the amount at which additional fertilizer would bring no additional yield) (FAO 2004).

Fertilizer management can make effective use of what is applied so that less fertilizer has to be used. Timing of fertilizer application is important because studies in Australia, China, and Pakistan found that later nitrogen fertilizer application led to increased uptake and yield (Hobbs 1998). In Ethiopia, Haile et al. (2012) found that the timing of the nitrogen application had a significant effect on yield on improved wheat varieties. The highest yield was achieved when ¼ of the nitrogen was applied during planting, ½ at mid-tillering, and ¼ at anthesis (flowering).

Using manure has benefits in addition to improving soil fertility because it increases water holding capacity and infiltration rate, provides biotic benefits such as antagonizing root diseases and generally improves the properties of soil as a growing medium. However, in SA use of manure is in decline because of decreased animal supply because of increased tractor use, increased use of manure as a cooking fuel, and increased labor costs of moving heavy manure to fields (Hobbs 1998).

Environmental Impacts of Soil Fertility Management

- *Surface water and groundwater contamination:* Fertilizer causes subsurface contamination of aquifers (Clay 2004, Hobbs 1998). Waterways become polluted from agrochemical runoff with nitrogen, phosphorous, and silt. Algal blooms in unintended areas from fertilizer runoff deplete oxygen and kill aquatic life (Clay 2004).
- *Greenhouse gas emissions:* Nitrous oxide, a potent greenhouse gas, is generated through use of manure or nitrogen fertilizer (Ortiz 2008).

Best Practices for Soil Fertility Management

- *Fertilizer management*: applying appropriate amounts at the right times.
- *Zero-tillage, crop rotations, or fallowing:* decreases erosion and retains nutrients.
- *Intercropping:* with nitrogen fixing legumes to retain nutrient content in the soil.

Biotic Stress Constraints: Rusts, Weeds, and Pests

Rusts and diseases are significant constraint to wheat production (Waddington 2010; Duveiller 2007). Rust and blotch diseases caused by *Puccinia striiformis* and *P. triticina, Bipolaris sorokiniana* are the most significant disease threats to wheat in India (Joshi 2007). Global migration has been shown to go from Africa through the Arabian Peninsula and then to Middle East, West Asia, and eventually to South Asia. Yellow rust followed this path and Ug99 currently in Kenya and Uganda expected to follow this path and seen as imminent threat to South Asia with current susceptible wheat varieties. Fifty-five percent of survey respondents in 19 developing countries in Kosina, et al. (2007) said that their wheat production was constrained by weeds and diseases.

Weeds decrease wheat yields through competition for nutrients, light, space and water. In Africa, unweeded conditions lead to crop losses for wheat of 50-80% (Gianessi et al., 2009). A survey in Ethiopia found that the weed population was 743 weeds per square meter, in comparison to only 149 wheat plants per square meter (Tanner & Sahile, 1991). In the rice-wheat cropping systems of South Asia, the most dominant weed, known as littleseed canarygrass (*Phalaris minor*), can cause yield reductions of up to 95% (Chhokar & Sharma, 2008).

Rodents are a major obstacle to wheat production in SSA. In a study in Ethiopia, higher levels of rodent damage were observed in the later development stages of the wheat crop, as well as in areas with a higher density of stone bunds (low-lying stone walls) (Yonas et al., 2011). Farmers in Ethiopia have also identified rodents as the number one pre- and post-harvest crop pests (Yonas et al., 2010).

Loss of diverse wheat varieties can make wheat crops more vulnerable to biotic stresses. Cultivation of wheat varieties that are genetically similar leaves the crop more vulnerable to the spread of disease (Smale et al, 2008).

Adaptations to Biotic Stress Constraints

- *Fungicides, herbicides, and pesticides*: The quantities of pesticides used per hectare are not large for wheat compared to other crops, but the amount of land that wheat is grown globally has a significant aggregate effect (Clay 2004).

Herbicide use among smallholder farmers in Sub-Saharan Africa is low, with an adoption rate of less than 5% (Gianessi & Williams, 2011).

Environmental Impacts of Pest and Disease Management

Use of fungicides, herbicides, and pesticides can lead to (Chatrath 2007):
- Herbicide resistant weeds
- Groundwater contamination
- Endangered species

In South Asia, reliance on herbicides has at times led to herbicide-resistant weeds, most notably in the early 1990s, when herbicide-resistant littleseed canarygrass (*Phalaris minor*) caused large-scale wheat crop devastation (Yadav & Malik, 2005).

South Africa is one of the largest importers of pesticides in Africa. Quin et al (2011) estimates that there is not sufficient water in the country to dilute the amount of pesticides used to acceptable levels. There are 11 critically endangered avian species and 43 listed as vulnerable and pesticides have been detected in wild bird species. As pesticides contaminate various habitats, this causes concern for the impact of agricultural activities on vulnerable species.

Best practices of Pest and Disease Management

- *Zero tillage:* in wheat-rice cropping systems had been shown to reduce weeds (Joshi 2007).
- *Increase diversity of wheat varieties:* diversify crops within and across growing seasons.
- *Crop rotation and fallowing*: breaks up disease and insect pest cycles (Hobbs 1998).

Post-production of Wheat

Post-Harvest Losses

Post-harvest losses at the farm level for wheat have been estimated at 3.28 kg/q and are highest during storage when temperature and moisture conditions allow fungal growth and insect infestation (Mathew 2011). A study of less developed countries estimated the postharvest loss of wheat in east and southern Africa to be around 13% (Hodges 2011). A study in Bangladesh found total post-harvest losses for wheat to be at 3.62% [consisting of .77% for harvesting, .09% transporting, .65% for threshing, .62% for drying, and 1.54% for storage]. (Bala et al 2010).

Adaptations to Post-Harvest Losses

While overall post-harvest losses are low, the greatest losses came from storage. Bala et al (2010) attributes this to lack of awareness about extent of storage loss, poor storage structures, and presence of rodents, insects, and dampness.

Environmental Impacts of Post-Harvest Losses

Post-harvest losses carry the burden of all resources consumed in creating the harvest that was lost. Reducing the loss therefore reduces the unit weight or unit area environmental impact of the wheat harvest each year.

Best Practices for Post-Harvest Losses

- *Secure metal storage:* Studies have found that iron silos or sealed steel hoppers can prevent fungi and insect infestation (Tefera et al 2011, Mann et al 1999).
- *Alternative storage options:* Dowell and Dowell (2012) discussed alternative low-cost storage solutions that are more accessible to smallholder farmers in developing countries such as using insecticide-treated bed nets or novel repellents, and creating modified atmospheres with carbon dioxide.

Crop Residues Disposal

In wheat-rice systems, the same land is used to grow two crops during the year. When crop residue is left on the land, nutrients will return to the soil through decomposition. However, with short seasons and a quick turnaround between crops, there may not be enough time for crop residue to decompose naturally before the next crop has to be planted.

Adaptations to handling Crop Residues

- *Crop residue burning:* the most common practice to remove crop residue between crops (Clay 2004, Prasad et al 1999).

Environmental Impacts of Crop Residue Burning

- *Air pollution and CO2 emissions*: The Indian Agricultural Research Institute estimates that 2% of total agricultural greenhouse gas emissions in India are caused by on-field crop residue burning (2012). A study in Suqian, China found that about 2 million tons of carbon dioxide were released from burning rice-wheat crop system residue (Yang el al 2008).

Best Practices for Crop Residue Management

- *Incorporate crop residues:* crop residue incorporation is the preferred alternative to avoid environmental hazards of crop residue burning.

In a study on rice-wheat systems in India, Prasad et al (1999) compared plots where crop residue was removed, burned, or incorporated with a plow. They found that wheat can be grown successfully immediately after the incorporation of rice residues without adversely affecting yields and that the practice gradually improves soil fertility for organic carbon, and available phosphorous and potassium.

Transportation

The wheat harvest must be transported great distances from farm to market and many countries such as Bangladesh are wheat-import reliant. In Ethiopia, the largest wheat producer in Africa, Amhara and Oromia regions produce 88% of wheat and then it must be transported to other regions for consumption, often hundreds of miles away. (EPAR brief No. 204). In India the average transportation distance for wheat is estimated at 250-1000 km for the upper and lower Indo-Gangetic plains, respectively (Pathak 2012). Pathak et al (2012) quantified greenhouse gas emissions (CO2, CH4, and N2O) from the rice - wheat systems in the Indo-Gangetic plains and estimated that transportation to market accounted for 30-32% of greenhouse gas emissions of the wheat production life cycle.

Climate Change

Joshi, et al. (2007) noted heat stress as the greatest constraint in India and climate change will continue to increase heat stress. In India wheat yields were steadily increasing for about 30 years until the year 2000 due to heat stress from rising temperatures. The cool period to grow wheat in India is shrinking. Several decades ago, temperatures above 40 were rare before March 30, but now temperatures above 40 degrees C are occurring about one week earlier. One study on spring wheat found that each degree Celsius of temperature increase during the growing season was linked to a 6% decline in grain yield (Bender et al., 1999).

Conclusions and Overall Best Practices

Wheat is a significant crop that will need to increase production to meet increasing demand. Most land suitable for wheat production is already under cultivation. Improved production methods are needed to address the demand and avert environmental impacts of producing wheat. It should not be assumed that improved varieties alone will be able to realistically address growing demands for wheat. Improved variety seeds should be combined with best practices of improved crop management techniques: optimal planting time, zero tillage, fertilizer management, intercropping, crop residue incorporation, and improved storage techniques.

Methodology

This literature review was conducted using databases and search engines including University of Washington Library, Google Scholar, as well as the following websites: UNFAO, CIMMYT, IFPRI, and IRRI. Searches used combinations of the following terms: wheat, environmental impact, Sub-Saharan Africa, Ethiopia, Kenya, South Asia, India, heat, drought, soil, weed, fungicide, herbicide, insecticide, fertilizer, pest, insect, rodent, land expansion, biodiversity, zero tillage, losses, emissions. The methodology also included searching for sources that were identified as central works and examining relevant lists of works cited. This literature review draws upon over 50 cited sources, and relied on peer-reviewed publications and data and publications from major international organizations, especially FAO.

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

Works Cited

Araya, T., Cornelis, W. M., Nyssen, J., Govaerts, B., Bauer, H., Gebreegziabher, T., ... & Deckers, J. (2011). Effects of conservation agriculture on runoff, soil loss and crop yield under rainfed conditions in Tigray, Northern Ethiopia. *Soil Use and Management*, *27*(3), 404-414.

Aune, J. B., Asrat, R., Teklehaimanot, D. A., & Bune, B. T. (2006). Zero Tillage or Reduced Tillage: The Key to Intensification of the Crop–Livestock System in Ethiopia. *Strategies for Sustainable Land Management in the East African Highlands*, *309*.

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. Retrieved from http://doi.wiley.com/10.1111/j.1475-2743.2008.00169.x

Bala, B. K., Haque, M. A., Hossain, A., & Majumdar, S. (2010). Post harvest loss and technical efficiency of rice, wheat and maize production system: assessment and measures for strengthening food security. *Bangladesh Agricultural University*.

Bender, J., Hertstein, U., & Black, C. R. (1999). Growth and yield responses of spring wheat to increasing carbon dioxide, ozone and physiological stresses: a statistical analysis of 'ESPACE-wheat'results. *European Journal of Agronomy*,*10*(3), 185-195.

Braun, H. J., Rajaram, S., & Ginkel, M. (1996). CIMMYT's approach to breeding for wide adaptation. *Euphytica*, *92*(1), 175-183.

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences*, *96*(11), 5952-5959.

Chatrath, R., Mishra, B., Ortiz Ferrara, G., Singh, S. K., & Joshi, A. K. (2007). Challenges to wheat production in South Asia. *Euphytica*, *157*(3), 447-456.

Chhokar, R. S., & Sharma, R. K. (2008). Multiple herbicide resistance in littleseed canarygrass (Phalaris minor): a threat to wheat production in India. Weed Biology and Management, 8(2), 112-123.

CIMMYT, (n.d.). *Global Wheat Program*. Retrieved from http://www.cimmyt.org/en/programs-and-units/global-wheat-program.

Clay, J. (2004). *World agriculture and the environment: a commodity-by-commodity guide to impacts and practices*. Island Press.

Di Falco, S., Chavas, J. P., & Smale, M. (2007). Farmer management of production risk on degraded lands: the role of wheat variety diversity in the Tigray region, Ethiopia. *Agricultural Economics*, *36*(2), 147-156.

Dixon, J. A., Gibbon, D. P., & Gulliver, A. (2001). *Farming systems and poverty: improving farmers' livelihoods in a changing world*. Fao Inter-Departmental Working Group.

Dowell, F. E., & Dowell, C. N. (2012). Novel storage solutions to improve food security for subsistence farmers. *Quality Assurance and Safety of Crops & Foods*, *4*(3), 143-143.

Druilhe, Z. and Barreiro-Hurle, J. (2012). Fertilizer subsidies in Sub-Saharan Africa. ESA Working paper No. 12-04. Rome, FAO. Retrieved from http://www.fao.org/docrep/016/ap077e/ap077e.pdf.

Duveiller, E., Singh, R. P., & Nicol, J. M. (2007). The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics. *Euphytica*, *157*(3), 417-430.

Ehui, S., & Pender, J. (2005). Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. *Agricultural Economics*, *32*(s1), 225-242.

EPAR Brief No. 202. Bihar.

EPAR Brief No.

FAO (2004). Fertilizer requirements in 2015 and 2030 revisited. Retrieved from ftp://ftp.fao.org/agl/agll/docs/fertreqrev.pdf.

FAO (2005). Fertilizer use by crop in India. Retrieved from ftp://ftp.fao.org/agl/agll/docs/fertuseindia.pdf.

Gebreegziabher, T., Nyssen, J., Govaerts, B., Getnet, F., Behailu, M., Haile, M., & Deckers, J. (2009). Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. *Soil and Tillage Research*, *103*(2), 257-264.

Gebreselassie, S. (2006, March). Intensification of smallholder agriculture in Ethiopia: options and scenarios. In *Future Agricultures Consortium Meeting at the Institute of Development Studies*.

Gianessi, L., Bruce, T., Foyer, C., Halford, N., Keys, A., Kunert, K., et al. (2009). Solving Africa's weed problem: increasing crop production & improving the lives of women. Proceedings of 'Agriculture: Africa's" engine for growth"-plant science and biotechnology hold the key', Rothamsted Research, Harpenden, UK, 12-14 October 2009. Association of Applied Biologists.

Gianessi, L., & Williams, A. (2011). Overlooking the obvious: the opportunity for herbicides in Africa. Outlooks on Pest Management, 22(5), 211-215.

Gupta, R. K., Hobbs, P. R., Ladha, J. K., & Prabhakar, S. V. R. K. (2002). Resource conserving technologies: transforming the rice-wheat systems of the Indo-Gangetic Plains. Rice-wheat Consortium-a success story. *Resource conserving technologies: transforming the rice-wheat systems of the Indo-Gangetic Plains. Rice-wheat Consortium-a success story*.

Gupta, R., & Seth, A. (2007). A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop protection*, *26*(3), 436-447.

Grace, P. R., Jain, M. C., Harrington, L., & Robertson, G. P. (2003). Long-term sustainability of the tropical and subtropical rice-wheat system: An environmental perspective. *ASA SPECIAL PUBLICATION*, *65*, 27-44.

Haile, D., Nigussie, D., & Ayana, A. (2012). Nitrogen use efficiency of bread wheat: Effects of nitrogen rate and time of application. *Journal of soil science and plant nutrition*, *12*(3), 389-410.

Hossain, M. I., Islam, M. K., Sufian, M. A., Meisner, C. A., & Islam, M. S. (2006). Effect of planting method and nitrogen levels on the yield and yield attributes of wheat. *Journal of Bio-Science*, *14*, 127-130.

Hobbs, P. R., Sayre, K. D., & Rosas, J. I. O. M. (1998). *Increasing wheat yields sustainably through agronomic means*. International Maize and Wheat Improvement Center.

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

IFPRI, (2012*) Crop Production in Ethiopia: Regional Patterns and Trends*, Retrieved from http://www.ifpri.org/sites/default/files/publications/essprn11.pdf.

IFPRI, (2012) *Sustainable Food Security Under Land, Water, and Energy Stresses.* Retrieved from http://www.ifpri.org/ghi/2012/sustainable-food-security-under-land-water-energy-stresses.

Jackson, M. T. (2009). Revitalizing the Rice-Wheat Cropping Systems of the Indo-Gangetic Plains: Adaptation and Adoption of Resource-Conserving Technologies in India, Bangladesh, and Nepal. *Final Report. IRRI Ref. No. DPPC2007-100*.

Joshi, A. K., Mishra, B., Chatrath, R., Ortiz Ferrara, G., & Singh, R. P. (2007). Wheat improvement in India: present status, emerging challenges and future prospects. *Euphytica*, *157*(3), 431-446.

Kato, E., Ringler, C., Yesuf, M., & Bryan, E. (2011). Soil and water conservation technologies: a buffer against production risk in the face of climate change? Insights from the Nile basin in Ethiopia. *Agricultural Economics*, *42*(5), 593-604.

Khan, S., Tariq, R., Yuanlai, C., & Blackwell, J. (2006). Can irrigation be sustainable?. *Agricultural Water Management*, *80*(1), 87-99.

Kosina, P., Reynolds, M., Dixon, J., & Joshi, A. (2007). Stakeholder perception of wheat production constraints, capacity building needs, and research partnerships in developing countries. *Euphytica*, *157*(3), 475-483.

IRRI, (2007) *Crop Residue Management*, retrieved from http://www.knowledgebank.irri.org/ckb/agronomy-wheat/crop-residue-management.html.

IRRI, (2007) *The importance of legumes in cereal cropping systems*, retrieved from http://www.knowledgebank.irri.org/ckb/agronomy-wheat/the-importance-of-legumes-in-cereal-cropping-systems.html.

IRRI, (2009) *Effective fertilization of cereal crops*, retrieved from http://www.knowledgebank.irri.org/ckb/agronomy-wheat/effective-fertilization-of-cereal-crop.html.

Ladha, J. K., Dawe, D., Pathak, H., Padre, A. T., Yadav, R. L., Singh, B., ... & Hobbs, P. R. (2003). How extensive are yield declines in long-term rice–wheat experiments in Asia?. Field Crops Research, 81(2), 159-180.

Lal, R. (2009). Soil degradation as a reason for inadequate human nutrition. *Food Security*, *1*(1), 45–57. Retrieved from http://www.springerlink.com/content/v16rj23l57444812/

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.

Lawlor, D. W., & Mitchell, R. A. (2000). Crop ecosystem responses to climatic change: wheat. *Climate change and global crop productivity. CAB Int., Wallingford, UK*, 57-81.

Laxmi, V., Erenstein, O., & Gupta, R. K. (2007). CIMMYT. Assessing the impact of natural resource management research: The case of zero tillage in India's rice–wheat systems. *The Impact of Natural Resource Management Research: Studies from the CGIAR. CAB International, Wallingord, UK*, 68-90.

Lillemo, M., Van Ginkel, M., Trethowan, R. M., Hernandez, E., & Crossa, J. (2005). Differential adaptation of CIMMYT bread wheat to global high temperature environments. *Crop Science*, *45*(6), 2443-2453.

Lobell, D. B., Ortiz-Monasterio, J. I., Sibley, A. M., & Sohu, V. S. (2012). Satellite detection of earlier wheat sowing in India and implications for yield trends. *Agricultural Systems*.

Mann, D., Jayas, D. S., White, N. D., & Muir, W. E. (1999). Preventing insect entry into welded-steel hopper. *Stored product protection. Schiuan Publ. House Sci. Technol., Chengdu*, 1326-1332.

Mathew, S., Thomas, G., & Ahmad, T. (2011). An Evaluation of the Fungi Isolated from Sub-epidermal Region of Post-harvested Stored Wheat Grains.Nepal Journal of Biotechnology, 1(1), 9-13.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., ... & West, J. (2004). Mapping vulnerability to multiple stressors: climate change and globalization in India. *Global Environmental Change*, *14*(4), 303-313.

Ortiz, R., Sayre, K. D., Govaerts, B., Gupta, R., Subbarao, G. V., Ban, T., ... & Reynolds, M. (2008). Climate change: Can wheat beat the heat?. *Agriculture, Ecosystems & Environment*, *126*(1), 46-58.

Passioura, J. B., & Angus, J. F. (2010). Improving productivity of crops in water-limited environments. *Advances in agronomy*, *106*, 37-75.

Pathak, H., Agarwal, T., & Jain, N. (2012). Greenhouse Gas Emission from Rice and Wheat Systems: A Life-Cycle Assessment. *Low Carbon Technologies for Agriculture: A Study on Rice and Wheat Systems in the Indo-Gangetic Plains*, 54.

Porter, J. R., & Gawith, M. (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy*, *10*(1), 23-36.

Prasad, R., Gangaiah, B., & Aipe, K. C. (1999). Effect of crop residue management in a rice–wheat cropping system on growth and yield of crops and on soil fertility. *Experimental Agriculture*, *35*(4), 427-435.

Quinn, L., de Vos, B. J., Fernandes-Whaley, M., Roos, C., Bouwman, H., Kylin, H., ... & van den Berg, J. (2011). Pesticide Use in South Africa: One of the Largest Importers of Pesticides in Africa.

Rahman, S. (2010). Six decades of agricultural land use change in Bangladesh: Effects on crop diversity, productivity, food availability and the environment, 1948–2006. *Singapore Journal of Tropical Geography*, *31*(2), 254-269.

Reeves, T., Pingali, P. L., Rajaram, S., & Cassaday, K. (2000, June). Crop and natural resources management strategies to foster sustainable wheat production in developing countries. In *Proceedings of the 6th International Wheat Conference* (pp. 22-36).

Reynolds, M. P., Pietragalla, J., & Braun, H. J. (2008). *International Symposium on Wheat Yield Potential: Challenges to International Wheat Breeding*. Cimmyt.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management*, *80*(1-3), 5-22. Retrieved from http://dx.doi.org/10.1016/j.agwat.2005.07.001

Sanchez, P.A., Swaminathan, M.S. (2005). Hunger in Africa: The link between unhealthy people and unhealthy soils. *Lancet*, 365: 442–444.

Sayre, K.D. (2002). Management of Irrigated Wheat. In B.C. Curtis, S. Rajarm & H. Gomez Macpherson, *Bread Wheat: Improvement and Production.* FAO.

Smale, M., Hartell, J., Heisey, P. W., & Senauer, B. (1998). The contribution of genetic resources and diversity to wheat production in the Punjab of Pakistan. *American Journal of Agricultural Economics*, *80*(3), 482-493.

Smale, M., Singh, J., Di Falco, S., & Zambrano, P. (2008). Wheat breeding, productivity and slow variety change: evidence from the Punjab of India after the Green Revolution*. *Australian journal of agricultural and resource economics*,*52*(4), 419-432.

Taffesse, A. S., Dorosh, P., & Asrat, S. (2011). Crop production in Ethiopia: regional patterns and trends. *Ethiopia Strategy Support Program II (ESSP II) Working Paper*, (0016). http://www.ifpri.org/sites/default/files/publications/essprn11.pdf

Tanner, G. T., & Sahile, G. (1991). Weed control research conducted on wheat in Ethiopia.

Tefera, T., Kanampiu, F., De Groote, H., Hellin, J., Mugo, S., Kimenju, S., ... & Banziger, M. (2011). The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries. *Crop Protection*,*30*(3), 240-245.

Tuong, T. P., Bouman, B. A. M., & Mortimer, M. (2004). More Rice , Less Water — Integrated Approaches for Increasing Water Productivity in Irrigated Rice-Based Systems in Asia, 1-13.

Yadav, A. and Malik, R. K. (2005). Herbicide Resistant Phalaris minor in Wheat – A Sustainability Issue. Resource Book. Department of Agronomy and Directorate of Extension Education, CCSHAU, Hisar, India pp. 152. Retrieved from http://www.hau.ernet.in/farmer/herbicide.pdf.

Yang, S., He, H., Lu, S., Chen, D., & Zhu, J. (2008). Quantification of crop residue burning in the field and its influence on ambient air quality in Suqian, China. *Atmospheric Environment*, *42*(9), 1961-1969.

Yonas, M., Welegerima, K., Deckers, S., Raes, D., Makundi, R., & Leirs, H. (2010). Farmers' perspectives of rodent damage and management from the highlands of Tigray, Northern Ethiopian. Crop Protection, 29(6), 532-539.

Yonas, M., Welegerima, K., Sluydts, V., Teferi, M., Yirga, G., Nyssen, J., Deckers, J., et al. (2011). Crop damage, rodent abundance and stone bund density in Tigray highlands, Ethiopia. Water 2011, Abstracts (pp. 105–105). Presented at the International congress Water 2011 : Integrated water resources management in tropical and subtropical drylands, VLIR UOS - Mekelle University IUC Programme.

Wada, Y., Beek, L., Kempen, C., Reckman, W. T., Vasak, S., & Bierkens, M. (2010). Global depletion of groundwater resources. *Geophysical Research Letters*, *37*. Retrieved from http://tenaya.ucsd.edu/~tdas/data/review_iitkgp/2010GL044571.pdf

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.

White, J. W., Tanner, D. G., & Corbett, J. D. (2001). *An agro-climatological characterization of bread wheat production areas in Ethiopia*. CIMMYT.