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Evans School Policy Analysis and Research (EPAR)
Professor Leigh Anderson, PI and Lead Faculty
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Agriculture-Environment Series:
Rice Systems At-A-Glance

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

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

	Pre-Production	*Production*		*Post-Production*
Environmental Constraints	**LAND CONSTRAINTS:** Open land suitable for rice is scarce in South Asia. In SSA, some land suitable for rice cultivation is not yet under production.	**WATER** is critically important to rice productivity. Current water use practices may not be sustainable given increasing global water demand.	**SOIL FERTILITY (SF) and BIOTIC FACTORS (BF):** Soil fertility and biotic factors are serious constraints to yields across rice growing systems in SSA and SA.	**POST-HARVEST LOSSES:** Losses due to inappropriate rice processing and storage practices are estimated to be between 15-16% of production.
Rank Importance	4	1	SF=2, BF=3	5
Adaptation Strategies	**EXPAND or INTENSIFY:** In SSA, area expansion possible; converts non-agric. land to crops. In SA limited scope to expand; use of inputs drives rice production.	**IRRIGATION:** Irrigation accounts for 90% of fresh water diverted in Asia; 50% of irrigation water is used in rice production. Irrigation use is far lower in Sub-Saharan Africa but growing.	**AGROCHEMICAL INPUT USE:** When farmers have access, many rice farmers apply synthetic fertilizers, pesticides, and herbicides.	**SECURE STORAGE:** Use of appropriate facilities, bagging, spacing and hygienic practices reduce losses from pests and grain contamination.
Environmental Impacts	**LAND & HABITAT/BIODIVERSITY DEGRADATION:** 55% of new agricultural land in Africa from 1975-2000 was developed through deforestation.	**WATER DEPLETION:** Irrigated rice production accounts for 79Mha of rice area and 75% of total production. Rice uses 2-3 times more water than other major cereal crops. Increasing water scarcity threatens the productivity of irrigated rice worldwide.	**AGROCHEMICAL MISUSE:** Overuse of fertilizers and pesticides reduces productivity (increases costs) and has led to resistant pests and health impacts for farmers and consumers. **GREENHOUSE GAS EMISSIONS:** Flooded rice fields are a major source of methane (CH_4), a potent greenhouse gas.	**LOCAL AIR POLLUTION:** Crop residue disposal often involves burning. In China and South Asia, an estimated 350Tgs of crop residues are burned each year.
Best Practices	**INTENSIFICATION:** Managing soils, crop rotation and prudent input use can raise productivity on good sites, avoiding critical habitat and marginal lands.	**WATER CONSERVATION & SPECIES SELECTION:** Water management including mid-season draining raises water use efficiency. Drought-tolerant varieties can also increase yields.	**INTEGRATED PEST MANAGEMENT:** A suite of farm management practices alongside prudent agrochemical use for outbreak control can reduce yield losses. **BALANCED NUTRIENT MANAGEMENT:** Use of well timed, site-specific nutrient packages can overcome key soil nutrient constraints.	**UTILIZE WASTES:** Integration of crop residues reduces CO_2 emissions and improves soils. However this may *increase* CH_4 emissions in submerged rice.

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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 rice production systems in South Asia (SA) and Sub-Saharan Africa (SSA), noting where the analysis applies to only one of these regions. We highlight crop-environment interactions at three stages of the rice value chain: pre-production (e.g., land clearing), production (e.g., water and other input use), and post-production (e.g., waste disposal). At each stage we emphasize environmental constraints on production (e.g., poor soil quality, water scarcity, crop pests) and also environmental impacts of crop production (e.g., soil erosion, water depletion, pest resistance). We then highlight best or good practices for minimizing negative environmental impacts in smallholder rice production systems.

Rice is the most important food crop of the developing world and is grown on over 155 million ha worldwide. Food security of the poor, especially in Asia, depends critically on rice availability at an affordable price. Meeting the food needs of a growing global population will require sustainable increases in rice productivity (Hazell, 2010). Rice productivity is largely determined by environmental resource limits, such as availability of water and soil nutrients, by technological options for overcoming such constraints, and by institutions and policies that either support or discourage productive and sustainable farming practices.

Agricultural intensification in East and South Asia, driven by adoption of irrigation, fertilizers, improved seed varieties, and pesticides, has contributed to dramatic gains in global rice yields, with worldwide rice production more than tripling between 1961 and 2008 (Dawe *et al.,* 2010). These large productivity gains have avoided many of the negative environmental consequences associated with agricultural extensification (bringing more land into cultivation). However, increasingly evidence suggests that intensive rice systems, if not properly managed, can cause substantial environmental damage (e.g., in East Asia) by reducing soil fertility, polluting soil and water resources, depleting groundwater supplies, and contributing to global warming.[1]

Promoting greater resource use efficiency and minimizing the negative environmental impacts of rice production will promote the long-term sustainability of rice farming systems. In the short term, however, improving the sustainable productivity of rice may require balancing competing environmental protection and food production priorities. Responses to resource constraints in rice production must therefore take into account the positive and negative environmental effects associated with different practices. Table 1 summarizes the key environmental constraints and environmental impacts associated with rice production in SA and in SSA.

As shown in this review, evidence on environmental issues in smallholder rice production is uneven. Far more research is available for Asian rice production systems, as compared to African rice systems. And with the possible exception of the evidence on water limits to increasing productivity, conclusions on the strength of published findings on crop-environment interactions in rice depends 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.

The last row of *Table 1* summarizes best, or good practices currently identified in the literature. However, the appropriate strategy in a given situation will vary widely based on contextual factors, such as local environmental conditions, market access, cultural preferences, production practices and the policy environment.

Rice Production Systems

Environmental interactions in rice cultivation are largely determined by the nature of rice production systems. Major rice production systems worldwide include irrigated lowland (88 to 90M hectares worldwide), rainfed lowland (44 to 46M hectares), rainfed upland (15 to 16M hectares) and deepwater/floating ecosystems (3 to 4M hectares) (FAO, 2012). Intensive rice systems, which are mostly irrigated, have higher productivity, but also require greater resources (especially water and fertilizers) and typically generate

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[1] In this brief, we focus on the contribution of rice production to climate change. However, we also note the potential impact of climate change on rice productivity. Climate change might negatively impact productivity by exacerbating the seriousness of some biotic and abiotic constraints to production, including temperature, salinity, flood, drought and pests (IRRI, 2004; Wassman *et al*. 2009). Estimates of the global impact of climate change on rice yields vary from relatively minor (Lobell *et al.,* 2011), to moderately severe (Nelson *et al.,* 2009; Kim *et al.,* 2013).

greater negative environmental externalities. Extensive (and usually rainfed) agricultural systems use fewer chemical inputs and less water, but also require more land, negatively impacting the environment when previously natural habitats are brought under cultivation. Broadly speaking, two distinctions are useful in framing discussion of rice environmental interactions in intensive systems:

- *Irrigation:* Intensive rice production systems rely (often heavily) on the use of irrigation water. Water use in rice production has a large positive impact on yield but also myriad environmental impacts. Irrigated rice generally outperforms rainfed rice in terms of per-hectare yields, but it also uses far more surface water and groundwater (Dawe *et al*. 2010), potentially contributing to water shortages. In addition, irrigated rice fields emit higher levels of methane compared to rainfed rice, substantially contributing to climate change (Yusuf *et al.,* 2012). In SA, an estimated 46% of rice is irrigated (Dawe *et al*., 2010); in SSA, only 20% of rice is irrigated, but the area is increasing rapidly (Balasubramanian, 2007).

- *Agrochemical use:* Intensive rice production systems rely (often heavily) on the use of agricultural inputs including synthetic fertilizers, pesticides and herbicides. While the use of inputs generally increases yields, overuse or misuse can lead to environmental damage in the form of pest resistance, impaired soil structure and fertility, and other consequences that may reduce rice productivity in the long-term. Use of agricultural inputs in rice production has consistently been higher in SA rice production compared to SSA rice production.

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

Pre-production of Rice

Land Constraints

One of the most binding constraints on any crop system is the availability of sufficient and suitable land to cultivate. With economic growth, competition for land for alternative uses (such development of industry, expansion of urban areas, or transport development) increases and agricultural production systems must adjust to this land scarcity.

Despite such economic pressures, globally, rice area harvested increased by 10% between 1980 and 2010, from 144 million hectares to 159 million hectares (FAO, 2012). Some of this growth reflects conversion of existing cropland from other crops to rice, or intensification in the form of harvesting two rice crops per plot each year. However, growth in rice area also reflects some conversion of non-farmland to agriculture, particularly in the smallholder rainfed systems of SA and SSA where rice-fallow production (one rice crop per year) is predominant (Dawe *et al*., 2010).

Adaptation to Land Constraints

Adaptations to land constraints vary by region. In South Asia, where land is relatively scarce, farmers have primarily responded to land constraints through intensification. Total rice area harvested in South Asia grew by 9 percent from 1980-2010, from 55M hectares to 60M hectares (FAO, 2012). This primarily reflects many farmers who have intensified production by harvesting 2 or sometimes even 3 rice crops per year from existing cropland (Timsina *et al*., 2010). Such intensification is typically facilitated by the adoption of irrigation, organic and synthetic fertilizers, and pesticides (discussed below).

In areas where land suitable for rice production is relatively abundant such as Sub-Saharan Africa (Sakurai, 2006) the dominant response to land constraints is conversion of forests, grasslands and other non-agricultural land to crops. While the overall rice area is much more modest in Africa, recent trends in land use change have been dramatic: the rice area harvested in Africa more than doubled from 1980-2010, from 4.7M to 9.3M hectares (FAO, 2012). Like in South Asia some of this expansion is attributable to intensification made possible by irrigation development (Larson *et al*., 2010).

Environmental Impacts of Land Use Strategies

Both agricultural intensification and agricultural expansion have potential negative environmental impacts in the short- and long-term. 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 also worsens wind and water erosion, particularly on sloping uplands (Bai *et al*., 2008).

- *Climate change*: Greenhouse gas emissions (such as methane and nitrous oxide) from rice fields tend to increase with increased cropping intensity, and with conversion of forests/grasslands to rice cropping.[2]

Additional environmental impacts from agricultural expansion and intensification relate to biodiversity loss, including:

- *Loss of wild biodiversity*: Cropland expansion, cropping intensification and repeated plantings can negatively affect wild biodiversity directly (e.g., pesticides killing non-target organisms or habitat loss), and indirectly (e.g., disrupting breeding cycles and destroying habitats of sensitive species) (Phalan, 2011; Altieri & Nicholls, 2004).

- *Loss of on-farm biodiversity and rice genetic diversity*: Shifts to more intensive farming may reduce the number of plant and animal species in agro-ecosystems and may inhibit provision of ecosystem services such as pollination, erosion control, etc. Replacement of multiple locally-adapted and genetically diverse crop varieties with a smaller number of modern rice varieties reduces local and regional agro-biodiversity.

Both forms of biodiversity loss can make rice crops vulnerable to biotic stress (e.g., crop pests and diseases, which can multiply dramatically on repeatedly-cropped land) and

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[2] The consequences of greenhouse gas emissions on climate change are in part attributable to general farming practices (as discussed further below) rather than individual rice farmer land use decisions.

abiotic stress (e.g., excessive heat or drought) (Borromeo, 2003). Such biodiversity-related production consequences are compounded by the intrinsic loss of value when local rice landraces disappear or wild plant and animal species are destroyed or inhibited from performing beneficial ecological functions. Although no estimates of plant and animal biodiversity loss specifically attributable to rice are available at this time, some research is underway (Phalan *et al*., 2011).

Best Practices for Pre-Production Land Use

Broadly, best practices for rice pre-production consist of the following:

- ➢ *Selecting sites suitable for rice cultivation*: Particularly in Africa where much new land is coming under cultivation, sloping land and ecologically beneficial lands (in terms of ecosystem services and habitat) may be unsuitable for rice when soil, climate and biodiversity impacts are considered.

- ➢ *Diversifying crops and retaining indigenous biodiversity:* Crop rotation and intercropping may offer opportunities for maintaining on-farm species diversity, though intercropping opportunities may be limited if rice is grown under flooded conditions. Using multiple rice varieties/landraces can help to maintain rice genetic diversity in communities.

- ➢ *Increasing rice productivity:* Higher productivity of rice reduces the need for area expansion and avoids the environmental consequences likely to arise from such expansion.

Production of Rice

Water Constraints

The single most significant environmental constraint to rice production is water. **Rice production is 2-3 times more water intensive than other major crops** (Bouman *et al*., 2007). Whether rice is grown in flooded systems, irrigated systems or rainfed systems the realization of optimal yields hinges on access to adequate and timely water supplies. Water constraints arise not only from shortage of water, but also from excess of water leading to production losses due to flooding and submergence. A study by Li *et al.* (2011) estimated that water constraints accounted for up to 23% of rice crop losses in the highly irrigated rice and rice-wheat systems of South Asia, and as much as 10-31% of rice crop losses in the rain-fed systems more common in Sub-Saharan Africa. Water shortage will likely become an even more serious issue in rice production in the future because irrigation water is becoming increasingly scarce, particularly in SA, due to increased demand from industrial sources and agricultural area expansion (Barker *et al.*, 2010; Wada *et al.*, 2010).

Adaptation to Water Constraints

Adaptation strategies to overcome water constraints have historically focused on increasing supply through irrigation (Cassman & Pingali, 1995). As a result irrigation is a major driver of water resource depletion in Asia, accounting for roughly 90% of total fresh water diverted (50% of which is used for rice) (IRRI, 2004). In contrast in Sub-Saharan Africa only 14% of rice area is irrigated, but irrigated rice makes up a large share of total production in the region, reaching 33% of rice produced in 2009 (Africa Rice Center, 2009).

Due to decreasing availability of irrigation water in many parts of the world, more recent adaptation strategies have focused on increasing water use efficiency. Water use efficiency for rice (defined as rice output per unit water input) varies widely, from 0.6-1.6 kg/m^3 (Zwart & Bastiaanssen, 2004), largely as a function of varied irrigation and soil management practices including:

- ➢ *Aerobic rice production:* IRRI experiments with aerobic rice production, in which rice fields are not flooded continuously, show significant increases in water use efficiency, potentially offering an avenue for reducing water use per unit area and expanding rice production to areas where water shortage currently limits production (IRRI, 2004).

- ➢ *Alternate wetting and drying:* Mixed flooded and aerobic systems, in which fields are alternately submerged and drained in the growing season, have been shown to sustain full rice yields while decreasing water use by up to 15% (Belder *et al*., 2004).

- ➢ *Improved stress-tolerant varieties:* Improved rice varieties that are tolerant of major water stresses such as drought and submergence offer promising avenues for adapting rice to water constraints (Serraj *et al.*, 2009). Several such varieties are currently available for SA and others are under development. Meanwhile myriad improved land and crop management practices, including direct seeding, land leveling, improved fertilization, and effective weed control have proven successful in improving seedling emergence, stand establishment, and yield under water-deficit conditions (Tuong *et al.*, 2005).[3]

Environmental Impacts of Water Use Strategies

Major environmental impacts of current water management practices for rice production include:

- ➢ *Water depletion:* Groundwater depletion (extraction faster than the recharge rate of groundwater) is a serious concern in some parts of Asia (Wada *et al.*, 2010). Given increasing water scarcity and increasing costs of water pumping due to well depth and fuel costs, significantly increasing rice production using current water-intensive irrigation methods in South Asia will not be possible (Rosegrant *et al.*, 2002; Tuong *et al.*, 2005; Rijsberman, 2006).[4]

- ➢ *Methane emissions:* Flooded rice production systems also impact climate via methane emissions. Submerged rice fields emit methane (CH_4), a powerful greenhouse gas over 20 times more effective at trapping heat than carbon

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[3] New experiments in Habitat Adapted Symbiosis (introducing beneficial organisms such as fungi to enhance drought-tolerance of existing rice varieties) have revealed the potential to reduce water consumption by as much as 20-30% (Redman *et al.* 2011).

[4] Decreasing groundwater resources in South Asia is due partly to water and energy subsidies that distort prices and encourage overuse of water resources (Pingali 2012, Shah *et al.* 2003).

dioxide (CO_2) (EPA, 2009). **Globally, rice production accounts for roughly 10 percent of methane emissions annually** (Yusuf *et al.*, 2012), with emissions heavily concentrated in the irrigated and flooded rice fields of China (7.41 Tg CH_4 per annum) and India (6.08 Tg CH_4 per annum). Africa's largely dryland systems are relatively insignificant contributors of methane (Yan *et al.*, 2009), though flood-based systems are emerging in some areas.

➢ *Disease vectors*: Flooded rice fields are also a breeding ground for mosquitos, posing a potential human health risk. One study estimated that 9-46% of the population in India might face higher malaria risk due to proximity to irrigation primarily for rice production (Keiser *et al.*, 2005). A review of rice-malaria studies in Africa concluded that risk of malarial transmission via irrigated rice fields was lower in areas where malaria was naturally more prevalent (i.e., where people had greater immunity), and higher in areas where malaria was less prevalent (Ijumba & Lindsay, 2001).

Best Practices for Water Management in Rice

Improved water management in rice production can immediately reduce pressure on scarce surface water and groundwater resources (Belder *et al.*, 2004). Meanwhile the same management improvements may also reduce methane emissions over time (Smith *et al.*, 2008; Wassman *et al.* 2009):

➢ *Midseason drainage or intermittent irrigation*: Midseason draining of a flooded rice field can reduce water use by 15% (Belder *et al.*, 2004), and the same practice even more significantly reduces methane emissions. In China, Lu *et al.* (2000) found mid-season drainage of paddies decreased methane by up to 44 percent. In India, Nelson *et al.* (2009) estimated one midseason draining of flooded rice fields could reduce annual methane emissions by 18 percent with only a 1.5 percent yield decline.

➢ *Timing of crop residue application*: Proper timing of crop residue and manure application also reduces methane emissions, with lower emissions if residues are applied when soil is dry (Yan *et al.*, 2009; Smith *et al.*, 2008).[5]

➢ *Combinations of improved management practices*: In a well-known experiment in Madagascar, the System of Rice Intensification (SRI) reported dramatically higher yields and water efficiency through a combination of aerobic production, improved seedling spacing, manual weeding and active organic soil nutrient management. However, SRI is labor intensive and farmer adoption has been very low (Moser & Barrett, 2003: Takahashi, 2013

Soil and Nutrient Constraints

Besides water, soil nutrient content remains one of the largest constraints to global rice production. IRRI's guide to nutrient management in rice (Witt *et al.*, 2007) reported that soil nutrient constraints, particularly nitrogen (N), phosphorus (P) and potassium (K) were responsible for roughly 20% of the rice yield gap. In studies by Waddington *et al.* (2009 & 2010), soil nutrient constraints represented 15-30% of the yield gap in rice production in South Asia and Sub-Saharan Africa.

Adaptation to Soil Nutrient Constraints

Adaptations to soil nutrient constraints summarily include:

➢ *Application of synthetic fertilizers*: Synthetic fertilizer application has become a standard method for addressing soil fertility constraints, with the best gains realized when site-specific soil tests allow for use of appropriate fertilizer mixtures to satisfy deficiencies (Zhu & Chen 2002). Key nutrients include nitrogen, phosphorus and potassium (N-P-K), but also iron, manganese, zinc and copper (Doberman & Fairhurst, 2000).

Application of organic soil amendments: Composting and manure management offer key opportunities to increase yields, especially in rice growing areas lacking access to inputs. Incorporation of crop residues also improves soil fertility status as measured by organic carbon, available phosphorus and available potassium (Prasad *et al.*, 1999).

Environmental Impacts of Rice Nutrient Mismanagement

The 2005 UNESCAP report on the state of the environment reported expanding fertilizer use had contributed to freshwater contamination throughout Asia. Excessive and inappropriate use of fertilizers can cause environmental damage from runoff and leaching, leading to surface water contamination, algal blooms and contamination of wells and drinking water (Zhu & Chen, 2002), although the specific contribution of rice production is not widely documented.

➢ *Surface water and groundwater contamination:* A study by Zhao *et* al. (2012) on nitrogen water pollution based on a three-year field experiment in a rice-wheat system in China found that annual N losses from runoff and leaching were between 55.3-93.1 kg/ha and represented a potentially serious source of water pollutants. Losses of N were greater during the wheat season (57-85%) than during the rice season (15-43%) (Ibid). A study in India along the Ganges found that water tested was highly contaminated with nitrate due in part to heavy agricultural activity including flooded rice production (Sankararamakrishan *et al.*, 2008). A 2006 IRRI study found Chinese farmers applied significantly more nitrogen (N) fertilizer than recommended and that additional nitrogen use at these high rates did not increase yields (Peng *et al.*, 2006).

➢ *Nitrous oxide emissions:* Nitrous oxide (N_20) is a potent greenhouse gas. The EPA estimates that one pound of nitrous oxide has over three-hundred times the impact of one pound of carbon on global warming (EPA, 2012). A number of studies have also identified nitrous oxide as the most important global ozone depleting emission (Ravishankara *et al.*, 2009; Portmann *et al.*, 2012). Of the estimated 40% of nitrous oxide emissions attributable to human activities, the majority are emissions from agricultural soils due to nitrogen fertilizer application (Reay *et al.*, 2012). Although the specific impact of rice production on N_2O has not been widely quantified, given the large global acreage devoted to rice and high levels of fertilizer application in intensive rice systems, it is likely rice production contributes significantly to global nitrous

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[5] New rice varieties with low methane exudation rates might also reduce methane emissions from rice fields (Aulakh *et al.* 2001).

oxide emissions. Furthermore, rice may become an even more serious emitter of nitrous oxide in the future because increasingly popular water-saving rice production strategies such as mid-season drainage of rice fields have the side-effect of increasing nitrous oxide emissions compared to flooded rice cultivation (Ussiri & Lal, 2013).

Best Management Practices for Soil Fertility Management

Site-specific nutrient management, with an emphasis on better fertilizer application timing, balanced application and lower application rates is critical to ensure optimal yields and minimize negative environmental consequences.

- *Application timing and dose*: Appropriate fertilizer use (applying N before cultivation to allow incorporation into soils, site-specific application rather than the usual blanket application (Gregory *et al.,* 2010)) and improved water management (timing of flooding, since flooding inhibits plants' ability to access N) increases yields and decreases waste from runoff and N_2O (Cai *et al.,* 1997).

- *Identification of constraining nutrients:* Other nutrients besides N and P are often the constraining nutrient for rice (often Potassium (K)), meaning that purchase and application of fertilizers with high N or N-P content alone can result in sizeable economic losses due to low yields. Training farmers to recognize visible seedling growth characteristics (size and coloration) can assist in the identification of key macro and micro-nutrient deficiencies (Doberman & Fairhurst, 2000, Gregory *et al*. 2010).

Optimal fertilizer application timing, controlled-released fertilizers, or using fertilizers stabilized with nitrification inhibitors all present promising avenues of decreasing nitrous oxide emissions due to rice production while maintaining yield (Reay, 2012). Site-specific nutrient management (SSNM) was developed by IRRI in an effort to reduce fertilizer use, raise yields, and avoid nitrate runoff and greenhouse gas emissions from rice paddies (Pampolino *et al.*, 2007).

Some farm management practices that reduce emissions of one type of greenhouse gas can increase emissions of others. Importantly, the level of N_2O emissions *increases* under intermittent flooding of rice fields. As a result, one of the best practices to reduce methane emissions from rice has the undesirable effect of increasing N_2O output. Reducing net greenhouse gas emissions in rice may therefore require balancing competing emission priorities.

<u>Crop Pest Constraints</u>

Worldwide, as much as 37% of rice production is lost to pests. Of rice production losses attributable to pests, major weeds (10% potential losses), animal pests (15% potential losses), and pathogens (12% potential losses) are of the greatest economic importance (Oerke, 2006). Weeds are the main production constraint in rainfed upland and rainfed lowland systems where flooding is often not an option for weed control (Doberman & Fairhurst, 2000).

Pest Adaptation Strategies

Strategies to reduce the seriousness of biotic constraints include the following.

- *Pesticide and herbicide use:* Worldwide, rice production accounted for an estimated $3.1 billion dollars in herbicide, insecticide and fungicide expenditure in 2007 with Asian countries accounting for the majority of expenditure (Norton *et al.*, 2010). Data on pesticide use in African rice farms is limited, however available evidence suggests a relatively low use. Pesticide use in Africa accounted for only 2-4% of the pesticide market in 2006 (Williamson *et al.*, 2008).

- *Manual weed control:* Hand-weeding is a labor-intensive traditional method that is still the predominant method of weed control in SSA. In SA, hand weeding is giving way to the use of herbicide due to the rising cost of labor.

- *Integrated pest management* (IPM) and use of new pest-resistant rice varieties have seen some adoption in a number of countries in Asia (Norton *et al.* 2010; Van den Berg & Jiggins, 2007). The International Rice Research Institute (IRRI) and the Africa Rice Center advocate IPM.

Environmental Impacts of Pesticide Use

Pesticide misuse can have substantial impacts on the environment, including:

- *Increased pest outbreaks:* Overuse of insecticide devastates populations of pest natural enemies, which can result in more severe pest outbreaks (Heong & Schoenly, 1998; Pimental *et al.,* 1992).

- *Development of pest strains resistant to pesticides:* Overuse of pesticides in rice production has led to the development of herbicide resistant weeds and insecticide resistant pests (Pimental *et al.*, 1992). Some planthopper populations in China and Vietnam have developed more than 200-fold resistance to insecticides (Norton *et al.* 2010).

- *Negative effects on human health:* Acute poisonings (including of downstream communities and farmer self-poisoning through improper pesticide handling) along with long-term risks associated with agrochemical use have been widely documented in Asia (Pingali & Rogers, 1995; Gupta, 2012).

- *Negative effects on non-target plants and animals:* Damage to fish and other non-target organisms has also been observed in flooded rice fields in a number of countries (Cattaneo *et al.*, 2011; Cagauan, 1995). Aquatic birds have also suffered from excessive use of pesticides and herbicides in rice production (Parsons *et al.*, 2010)

Best Practices for Pest Management

Primary recommendations for improved pest management in rice include:

- *Integrated pest management (IPM)* including appropriate plant spacing, nutrient management incorporating both organic and chemical inputs where available, and water management, alongside prudent agrochemical use for outbreak control (Norton *et al.,* 2010; Nguyen, 2008).

- *Pest and disease resistant varieties:* Developing rice varieties with increased resistance to pests and diseases is an important avenue for reducing the seriousness of biotic constraints (Norton *et al.*, 2010).

- *Maintain on-farm species and genetic diversity:* The presence of pest natural enemies, such as predatory insects and spiders, can reduce the seriousness of damage from rice pests and diseases (e.g. Heong & Schoenly, 1998). Similarly, maintaining genetic diversity may also reduce overall susceptibility of the rice crop to biotic stressors (Zhu *et al.*, 2000; Hajjar, 2008).

Rice Post-Harvest

Post-Harvest Constraints

Rice systems in Asia experience significant post-harvest losses from several sources. IRRI reported losses through the chain of postharvest operations in Southeast Asian rice systems including: cutting/handling (1-5%), manual threshing (1-5%), sun drying (3-5%), traditional storage (5-10%) and village milling (20-30%) (Gummert *et al.*, 2010). The FAO estimated post-harvest losses in rice at 15-16% of total production, and as high as 40-50% in countries with monsoons (Mejia, 2004). A recent report by the Indian Ministry of Agriculture estimated 9% of rice is lost due to improper handling and processing. Losses also occur as a result of rodent and insect pests. IRRI suggests that rodents are responsible for chronic and acute pre- and post-harvest losses in major Asian rice growing countries (Singleton *et al.*, 2010). Singleton (2003) estimated annual post-harvest rice losses due to rodents in India at 25-30%, while Meerburg *et al.* (2009) reported annual grain losses between 5-10% in Indonesia.

Adaptation to Post-Harvest Loss Constraints

Current practices widely used to reduce post-harvest losses in SA and SSA include:

- *Rice processing technologies,* such as mechanical threshers and improved drying methods can reduce post-harvest losses and improve production efficiency. Gummert *et al.*, (2010) reported that rice drying machines had seen some adoption in Asia, generally by rice millers who saw the greatest benefit from improved rice quality.

- *Storage technologies,* including silos and hermetically sealed bags, can reduce rice losses due to rotting and pests. A study by IRRI on rice grain storage in Asia found that rice grain stored hermetically had lower moisture content variability, lower prevalence of insects and improved subsequent rice seed germination compared to traditional storage methods (Rickman & Aquino, 2004).

Environmental Impacts Related to Post-Harvest Practices

Direct environmental impacts associated with post-production in rice include air pollution and greenhouse gas emissions from crop residue disposal. Post-harvest practices also entail indirect environmental impacts in the form of wasted resources and wasted effort when stored crops spoil after harvest:

- *Wasted effort:* 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 rice harvest each year.

- *Greenhouse gas emission from crop residue burning:* China and South Asia burn an estimated 180 and 170 Tgs respectively of biomass per year, of which crops wastes make up the majority (Streets *et al.* 2003). Crop residue burning contributes to the emission of greenhouse gases. Andreae & Merlet (2001) estimated that each 1,000 grams of crop residue burned emitted approximately 1,515 grams of CO_2, 92 grams of CO (carbon monoxide) and 2.7 grams of CH_4 (methane). Residue burning also harms air quality, leading in some cases to respiratory ailments (Awasthi *et al.*, 2010).

Best Practices for Rice Post-Production

Recommendations for rice post-production best practices from FAO and IRRI include:

- *Improved storage, drying and processing technology*: FAO suggests small metal grain silos would substantially reduce storage losses for small and medium scale rice producers (Mejia, 2004). IRRI advocates the wider dissemination of rice driers, mechanized rice harvesting systems, and hermetic storage (Gummert *et al.*, 2010). Rodent-proof storage offers an avenue for reducing losses from rodents and other pests without the use of pesticides (Singleton, 2003).

Recommendations for mitigating the impact of rice crop residue burning include:

- *Managing crop residues*: Crop residues are a source of valuable nutrient resources. IRRI estimated that rice residues by percentage are 41% carbon, .5-.8% nitrogen, .05-.1% phosphorous, and .3-2% potassium (IRRI, 2004). Utilizing crop residue in production can serve as a valuable resource in soil nutrient management. Integration, mulching and composting rice residue are methods of utilizing crop residue in production, however the benefits vary depending on cropping conditions (Bijay-Singh *et al.*, 2008). A downside of incorporation under flooded conditions is that it increases methane emissions in rice production (Smith *et al.*, 2008).

- *Animal feed*: Crop residues are also a valuable source of animal feed. Devendra & Thomas (2002) reported that 30% of rice straw was used for animal feed in Southeast Asia, Mongolia and China; and in Thailand between 75-82% of rice residue was used as feed.

- *Feedstock for bio-energy production*: Rice straw and husks can be important feedstock for bioenergy production (Lal, 2005). Rice husk stove for cooking and rice husk furnaces for heating air in rice dryers have been in use traditionally. However, not enough is known about the economics and the carbon life-cycle effect of the use of these residues for energy production at industrial scale.

Conclusions

As highlighted in this brief, environmental interactions in rice production are complex and the environmental consequences of interventions context specific, making it difficult to provide any generalized "conclusions" regarding rice-environmental interactions. Nevertheless, the inherent trade-offs between production and environmental effects can be reduced considerably (or even eliminated to arrive at "win-win" solutions) through the application of contextually appropriate improved technologies. It is critically important to reduce the environmental footprint of rice while increasing its production given the importance of rice for food security of the poor. Progress in this regard will most likely be made on an incremental basis with accumulation of knowledge over time.

Nevertheless, in the more immediate future, yield gains can be realized – and environmental damages averted – through the relatively simpler interventions of (i) improved water management, including intermittent flooding; (ii) improved fertility management, including ensuring farmers do not over-use fertilizers and promoting incorporation of agricultural residues, and (iii) improved pest management both on fields (through IPM including judicious pesticide use) and in post-harvest (through improved storage facilities).

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: IRRI, African Development Bank, World Bank, UNFAO, UNEP, Millenium Ecosystem Assessment and IPCC. Searches used combinations of the following terms: rice, paddy, environment, environmental, environmental impacts, developing world, Sub-Saharan Africa, South Asia, rain-fed agriculture, emissions, biodiversity, water, water resources, water quality, irrigation, soil, land, natural resource use, climate change, global warming, air pollution, smallholder, sustainability. The methodology also included searching for sources that were identified as central works and examining relevant lists of works cited. This literature review draws upon over 50 cited sources, and relied in equal parts on peer-reviewed publications and data and publications from major international organizations, especially FAO, and IRRI.

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

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