Evans School of Public Affairs
UNIVERSITY OF WASHINGTON

Evans School Policy Analysis and Research (EPAR)
Professor Leigh Anderson, PI and Lead Faculty
Associate Professor Mary Kay Gugerty, Lead Faculty

Environmental Impacts of Agricultural Technologies

EPAR Brief No. 65

Katherine Killebrew and Hendrik Wolff

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

March 17, 2010

Overview

Ecosystem services are the benefits people obtain from ecosystems, such as provisioning of fresh water, food, feed, fiber, biodiversity, energy, and nutrient cycling. Agricultural production can substantially affect the functioning of ecosystems, both positively and negatively. Growth in global food production over the past half century has required trade offs between ecosystem services, resulting in an overall decline in the supply of services other than food, feed, and fiber.[1]

The purpose of this report is to provide an overview of the impacts of agricultural technologies and practices on ecosystem services such as soil fertility, water, biodiversity, air, and climate. Intensification allows farmers to obtain greater yields per unit time and area by planting more crops each year, specializing in repetitive cultivation of modern varieties, and using higher amounts of external inputs.[2] The report describes the environmental impacts of different aspects of intensification in the following sections. Table 1 contains a summary of technologies and their environmental impacts.

- Section One describes the impacts of **intensive cropping practices**, including monoculture, continuous cropping, conventional tillage, intensive livestock systems, and cultivation in fragile hillside areas.
- Section Two covers the impacts of using **inputs associated with intensification**, such as inorganic fertilizers, pesticides, irrigation systems, and new seed varieties.
- Section Three exemplifies the impacts of intensive cropping practices and inputs by examining **intensive rice systems**.
- Section Four extends the discussion from farming practices to examine the impacts of **industrial crop processing**.

Although this report focuses on the impacts of agricultural practices on the environment, many of the practices also have implications for plant, animal, and human health. Farmers and others who come in contact with air, water, and soils polluted by chemical fertilizers and pesticides, for example, may face negative health consequences. By degrading components of the ecosystem, these practices affect the health of plants and animals living within the ecosystem.

---

[1] Millennium Ecosystem Assessment, 2005, p. 27
[2] Cassman & Pingali, 1995, p. 299

Table 1. Overview of agricultural technologies and impacts on ecosystem services

Technology	Impacts on Soils	Impacts on Water	Impacts on Biodiversity	Impacts on Air/Climate	Case Example
Monoculture			Reduces habitat for insects and wildlife, leading to increased need for pesticides		Reduced bird populations in monocropped coffee fields in Colombia and Mexico
Continuous Cropping	Soil fertility declines due to nutrient mining		Reduces farmers' ability to use natural pest cycles, leading to increased need for pesticides		Nutrient offtake in reduced fallow cassava farms in Kenya and Uganda
Conventional Tillage	Reduces soil organic matter, leading to increased erosion			Contributes to CO_2 emissions due to decomposition of soil organic matter	Soil compaction due to tillage in maize fields in Nigeria
Intensive Hillside Cultivation	Increases erosion, leading to soil degradation				Significant soil loss rates due to erosion in Ethiopian highlands
Intensive Livestock Systems	Increases erosion and soil compaction due to overgrazing and hoof action	Untreated livestock waste degrades water quality; water usage competes with other needs	Degrades grassland habitat due to overgrazing	Contributes to CH_4 and N_2O emissions due to enteric fermentation and manure management	Soil degradation and erosion caused by overgrazing in the Irangi Hills in Tanzania
Inorganic Fertilizers	Increases soil acidification due to nitrate leaching	Reduces oxygen levels due to run-off, harming aquatic ecosystems; impairs water for human uses		Contributes to smog, ozone, acid rain, and N_2O emissions	Eutrophic dead zones in the Baltic Sea, Black Sea, and west coast of India
Pesticides			Harms animal and human health by accumulating in soils and leaching into water bodies		Use of unauthorized pesticide recipes in maize fields in Ethiopia

Irrigation Systems	Inadequate drainage and over-irrigation causes waterlogging and salinization	Degrades downstream ecosystems due to polluted run-off and over-extraction of water			Shrinking of Aral Sea due to over-extraction for irrigation, particularly for cotton cultivation
New Seed Varieties	May increase need for inputs that negatively impact soils	May increase need for inputs that negatively impact water quality and quantity	Reduces maintenance of genetic diversity in landrace varieties	May increase need for fertilizer, leading to increased greenhouse gas emissions	
Intensive Rice Production	Inadequate drainage and continuous flooding causes waterlogging, salinization, and nutrient problems	Degrades downstream ecosystems due to polluted run-off and over-extraction of water		Contributes to CH_4 emissions due to anaerobic conditions in paddy fields	Over-extraction for rice irrigation in Tamil Nadu, India
Industrial Crop Processing		Degrades downstream ecosystems due to water requirements and discharge of untreated wastewater		Contributes to CO_2 emissions due to energy requirements of machinery	Water pollution near coffee processing plants in Mexico

Source: Compiled by Killebrew, 2010

Section One: Intensive Cropping Practices

<u>Monoculture</u>

A key component of agricultural intensification is monoculture, the cultivation of a single crop species in a field. Unlike traditional polyculture cropping configurations, which mix crop varieties or intersperse crops with trees or domesticated animals, monoculture allows farmers to specialize in crops that have similar growing and maintenance requirements. Farmers around the globe have increasingly adopted monoculture to achieve higher yields through economies of scale.[3] However, monoculture may negatively impact several scales of *biodiversity*.

- *Impacts on Biodiversity*: Monoculture systems provide a narrower range of habitat than polyculture fields, leading to an increased need for chemical pesticides.

[3] Gliessman, 2000, p. 4

Agricultural systems contain several dimensions of biodiversity. "Planned" biodiversity refers to the diversity of crops and animals chosen by a farmer for production, while "associated" biodiversity includes the micro-organisms, insects, birds, and other wildlife that both depend upon and help maintain agroecosystems.[4,5]

By reducing planned biodiversity to include only one crop, monoculture affects the composition and abundance of associated biodiversity. For example, the balance of plant pests and their natural enemies that may exist in polyculture fields can be disrupted in monoculture systems, which provide habitat for a narrower range of insects.[6] Populations of bees, flies, moths, bats, and birds, which provide important pollinating and pest pressure services to crops, also tend to be lower in monocultures than in fields containing diverse forage and nesting sites.[7] For example, full-sun monocrop coffee fields in Colombia and Mexico have been found to support 90 percent fewer bird species than shade-grown coffee systems.[8]

As a result of reduced biodiversity, monoculture systems have been found to be more susceptible than polycultures to insect infestation and plant viruses. Pingali & Rosegrant (1994), for example, found evidence of reduced rice yields throughout Southeast Asia due to increased pest populations in monoculture rice systems.[9] To manage pests in monoculture fields, farmers must apply chemical pesticides, leading to negative impacts on water quality, wildlife populations, and human health.[10]

<u>Continuous Cropping</u>

In addition to modifying spatial arrangements to increase production, farmers have made adjustments to the timing of growing practices to obtain more crops per year.[11] Historically, farmers have alternated cultivation with long fallow periods or rotations with other crops to manage soil fertility. In response to rising demand for food and reduced space for agricultural expansion, farmers have shortened or abandoned fallow periods and crop rotations in favor of continuous production.[12] While the ability to produce two or three crops per year on a single plot has significantly increased global food supply, continuous cropping can have detrimental impacts on *soil conditions*.

- *Impacts on Soils:* Without adequate fertility management practices, soil fertility declines as consecutive crop cycles mine nutrients from the soils.

  As plants grow, they absorb nutrients from the soil such as nitrogen, phosphorous, potassium, and calcium. Harvesting crops removes these nutrients from the soil. Unless nutrients are restored through fallow, leguminous crop rotation, or application of organic or inorganic fertilizers, soils eventually develop nutrient deficiencies.[13]

  In regions with good soils, adequate rainfall or irrigation, and access to agricultural inputs, farmers can use fertilizers to maintain soil fertility.[14] However, even in these areas, continuous cropping can have long-term negative impacts on soils. For example, intensive rice cultivation in Asia, in which farmers have moved from one crop per year followed by a dry season fallow to two or three consecutive crops, has been shown to cause soil micro-nutrient deficiencies by altering soil organic matter and microbial activity. Farmers must apply higher amounts of fertilizer to

[4] Millennium Ecosystem Assessment, 2005, p. 756
[5] FAO, 2003, p. 350
[6] Matson Parton, Power, & Swift,, 1997, pps. 504-505
[7] Millennium Ecosystem Assessment, 2005, p. 759
[8] Clay, 2004, p. 82
[9] Pingali & Rosegrant, 1994, p. 20
[10] Millennium Ecosystem Assessment, 2005, p. 760
[11] Wood Sebastian & Scherr, 2000, p. 66
[12] Wood et al., 2000, p. 45
[13] Millennium Ecosystem Assessment, 2005, pps. 764-766
[14] Millennium Ecosystem Assessment, 2005, p. 766

make up for reduced nitrogen supplying capacity, thereby increasing the negative environmental effects of fertilizer described below.[15]

In Sub-Saharan Africa, population pressure has led to increasing use of continuous cropping without corresponding increases in organic or chemical fertilizer use.[16] Over time, inherently low-fertility soils have been degraded further due to extracting nutrients at rates higher than they are replaced or can naturally regenerate.[17] For example, a recent study of cassava-based farming systems in western Kenya and central/eastern Uganda found that over the past three to four decades, many farmers have eliminated single-season fallow periods in favor of growing second season crops. As a result of this intensification, offtake of nitrogen, phosphorous, and potassium has more than doubled since the 1960s and 1970s.

While farmers have begun rotating cassava with cereal crops in this area in an effort to restore soil fertility, one crop of cassava recycles only half the amount of nutrients recycled by two single-season fallows. The study found that in some sites, farmers have switched from growing crops that require fertile soils, such as bananas, to those that grow well in nutrient-poor soils, such as cassava.[18]

- *Impacts on Biodiversity*: Continuous cropping may lead to higher pesticide use by disrupting farmers' ability to take advantage of natural pest balances.

In many traditional African agricultural systems, farmers manage pests using fallow periods or by timing planting or harvesting to avoid peaks of pest populations. In slash-and-burn systems, for instance, fallow periods help relieve pest pressure by restoring the interplay between pests and their natural enemies.[19] Farmers are often aware of pest population fluctuations and may use variable planting or harvesting dates to avoid peak populations. In western Kenya, for example, farmers delay sweet potato planting to avoid sweet potato weevil damage.[20] Transition to continuous cropping reduces the ability of farmers to take advantage of natural pest cycles, requiring instead use of chemical pesticides that may harm soil organisms, aquatic species, other nearby wildlife, and human health.

Conventional Tillage

Conventional farming involves plowing the soil regularly and deeply for the purposes of loosening the soil structure, promoting drainage and aeration, controlling weeds, and turning under crop residues.[21] Globally, the vast majority of agricultural land undergoes some degree of tillage before every crop.[22] Farmers can use hand tools, animal plows, or mechanical equipment to accomplish tillage. In Africa, most farmers prepare fields by hand or using animal-drawn tools, though some commercial farms in countries such as South Africa, Zimbabwe, and Nigeria are increasingly using tractor-powered tillage tools.[23] Tillage causes detrimental changes in *soil structure and fertility* and *greenhouse gas emissions*.

- *Impacts on Soils*: Tillage reduces soil organic matter, making soils less able to absorb and retain water and more prone to erosion and run-off.

---

[15] Pingali & Rosegrant, 1994, pps. 19-20
[16] Millennium Ecosystem Assessment, 2005, p. 765
[17] Wood et al., 2000, p. 51
[18] Fermont, van Asten & Giller, 2008, pps. 240-247
[19] Kleinman, Pimentel & Bryant, 1995, p. 237
[20] Abate, van Huis & Ampofo, 2000, p. 644
[21] Gliessman, 2000, pps. 3-4
[22] FAO, 2003, p. 306
[23] Mrabet, 2002, p. 121

Many of tillage's environmental impacts stem from its detrimental effects on soil organic matter (SOM), the portion of soil that originates from animals and plants. An important indicator of overall soil quality, SOM provides many benefits to soils and crops, such as protecting against erosion by binding and stabilizing soil particles together, providing carbon and energy for soil micro-organisms, enhancing storage and transmission of water and nutrients, preventing soil compaction, and storing carbon from the atmosphere.[24]

Intensive tillage tends to reduce SOM levels by causing oxidation of organic matter.[25] As SOM declines, soils become more compacted, less able to absorb and retain water, and more prone to water loss from evaporation and rapid run-off. Susceptibility to wind and water erosion increases, thus negatively affecting air and water quality.[26] The number and type of soil micro-organisms also declines, causing a reduction in the nutrient cycling and regulating services these communities provide.[27]

As reviewed by Mrabet (2002), studies throughout Africa have found reduced SOM in fields under conventional tillage compared to those under reduced or no till. In continuously cropped maize fields in western Nigeria, researchers noted a decline in soil quality over time under conventional tillage compared to no-tillage due to compacted soil and reduced water infiltration and holding capacity.[28] Comparing conventionally ploughed fields to reduced tillage and residue retention fields in Zimbabwe, researchers found higher rates of water run-off and erosion on the conventionally tilled plots.[29]

- *Impacts on Greenhouse Gas Emissions:* Tillage increases CO_2 emissions by causing decomposition of SOM and soil erosion.

Intensive tillage practices also emit carbon dioxide (CO_2), a greenhouse gas that contributes to climate change. Mechanical tillage tools release CO_2 through the combustion of fossil fuels, and tillage itself stimulates CO_2 emissions by enhancing decomposition of soil organic matter.[30] The tendency for tillage to increase erosion also contributes to CO_2 emissions. A large percentage of soil carbon particles carried by erosion are emitted into the atmosphere as CO_2 rather than buried and sequestered in deposit sites.[31]

Intensive Cultivation in Hillside Areas

The environmental impacts of intensive agriculture are magnified when cultivation takes place on sensitive land, such as steep slopes. Due to population pressure and land scarcity, farmers in some areas are increasingly adopting intensive cultivation methods on hillside areas. Without adequate soil and water conservation techniques in place, such as terraces, grass strips, and reduced tillage, cultivation on slopes steeper than ten to 30 percent can have significant impacts on *soil conditions*.

- *Impacts on Soils:* Erosion may occur in cultivated areas without proper conservation techniques in place, leading to soil degradation.[32]

As rainfall hits loose or unprotected soil on cultivated sloping land, soils erode and carry away sediments and nutrients. The resulting redistribution of nutrients may leave upward sloping soils less fertile than lower areas, and

[24] Wood et al., 2000, p. 50
[25] Wood et al., 2000, p. 50
[26] FAO, 2003, p. 344
[27] Millennium Ecosystem Assessment, 2005, p. 759
[28] Lal, 1997, pps. 155-159
[29] Thierfelder & Wall, 2009, p. 217
[30] Smith et al., 2008, p. 791
[31] Millennium Ecosystem Assessment, 2005, p. 768
[32] FAO, 2003, p. 339

fertilizers or other chemical particles in run-off may negatively impact ecosystems and water quality for downstream human populations.[33]

Throughout the East African highlands, which include areas above 1,200 meters in Burundi, Ethiopia, Kenya, Rwanda, northern Tanzania, and Uganda, soil erosion from crop production on steep slopes is a significant problem. Cultivation of annual crops with little vegetative cover combined with limited adoption of soil and water conservation methods have resulted in high erosion rates.[34] In the Ethiopian highlands, for example, over 40 tons of soil per hectare are lost every year due to erosion.[35] Partly as a result of erosion, soil nutrient depletion is higher in the East African highlands than in other parts of Sub-Saharan Africa (SSA).[36]

Hillside soils are often of inherently poor quality, and erosion from intensive cultivation degrades them further. In the Philippines, rice farmers have been forced by population growth and a decrease in agricultural land to farm on steeply sloping soils that are acidic, deficient in organic matter and phosphorous, and have low water retention capacity. Rice cultivation in these areas has increased erosion rates, leading to a decline in soil nutrient levels and plant rooting depth.[37]

Intensive Livestock Systems

Livestock play an important role in agricultural systems throughout the developing world. Cattle, sheep, and goats can provide manure for fertilizer, draft power for field operations, and a diversified source of food and income.[38] Traditional livestock management in Africa and Asia involves mixing animals and crops on the same farm or grazing livestock on grasslands. These systems are increasingly undergoing intensification, with farmers grazing higher densities of livestock on pastureland or transitioning from grazing to confined operations.[39] Intensive livestock systems exacerbate the impacts that livestock activities have on the environment, including effects on *soil conditions*, *biodiversity*, *water quality and quantity*, and *greenhouse gas emissions*.

- *Impacts on Soils:* Livestock may overgraze vegetation and cause soil compaction and erosion.

Increased animal stocking rates puts pressure on grazing lands, leading in some cases to soil compaction and erosion, grasslands degradation, and desertification in semi-arid areas.[40] Concentrated "hoof action" compacts wet soils, making them less able to absorb water and more prone to run-off and erosion. Livestock grazing between land and streams can destabilize stream banks and release large amounts of sediment into fragile aquatic ecosystems.[41] In the Irangi Hills of central Tanzania, the government evicted all livestock in 1979 due to extensive soil degradation and erosion caused by overgrazing. Although the prohibition is still in place, farmers are increasingly allowing livestock to graze freely, threatening ongoing land recovery.[42] In other parts of SSA, restrictions on traditional migratory routes through border crossings and establishing permanent watering holes have caused problems with overgrazing and land degradation.[43]

- *Impacts on Biodiversity:* Overgrazing destroys grassland habitat and may require reseeding natural meadows.

---

[33] Acharya, 2008, p. 539
[34] Ehui & Pender, 2005, p. 230
[35] Pender, 2004, p. 340
[36] Ehui & Pender, 2005, p. 230
[37] Labios, Montesur, J. G., & Retales, 1995, p. 452
[38] Millennium Ecosystem Assessment, 2005, p. 751
[39] FAO, 2003, pps. 349-350
[40] FAO, 2003, p. 346
[41] FAO, 2003, p. 161
[42] Kangalawe, Christiansson & Ostberg, 2008, p. 33
[43] FAO, 2003, p. 346

Intensive grazing impacts biodiversity in several ways. Populations of birds, rodents, and other wildlife that depend on grasslands for food and habitat may decline as livestock densities increase. In addition, intensive grazing often involves reseeding natural meadows, resulting in a loss of native grassland plants. Higher rates of organic or inorganic fertilizer application typically accompany reseeding, which may degrade water quality through nitrogen or phosphorous leaching.[44]

- *Impacts on Water Quality and Quantity:* Untreated livestock waste causes high nutrient concentrations in water bodies, also known as eutrophication. Raising livestock can require substantial quantities of water to provide to animals for drinking and to maintain livestock facilities.

  Untreated livestock waste can significantly impact water quality. Manure contains high amounts of nitrogen, phosphorous, and potassium and may enter water directly when livestock graze near streams or indirectly through run-off or percolation into groundwater. Confined livestock systems present especially high risks of water pollution due to difficulties containing and treating large quantities of manure. Waste from the industrial swine industry in China, Thailand, and Vietnam, for instance, contributes more to pollution in the South China Sea than human domestic sources in those three countries.[45] High nutrient concentrations in water (also known as eutrophication) can lead to excessive algae and bacterial growth and loss of native fish and plant species.[46] Degraded water quality may also pose health risks to humans who rely on the water for drinking and other household uses.

  Water quantity is also under pressure from livestock intensification. Livestock require water for drinking, and in confined livestock systems, water is used to clean animals and their facilities and dispose of manure. Extracting water for livestock is significant in some countries and can compete with other natural and human water needs. In Botswana, for instance, the livestock sector accounts for 23 percent of total water use in the country.[47]

- *Impacts on Greenhouse Gas Emissions:* Enteric fermentation and livestock manure are significant sources of CH_4 and N_2O emissions.

  Ruminant livestock such as cattle and sheep release methane (CH_4) during enteric fermentation, the microbial digestion of fibrous plants.[48] Animal manure emits nitrous oxide (N_2O) and CH_4 during storage and after application to croplands or grazing areas. Additional activities related to raising livestock are responsible for emissions such as releases of CO_2 in producing fertilizer for grazing lands and animal feed, N_2O emissions from applying fertilizer, and CO_2 emissions from overgrazing and land degradation.[49] Globally, agriculture accounts for 13.5 percent of total greenhouse gas emissions.[50] Enteric fermentation and manure management are responsible for 32 percent and seven percent of the agriculture sector's contribution to climate change respectively.[51]

Section Two: Inputs Associated with Intensification

<u>Inorganic Fertilizers</u>

Supplementing agricultural systems with synthetically derived nitrogen (N), phosphorous (P), potassium (K), calcium, magnesium, and micronutrients has allowed humans to increase per area yields dramatically over the

[44] FAO, 2003, p. 350
[45] FAO, 2006, p. 139
[46] FAO, 2006, p. 138
[47] FAO, 2006, p. 129
[48] FAO, 2006, p. 83
[49] FAO, 2006, pps. 83-105
[50] IPCC, 2007a, p. 105
[51] IPCC, 2007b, p. 503

past half-century.[52] However, due to inefficiencies in fertilizer application and crop uptake, increases in fertilizer use have impacted *soil fertility*, *water quality*, *air quality*, and *greenhouse gas emissions*.

- *Impacts on Soils:* Nitrate leaching and ammonium-based fertilizers contribute to soil acidification.

  High rates of nitrogen fertilization can lead to soil acidification, a process that results in toxic levels of aluminum and manganese and reduced amounts of essential nutrients. Acidification occurs when ammonium in certain nitrogen fertilizers undergoes nitrification to form nitrate, and then the nitrate leaches into the soil. Ammonium-based fertilizers can also contribute directly to acidification in the absence of nitrate leaching.[53] Soil acidification is a problem in developed and developing countries, particularly in East Asia.[54] For example, a recent survey of China's major crop-production areas found significant acidification of all topsoils primarily due to high nitrogen fertilizer inputs.[55]

- *Impacts on Water Quality:* Nutrient contamination in water bodies reduces oxygen levels and harms fish and plant populations.

  Nitrogen is an extremely mobile nutrient that is easily lost from agricultural soils. Average fertilizer uptake efficiency is only 30 to 50 percent, meaning that soils may accumulate large quantities of unabsorbed nitrogen and other nutrients. These nutrients can leak into aquatic ecosystems in a number of ways.[56] Excessive rainfall or irrigation can cause accumulated soil nitrates to leach below a crop's rooting zone and enter groundwater. Nitrates can also flow over soil surfaces into surrounding surface water ecosystems.[57]

  Leaching of nitrogen and other fertilizer nutrients into fresh and saltwater environments can lead to a state of eutrophication (overabundant nutrient concentrations), resulting in increased algae blooms and oxygen depletion. "Dead zones" may develop in these areas, whereby decreased oxygen levels dramatically reduce fish populations and species diversity. The Baltic Sea, Black Sea, west coast of India, and outlet of the Mississippi River in the Gulf of Mexico contain significant dead zones caused by eutrophication.[58] Consumption of polluted water may also negatively impact human health. Even after nitrogen leakage is slowed or eliminated, contaminated water bodies may require decades to recover.[59]

- *Impacts on Air Quality:* Nitric gas contributes to smog, ozone, and acid rain.

  During the microbial processes of nitrification and denitrification that take place in fertilized soils, nitric (NO) gas is released. Nitric emissions impact local and regional air quality by contributing to the formation of smog, ozone, and acid rain.[60]

- *Impacts on Greenhouse Gas Emissions:* Inefficient fertilization is a major source of N_2O emissions.

  Unabsorbed nitrogen from fertilization is susceptible to emission into the atmosphere as nitrous oxide (N_2O), a greenhouse gas. Inefficient fertilizer practices, such as applying fertilizer in excess of immediate plant requirements or over-fertilizing in wet conditions, contribute to nitrogen losses in the atmosphere. Globally, N_2O emissions from

[52] Crews & Peoples, 2004, p. 280
[53] Crew & Peoples, 2004, pps. 282-283
[54] FAO, 2003, p. 348
[55] Guo et al., 2010, p. 1008
[56] Millennium Ecosystem Assessment, 2005, p. 767
[57] Crews & Peoples, 2004, p. 283
[58] McNeely & Scherr, 2003, p. 73
[59] FAO, 2003, p. 348
[60] Crews & Peoples, 2004, p. 284

soils are responsible for 38 percent of total agricultural greenhouse gas emissions.[61] In addition, use of natural gas and coal to manufacture inorganic fertilizer contributes to CO_2 emissions.[62]

Pesticides

Since the mid-1900s, farmers have increasingly used chemical pesticides (defined here to include insecticides, nematocides, fungicides, and herbicides) to limit crop losses from pests, diseases, and weed competition.[63] Developing countries have used fewer pesticides in the past, but pesticide use is expected to grow more rapidly in these countries than in the developed world.[64] Due to leaching into soil and water, pesticide's primary environmental impact relates to *biodiversity*.

- *Impacts on Biodiversity:* Pesticide filtration into soil and water harms animal and human health, and effects may be magnified in Africa.

  Efficiency rates of pesticide application are even lower than for fertilizer, with some estimating that less than 0.1% of pesticides applied to crops actually reach the intended pest.[65] The remainder accumulates in soils, where it may filter into ground or surface water and prove toxic to micro-organisms, aquatic animals, and humans. Accumulated pesticides in soils may harm arthropods, earthworms, fungi, bacteria, protozoa, and other organisms that contribute to the function and structure of soils. Exposure of birds to pesticides can cause reproductive failure, or even kill them directly in high enough doses. Domesticated livestock may also be affected by exposure to pesticides.[66]

  Once pesticides enter an ecosystem, they may persist for long periods. Organochlorine insecticides such as DDT, for instance, were detected in surface waters in the U.S. 20 years after their use had been banned. Furthermore, pesticides that enter the food chain may undergo biomagnification, whereby accumulated concentrations in the tissues of organisms are many times higher than in the surrounding environment.[67]

  Average pesticide use in Africa is estimated at 1.23 kg per hectare. Although this is low compared to 7.17 and 3.12 kg for Latin America and Asia, respectively, harmful environmental effects are magnified by the use of banned or unauthorized products and mishandling of chemicals.[68] In areas with lax pesticide regulations, farmers may use cheap, locally produced pesticides that would be illegal elsewhere. For instance, a study on pesticide use in Ethiopia found that maize farmers had developed their own pesticide "recipe" by mixing malathion with DDT. Although DDT is banned worldwide for agricultural purposes, it is widely available in Ethiopia through a malaria control program.

  Farmers may face negative health impacts from exposure to or mishandling of pesticides. In the Ethiopian study, farmers reported risky handling and storage techniques, such as applying pesticides to human hair or skin to treat lice or open wounds.[69] A survey of pesticide use among smallholder cotton farmers in Zimbabwe found that over half had experienced acute pesticide poisoning symptoms, including skin irritation, eye irritation, and stomach

[61] IPCC, 2007b, pps. 501-507
[62] FAO, 2006, p. 86
[63] Wood et al., 2000, p. 36
[64] FAO, 2003, p. 348
[65] Arias-Estevez, Lopez-Periago, Martinez-Carballo, Simal-Gandara, Mejuto & Garcia-Rio, 2008, p. 248
[66] Wilson & Tisdell, 2001, p. 452
[67] Arias-Estevez et al., 2008, p. 250
[68] Williamson, Ball & Pretty, 2008, p. 1327
[69] Williamson et al., 2008, p. 1330

poisoning.[70] Risk of adverse health effects from pesticide use are often exacerbated in developing countries by poor access to pesticide information, farmer illiteracy, and unavailable or unaffordable protective equipment.[71]

Increasing pesticide use may spur weeds, viruses, and pests to develop pesticide resistance, resulting in a constant need to develop new products. While scientists debate the extent of the ability of pests to adapt to pesticides, one estimate suggests that 1,000 major agricultural pests are now resistant to most commercially available pesticides.[72] This "pesticide treadmill" may lead farmers to use stronger concentrations or more frequent pesticide applications, raising the risk of negative impacts on animal and human health.[73]

Irrigation Systems

The area of cropland under irrigation has grown significantly in modern times, increasing fivefold globally since the beginning of the twentieth century.[74] Only six percent of the cultivated land in Africa is irrigated, yet irrigation represents 85 percent of total annual water withdrawals. The percentage of cultivated area under irrigation in Africa varies by precipitation. It ranges from almost zero in the Central Africa Republic to 100 percent in Egypt.[75] Irrigation has the potential to impact *soil conditions* as well as *water quality and quantity*.

- *Impacts on Soils:* Over-irrigation and poor drainage can cause waterlogging and soil salinization, which decrease soil productivity.

  Waterlogging typically precedes salinization and occurs when poor drainage prevents plant roots from obtaining adequate oxygen. Salinization involves an increase in the concentration of dissolved solids in soil and soil water.[76] The most common negative environmental impact associated with irrigation, it occurs when excess water causes water tables to rise. As water tables reach the surface and evaporate, salt is left behind.[77,78] The resulting increase in salinity reduces soil productivity by making it more difficult for plants to absorb water from the soil.[79] In advanced stages of salinization, soil becomes unsuitable for cultivation.[80]

  Semi-arid and arid regions are particularly prone to salinization due to higher rates of irrigation and evaporation and lower amounts of rainfall to clear away accumulated salts.[81] Salinization is a significant problem in Morocco, Nigeria, and Sudan, where salinized areas exceed 100,000 hectares in each country. [82] India has lost approximately seven million hectares of cultivated land due to salinization. The Food and Agriculture Organization (FAO) estimates that ten to 50 percent of irrigated land in semi-arid countries is affected by elevated salinity, resulting in yield declines of ten to 25 percent for many crops.[83]

- *Impacts on Water Quality and Quantity:* Run-off from irrigation and high extraction rates can damage downstream natural ecosystems.

---

70 Maumbe & Swinton, 2003, p. 1564
71 Maumbe & Swinton, 2003, p. 1560
72 Wood et al., 2000, p. 37
73 Wilson & Tisdell, 2001, p. 450
74 Millennium Ecosystem Assessment, 2005, p. 761
75 FAO, 2005, p. 28
76 FAO, 1997
77 FAO, 1997
78 Ghassemi, Jakeman & Nix, 1995, p. 31
79 FAO, 1997
80 Ghassemi et al., 1995, p. 45
81 FAO, 1997
82 FAO, 2005, p. 39
83 FAO, 2003, p. 347

Irrigation discharge contains numerous suspended particles that can degrade ground and surface water quality if not disposed of properly. In sufficient quantities, naturally occurring elements (salts, silt, selenium, arsenic, and boron) and residues from fertilizers and pesticides in irrigation drainage can harm aquifers and downstream watersheds and make the water unfit for human consumption.[84]

Extraction of groundwater beyond natural recharge rates is a problem in many countries, particularly in regions that lack effective water management institutions or conservation incentives. Among African countries, Algeria, Cape Verde, Djibouti, Morocco, Nigeria, Senegal, and Tunisia have reported overexploitation of aquifers, with Algeria and Cape Verde experiencing seawater intrusion into freshwater resources as a result. In Libya and Algeria, overuse of fossil aquifers (those that have very low rates of recharge) is unsustainable in the long-term and may force farmers to abandon cultivated land.[85]

Finally, extraction of water for irrigation competes with natural ecosystems that depend on an adequate water supply. Nigeria, for example, has lost half of its wetlands due to drought and diversion of water for agricultural uses.[86] The Aral Sea in Central Asia has been reduced to a small percentage of its original size due to over-extraction for irrigation, resulting in an almost complete loss of fish populations.[87] Much of the water taken from the rivers that drain into the Aral Sea has been used to irrigate cotton in desert areas.[88]

New Seed Varieties

Traditionally, farmers have selected and manipulated differences between crop species to enhance favorable traits, such as an ability to provide high yields or resistance to pests.[89] Recent technological advances have vastly increased scientists' ability to manipulate plants' genes. For example, hybrid seeds combine the genetic sequences of two or more crop strains to achieve higher yields. Through genetic engineering, scientists have been able to splice genes from a variety of organisms into plant genomes.[90] These transgenic seeds can contain coding for a number of desirable characteristics, such as herbicide resistance or frost tolerance.[91]

Adoption of high-yielding wheat, maize, and rice varieties has been extensive in Asia and Latin America. In Asia, for example, more than 75 percent of rice planted is an improved semi-dwarf variety. In developing countries as a whole, modern semi-dwarf wheat varieties make up about 80 percent of wheat cultivated area.[92] Compared to Asia and Latin America, traditional varieties and locally adapted seeds still dominate throughout much of Africa.[93] Environmental concerns around improved seeds relate to their *high input requirements* and effects on *biodiversity*.

- *Impacts due to High Input Requirements:* Increased fertilizer, pesticide, and water needs of improved seeds may negatively impact soil conditions, water quality and quantity, and biodiversity.

  To realize the high yield potential of improved seed varieties, farmers must supply crops with adequate nutrients, water, and protection from pests.[94] As a result, adopting high-yielding varieties often goes hand-in-hand with

[84] Wichelns & Oster, 2008, p. 116
[85] FAO, 2005, pps. 38-39
[86] FAO, 2005, p. 445
[87] Ghassemi et al., 1995, p. 263
[88] Chapagain, 2006, p. 187
[89] Brown & Hodgkin, 2007, p. 14
[90] Gliessman, 2000, p. 4
[91] Wood et al., 2000, p. 70
[92] Millennium Ecosystem Assessment, 2005, p. 757
[93] Wood et al., 2000, p. 69
[94] Gliessman, 2000, p. 6

adopting other intensive inputs, such as nitrogen fertilizers or irrigation systems. In developing countries, irrigation is almost synonymous with using improved rice and wheat varieties: 95 percent of irrigated rice systems and 91 percent of irrigated wheat systems are devoted to high-yielding varieties.[95]

As the use of improved seeds becomes more widespread, farmers must carefully manage increasing applications of fertilizers, pesticides, and irrigation water to avoid the negative environmental impacts that may result from these inputs. Farmers cultivating herbicide-tolerant transgenic crops, for instance, may spray broad-spectrum herbicides that are more toxic to surrounding ecosystems than conventional herbicides. Leaching of these chemicals can negatively affect soil and water quality and the plants and animals residing in these ecosystems.[96]

- *Impacts on Biodiversity:* Improved seeds may threaten the maintenance of genetic diversity in landrace varieties.

Genetic variation among crop varieties is vitally important to the future development of new seed varieties. Traditional landrace seeds have adapted over time to local conditions, developing resistance to certain pests or weather conditions, for instance. Conventional breeding and biotechnology draw on the stocks of genetic diversity contained in landraces to develop seeds that are responsive to new environmental conditions. As more farmers sow monoculture fields of improved seed varieties, however, the maintenance of genetic diversity in landraces is lost.[97] While several countries and research centers have developed genebanks to conserve genetic diversity, these *ex-situ* collections separate seed germplasm from its natural ecosystem, thus preventing effective adaptation to crop stressors that occurs when the seed and germplasm are preserved in the natural environment.[98]

In the case of genetically modified seeds, some scientists are concerned about the consequences of genetic exchange between transgenic crops and wild plant populations. While conventionally bred seeds often spread and mix with wild seeds, the impacts of introducing non-plant genes that are contained in transgenic seeds into landrace seeds are unknown.[99]

Section Three: Intensive Rice Production

Intensive rice systems use many of the technologies described above – monoculture, continuous cropping, irrigation, and fertilizer and pesticide use – for the purpose of producing more rice per area and per season. Beginning in the 1960s, many farmers in Asia moved from cultivating one rice crop per year followed by a dry season fallow, to growing two or three rice crops consecutively per year on the same plot.[100] These intensive rice systems have impacts on *soil conditions*, *water quantity and quality*, *biodiversity*, and *greenhouse gas emissions*.

- *Impacts on Soils:* Inadequate drainage and continuous flooding can cause waterlogging, soil salinization, nutrient deficiencies, and increased soil toxicities.

In intensive rice production, rice paddies are flooded for most of the year. Poorly designed irrigation systems can prevent adequate drainage, leading to soil waterlogging and salinization as water tables rise toward the surface. In the southern Indus valley in Pakistan, for instance, extensive rice irrigation caused water tables to rise from a depth of 20 to 30 meters to one to two meters within 20 years.[101] Increased soil salinity reduces yields in the short-term,

---

[95] Wood et al., 2000, p. 69
[96] Wood et al., 2000, p. 71
[97] Millennium Ecosystem Assessment, 2005, pps. 757-758
[98] Wood et al., 2000, p. 69
[99] Wood et al., 2000, p. 69
[100] Pingali & Rosegrant, 1994, p. 10
[101] Moormann & van Breemen, 1978, p. 126

and may lead to abandonment of paddy fields over time.[102] Long-term water saturation and continuous monoculture can also affect soil conditions by causing micro-nutrient deficiencies, particularly of zinc, and increased soil toxicities, especially due to iron build-up. Continuous flooding may also lead to a decline in the capacity of soils to supply nitrogen to plant roots.[103]

- *Impacts on Water Quantity and Quality:* Irrigation for intensive rice production requires large quantities of water and may leach chemicals into downstream ecosystems.

  The majority of global rice production comes from irrigated fields. In areas lacking water management institutions or efficient irrigation methods, withdrawals for rice irrigation can deplete water supplies. In India's Tamil Nadu region, for example, over 80 percent of paddy fields are irrigated. Due to over-extraction for irrigation, in one decade the region's water table fell by 25 to 30 meters.[104,105]

  High fertilizer and pesticide use characterize intensive rice systems; about ten percent of global nitrogen fertilizer use is dedicated to rice production.[106] When applied under flooded conditions, fertilizers can lose nitrogen compounds through leaching, denitrification, volatilization, and runoff. Urea, which provides about 80 percent of nitrogen demand to rice in nitrogen fertilizers, is highly water soluble and particularly susceptible to losses. Escaped nitrogen from rice systems causes air and water pollution and may be especially lethal to fish in downstream ecosystems.[107] Leaching of pesticides into water systems can also lead to negative impacts on human health and on the quantity and diversity of insects and wildlife near rice paddies.

- *Impacts on Greenhouse Gas Emissions:* The low-oxygen conditions of flooded rice paddies support methane-producing organisms.

  The warm, waterlogged soils in rice paddies are an ideal habitat for methane-producing microbes. As a result, rice production is a significant emitter of methane. Globally, rice systems account for 11 percent of agricultural greenhouse gas emissions, with South and East Asia responsible for 82 percent of total CH_4 emissions from rice.[108] Continuously flooded, irrigated rice fields produce more methane than rainfed systems that are drained for short periods.[109,110]

Section Four: Industrial Crop Processing

The post-harvest processing of crops–particularly cash crops bound for export such as coffee, cotton, and cocoa–has impacts on water quality and quantity, air quality, and climate change.

- *Impacts on Water Quantity and Quality:* Processing often requires substantial amounts of water, which may flow untreated into adjacent water bodies.

  Water use for processing varies by processing method and water availability. In many facilities, water is an essential resource for one or more processing steps and may be used in great quantities. 'Wet method' coffee processing, for example, uses water to separate quality coffee berries from defective ones, to transport berries between processing

---

102 Pingali & Rosegrant, 1994, p. 16
103 Pingali & Rosegrant, 1994, pps. 17-19
104 Wood et al., 2000, p. 66
105 Hossain, 1995, p. 8
106 Ghosh & Bhat, 1998, p. 123
107 Ghosh & Bhat, 1998, p. 123
108 IPCC, 2007b, p. 503
109 Yan, Ohara, T., & Akimoto, 2003, p. 237
110 Wassman et al., 1995, p. 223

machinery, to remove berry husks from coffee grains, and to wash the final product after fermentation.[111] Depending on water availability, the ground or surface water diverted for processing may threaten the supply of water for other natural or human uses.

Water used for processing becomes polluted with chemicals or heavy metals from all stages of the production cycle. Effluent from processing plants may contain traces of pesticides and fertilizers applied to raw crops or heavy metals from corrosion of the plant's machinery. For example, analysis of wastewater from coffee processing facilities in Mexico found particles of zinc leftover from coffee fertilizers and cadmium that had rubbed off from the machinery's enamel and paint.[112] In many developing countries, lax or unenforced wastewater regulations may result in untreated effluent being discharged into rivers or other water bodies. One study estimated that of the amount of water used to make cotton products globally, 19 percent goes to diluting the pollution caused by cultivation and processing.[113] Signs of pollution may be visible, such as colored water from chemical dyes added to cotton products, or noticeable only to smaller organisms, such as negative impacts on small fish from depleted oxygen levels.[114]

- *Impacts on Greenhouse Gas Emissions:* Energy-intensive processing machinery is a source of CO_2 emissions.

Many processing facilities require energy-intensive machinery powered by fossil fuels. As a result, processing contributes to CO_2 emissions. In Ghana, cocoa bean boilers and roasters were found to be the largest drivers of negative environmental impacts during processing due to their large fossil fuel requirements. Processing as a whole accounted for 81 percent of the cocoa sector's contribution to climate change, with crop cultivation and transportation responsible for the remainder. Emissions from processing plants may also degrade air quality by contributing to acid rain and ozone depletion.[115]

Conclusion

The unintended environmental consequences of intensive agricultural practices and inputs are varied and potentially severe. In some cases, sustaining or increasing agricultural productivity depends upon reducing impacts to the environment, such as maintaining productive soils by avoiding salinization from irrigation water. In other cases, however, eliminating negative environmental impacts may involve unacceptable trade-offs with providing food and viable livelihoods, or other development goals. Determining the appropriate balance of costs and benefits from intensive agricultural practices is a location-specific exercise requiring knowledge about, and a valuation of, natural, economic, and social conditions.

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

References

Abate, T., van Huis, A., & Ampofo, J. K. O. (2000). Pest management strategies in traditional agriculture: an African perspective. *Annual Review of Entomology, 45,* 631-659. doi: 10.1146/annurev.ento.45.1.631

Acharya, G. P., Tripathi, B. P., Gardner, R. M., Mawdesley, K. J., & McDonald, M. A. (2008). Sustainability of sloping land cultivation system in the mid-hills of Nepal. *Land Degradation & Development, 19,* 530-541. doi: 10.1002/ldr

[111] Siu, Mejia, Mejia-Salavedra, Pohlan & Sokolov, 2007, p. 400
[112] Siu et al., 2007, p. 402
[113] Chapagain, 2006, p. 186
[114] Chapagain, 2006, p. 187
[115] Ntiamoah, 2008, p. 1738

Arias-Estevez, M., Lopez-Periago, E., Martinez-Carballo, E., Simal-Gandara, J., Mejuto, J. C., & Garcia-Rio, L. (2008). The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agriculture, Ecosystems and Environment, 123,* 247-260. doi: 10.1016/j.agee.2007.07.011

Brown, A. H. D., & Hodgkin, T. (2007). Measuring, managing, and maintaining crop genetic diversity on farm. In D. I. Jarvis, C. Padoch & H. D. Cooper (Eds.), *Managing biodiversity in agricultural ecosystems* (pp. 13-33). New York: Columbia University Press.

Cassman, K. G., & Pingali, P. L. (1995). Intensification of irrigated rice systems: learning from the past to meet future challenges. *GeoJournal, 35.3,* 299-305. doi: 10.1007/BF00989137

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., & Gautam, R. (2006). The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics, 60,* 186-203. doi: 10.1016/j.eco

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

Crew, T. E., & Peoples, M. B. (2004). Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agriculture, Ecosystems and Environment, 102,* 279-297. doi: 10.1016/j.agee.2003.09.018

Ehui, S., & Pender, J. (2005). Resource degradation, low agricultural productivity, and poverty in sub-Saharan Africa: pathways out of the spiral. *Agricultural Economics, 32,* 225-242. doi: 10.1111/j.0169-5150.2004.00026.x

FAO. (2006). *Livestock's long shadow: environmental issues and options*. Available from http://www.fao.org/docrep/010/a0701e/a0701e00.htm

FAO. (2005). *Irrigation in Africa in figures: AQUASTAT survey – 2005*. Available from http://www.fao.org/nr/water/aquastat/regions/africa/index.stm

FAO. (2003). *World agriculture: towards 2015/2030*. Rome: Earthscan. Retrieved from ftp://ftp.fao.org/docrep/fao/004/y3557e/y3557e.pdf

FAO. (1997). *Irrigation potential in Africa: a basin approach*. Available from http://www.fao.org/docrep/w4347e/w4347e00.htm

Fermont, A. M., van Asten, P. J. A., & Giller, K. E. (2008). Increasing land pressure in East Africa: the changing role of cassava and consequences for sustainability of farming systems. *Agriculture, Ecosystems and Environment, 128,* 239-250. doi: 10.1016/j.agee.2008.06.009

Ghassemi, F., Jakeman, A. J., & Nix, H. A. (1995). *Salinisation of land and water resources*. Oxfordshire, UK: CAB International.

Ghosh, B. C., & Bhat, R. (1998). Environmental hazards of nitrogen loading in wetland rice fields. *Environmental Pollution, 102,* 123-126. doi: 10.1016/S0269-7491(98)80024-9

Gliessman, S. R. (2000). *Agroecology: ecological processes in sustainable agriculture*. Boca Raton, FL: CRC Press.

Guo, J. H., et al. (2010). Significant acidification in major Chinese croplands. *Science, 327,* 1008-1010. doi: 10.1126/science.1182570

Hossain, M. (1995). Sustaining food security for fragile environments in Asia: achievements, challenges, and implications for rice research. In *Fragile lives in fragile ecosystems: proceedings of the International Rice Research Conference, 13-18 Feb. 1995* (pp. 3-23). Los Banos, Philippines: International Rice Research Institute.

Intergovernmental Panel on Climate Change. (2007a). Introduction. In *Climate change 2007: mitigation. Contribution of working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter1.pdf

Intergovernmental Panel on Climate Change. (2007b). Agriculture. In *Climate change 2007: mitigation. Contribution of working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter8.pdf

Kangalawe, R. Y. M., Christiansson, C., & Ostberg, W. (2008). Changing land-use patterns and farming strategies in the degraded environment of the Irangi Hills, central Tanzania. *Agriculture, Ecosystems and Environment, 125,* 33-47. doi: 10.1016/j.agee.2007.10.008

Kleinman, P. J. A., Pimentel, D., & Bryant, R. B. (1995). The ecological sustainability of slash-and-burn agriculture. *Agriculture, Ecosystems and Environment, 52,* 235-249. doi:10.1016/0167-8809(94)00531-I

Labios, R. V., Montesur, J. G., & Retales, R. O. (1995). Alley cropping in sloping upland rice areas of Cavite, Philippines. In *Fragile lives in fragile ecosystems: proceedings of the International Rice Research Conference, 13-18 Feb. 1995* (pp. 451-457). Los Banos, Philippines: International Rice Research Institute.

Lal, R. (1997). Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. I. Crop yield and soil physical properties. *Soil & Tillage Research, 42,* 145-160. doi: 10.1016/S0167-1987(97)00006-8

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science, 277,* 504-509. doi: 10.1126/science.277.5325.504

Maumbe, B. M., & Swinton, S. M. (2003). Hidden health costs of pesticide use in Zimbabwe's smallholder cotton growers. *Social Science & Medicine, 57,* 1559-1571. doi: 10.1016/S0277-9536(03)00016-9

McNeely, J. A., & Scherr, S. J. (2003). *Ecoagriculture: strategies to feed the world and save wild biodiversity.* Washington, DC: Island Press.

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: current state and trends, volume 1.* Washington: Island Press. Available from http://www.millenniumassessment.org/en/Condition.aspx#download

Moormann, F. R., & van Breemen, N. (1978). *Rice: soil, water, land.* Los Banos, Philippines: International Rice Research Institute.

Mrabet, R. (2002). Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. *Soil & Tillage Research, 66,* 119-128. doi: 10.1016/S0167-1987(02)00020-X

Ntiamoah, A., & Afrane, G. (2008). Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach. *Journal of Cleaner Production, 16,* 1735-1740. doi: 10.1016/j.jclepro.2007.11.004

Pender, J. (2004). Development pathways for hillsides and highlands: some lessons from Central America and East Africa. *Food Policy, 29,* 339-367. doi: 10.1016/j.foodpol.2004.07.005

Pingali, P. L., & Rosegrant, M. W. (1994). *Confronting the environmental consequences of the Green Revolution in Asia.* Washington, DC: International Food Policy Research Institute.

Smith, P., et al. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B, 363,* 789-813. doi: 10.1098/rstb.2007.2184

Siu, Y., Mejia, G., Mejia-Salavedra, J., Pohlan, J., & Sokolov, M. (2007). Heavy metals in wet method coffee processing wastewater in Soconusco, Chiapas, Mexico. *Bulletin of Environmental Contamination and Toxicology, 78,* 400-404. doi: 10.1007/s00128-007-9094-x

Thierfelder, C., & Wall, P. C. (2009). Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil & Tillage Research, 105,* 217-227. doi: 10.1016/j.still.2009.07.007

Wassmann, R., et al. (1995). Methane emissions from rainfed rice fields. In *Fragile lives in fragile ecosystems: proceedings of the International Rice Research Conference, 13-18 Feb. 1995* (pp. 217-225). Los Banos, Philippines: International Rice Research Institute.

Wichelns, D., & Oster, J. D. (2008). Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management, 86,* 114-127. doi: 10.1016/j.agwat.2006.07.014

Williamson, S., Ball, A., & Pretty, J. (2008). Trends in pesticide use and drivers for safer pest management in four African countries. *Crop Protection, 27,* 1327-1334. doi: 10.1016/j.cropro.2008.04.006

Wilson, C., & Tisdell, C. (2001). Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecological Economics, 39,* 449-462. doi: 10.1016/S0921-8009(01)00238-5

Wood, S., Sebastian, K., & Scherr, S. J. (2000). *Pilot analysis of global ecosystems: agroecosystems.* Washington, DC: World Resources Institute and International Food Policy Research Institute.

Yan, X., Ohara, T., & Akimoto, H. (2003). Development of region-specific emission factors and estimation of methane emission from rice fields in the East, Southeast, and South Asian countries. *Global Change Biology, 9,* 237-254. doi: 10.1046/j.1365-2486.2003.00564.x