CHAPTER
7

Enhancing Eco-Efficiency in the Intensive Cereal-Based Systems of the Indo-Gangetic Plains

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Abstract

The northwest and central parts of the Indo-Gangetic Plain (IGP) of South Asia are among the most productive agricultural regions of the world. But production is becoming unsustainable due to depletion or degradation of soil and water resources, rising production costs, decreasing input use efficiency, and increasing environmental pollution. In contrast, cereal production systems in the eastern IGP are largely traditional, with low yields and farm income. Eco-efficient farming can be used to enhance productivity throughout the IGP. Eco-efficient agriculture can borrow technologies or packages of practices from intensive agriculture and marry them with practices that reduce environmental impacts, such as laser-aided land leveling, reduced or zero tillage and direct/drill seeding, precise water management, crop diversification, and improved plant nutrient management. Such eco-efficient practices are expected to raise land and water productivity, improve resource use efficiency, reduce risks and vulnerability of cropping systems to climate change, diversify farm income, and improve family nutrition and livelihood. A comprehensive understanding of scientific, technical, environmental, economical, and societal issues, including farmers' re-education, are prerequisite to effectively promote eco-efficient farming practices.

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The Indo-Gangetic Plains

The Indo-Gangetic Plains cover some 700,000 km^2 in Pakistan, India, Nepal, and Bangladesh and are home to nearly one billion people.

Narang and Virmani (2001), divided the IGP into five subregions, based on physiographic, climatic, and vegetation patterns (Figure 1).

Subregions 1 and 2 (northwestern IGP) have a semiarid climate with 400–800 mm annual rainfall. The land is gently sloping or flat. The topography is dotted with saucer-shaped depressions with poor drainage, locally named as "chaurs". These create flood-plain lakes or wetlands with 50 to 400 cm water depth during the peak rainy season. They are more abundant in the eastern than in the western part of the IGP. In coastal areas, these depressions form the marshy/swampy lands. They are used as community fishing ground in the wet season, and for winter rice, maize and vegetable crops after the water recedes. Soils are alluvial and calcareous with some alkaline soils in pockets. The groundwater is mostly depleted or of marginal quality. Mean farm size is 3.55 ha, mostly irrigated and mechanized (Table 1). Some parts are intensively cultivated, with liberal application of chemical inputs, while agriculture in other areas is rainfed with limited use of inputs (Singh et al., 2009). Surface water and groundwater are used for irrigation and many farmers take full advantage of improved technologies to enhance crop yields and profit (Erenstein et al., 2007; Erenstein and Laxmi, 2008; Singh et al., 2009). Wheat and basmati and non-basmati long grain rice are the main crops in subregion 1, while the main crops in subregion 2 are basmati and long grain rice, wheat, maize, black gram (*Phaseolus mungo* L.), green gram or mung bean [*Vigna radiate* (L.) R. Wilczek], sunflower, potato, sugarcane, cowpea, and dhaincha (*Sesbania aculeata* Pers.) grown for green manure in rice-based systems (Gupta et al., 2005). The annual land use intensity (LUI) is relatively low (182%) (Singh et al., 2009).

In the central IGP (subregion 3), the climate is hot subhumid, with 650–970 mm of annual rainfall. The topography is mostly saucer-shaped (see description above for subregions 1 and 2). Soils are alluvial with pockets of alkaline soils on the plains and acidic soils on the hills. Major crops cultivated include rice, sugarcane, wheat, maize, soybean, cotton, potato, and pigeon pea in rice- or maize-based systems, with an annual LUI of 191%. Mean farm size is 0.94 ha (Table 1), with limited farm mechanization and adoption of resource conserving technologies (RCTs) (Singh et al., 2009).

Figure 1. Five sub-regions of the Indo-Gangetic Plains (IGP) in South Asia.
SOURCE: Narang and Virmani (2001).

Table 1. Selected indicators of farmers' resource endowments and farm characteristics in the Indo-Gangetic Plains (IGP).

Particulars	Northwest IGP	Central IGP	Eastern IGP
Mean farm size (ha/household)	3.55	0.94	0.59
Share of operational land owned (%)	91	85	86
Irrigated land (%)	100	60	90
Rainfed land (%)	0	40	10
Depth to water table, 1997/98 (m)	11	8	32
Depth to water table, 2007/08 (m)	19	14	39
Annual land use intensity (% of cultivated area)	182	191	233
Crops			
Monsoon season	Rice, sugarcane, fodder, pearl millet	Rice, maize, pulses	Rice, maize, fiber crops, vegetables
Winter season	Wheat, sugarcane, fodder, vegetables	Wheat, vegetables, pulses, mustard	Boro rice, maize, vegetables, wheat
Livestock (per household)			
Cattle	4.3	1.4	1.9
Goats/sheep	0.7	1.1	1.9
Chickens	14.1	5.2	6.9
Agricultural implements			
Tractors (per 1,000 households)	260.6	36.3	2.0
Power tillers (per 1,000 households)	0.0	7.0	33.6
Zero-till seed drills (per 1,000 households)	35.2	10.9	0.0
Rotovators (per 1,000 households)	7.8	0.8	0.0
Reapers (per 10,000 households)	8.9	0.0	0.0
Combine harvesters (per 10,000 households)	5.1	0.0	0.0
Laser levelers (per 100,000 households)	2.5	0.0	0.0

SOURCE: Singh et al. (2009).

Eastern IGP (subregions 4 and 5) has a hot subhumid climate with a mild winter (5.4 °C in January) and higher rainfall (1000–1800 mm per annum) than other regions. The land is gently sloping with alluvial, calcareous/alkaline, and acidic soils that are poorly drained. Flooding is a serious problem in this area. The rich groundwater resource is contaminated with fluoride and arsenic in some pockets. Half of the irrigated area is supplied with surface water and half using groundwater. Rice is the dominant crop, followed by potato, wheat, maize, sunflower, onion, jute, and lentil in rice-based cropping systems. Cropping intensity is quite high (LUI of 233%) (Singh et al., 2009) and mean farm size is only 0.59 ha (Table 1). Farmers are relatively poor, and use power tillers for land preparation and seeding (Singh et al., 2009). Farmers supplement their income with other activities such as working as laborers on other farms or in local industries, services, and business (Erenstein, 2009). Migration for off-farm employment is also common in other subregions.

Two or more crops are grown each year in most parts of the IGP. Rice followed by wheat (R–W) is the predominant cropping system in the IGP in India, and Nepal, while double-cropping with rice (R–R) is the predominant cropping system in the IGP in Bangladesh, and cotton–wheat (Cot–W) is predominant in Pakistan (Table 2). Maize cultivation has increased in recent times both in terms of area and production in the eastern IGP because winter maize is more productive and profitable and requires less water than winter (*boro*) rice (Timsina et al., 2011).

Table 2. Major cereal cropping systems (area in m ha and % of total area) in four South Asian countries.

Cereal cropping	Bangladesh		India		Nepal		Pakistan		Total	
Systems	m ha	%	m ha	%	m ha	%	m ha	%	m ha	%
R–W	0.60	5.05	9.20	11.81	0.57	18.15	2.20	17.09	12.57	11.88
R–R	4.50	37.88	4.70	6.03	0.30	9.55	–	–	9.50	8.98
R–R–R	0.30	2.53	0.04	0.05	–	–	–	–	0.34	0.32
R–M	0.35	2.95	0.53	0.68	0.43	13.69	–	–	1.31	1.24
R–Pulses	–	–	3.50	4.49	–	–	–	–	3.50	3.31
R–Veg	–	–	1.40	1.80	–	–	–	–	1.40	1.32
R–Potato	0.30	2.53	–	–	–	–	–	–	0.30	0.28
Cot–W	–	–	1.39	1.78	–	–	3.10	24.09	4.49	4.24
M–W	–	–	1.80	–	0.04	1.27	1.00	7.77	2.84	2.68
Millet–W	–	–	2.44	3.13	–	–	–	–	2.44	2.31

R = Rice; W = Wheat; M = Maize; Veg = Vegetables; Cot = Cotton; – refers either data not available or negligible area.
SOURCE: Jat et al. (2011).

Cereals may also be alternated with other crops, such as potato, lentil, chickpea, mustard, or sunflower in winter, and jute, fodder maize, rice, mung bean, or cowpea during the spring season.

The area under R–W on the IGP trebled and production increased fivefold from 1960 to 2000 (Saharawat et al., 2009). Now, however, the cereal systems in subregions 1–3 are becoming more and more unprofitable and less sustainable due to yield stagnation, a 50% decline in total factor productivity, increasing production costs (high cost of land, labor, and chemical inputs), and declining returns from additional inputs (Ladha et al., 2003; Singh et al., 2009). Despite this, farmers continue to intensify R–W systems and are reluctant to diversify to crops with lower water requirements, mainly because of high subsidies for power, fertilizer, and irrigation water, and well-developed production and marketing systems for rice and wheat in the region (Erenstein, 2009; Saharawat et al., 2009). In the eastern IGP (subregions 4 and 5), rice and wheat are produced in traditional, labor-intensive systems on small (average 0.59 ha) farms. Frequent droughts, flooding in the monsoon season, late rice harvests which delay planting of wheat, and limited use of inputs are common and lead to low productivity and returns (Gupta and Seth, 2007). However, LUI is high (233%) because of year-round cropping (Erenstein, 2009; Singh et al., 2009).

The problems of both regions of the IGP can be addressed through adoption of eco-efficient agriculture that enhances and sustains productivity and profitability of the rice-, wheat- and maize-based systems while minimizing the adverse impact on the environment.

Rising Demand, Declining Yields: the Need for Eco-Efficient Agriculture

It is estimated that demand for food and non-food commodities is likely to increase by 75–100% globally between 2010 and 2050 (Keating et al., 2010; Tilman et al., 2011). The increase in demand in South Asia is expected to be at least as much. As there is little scope for expanding the area under cultivation in South Asia, there is thus an urgent need to further intensify land use and increase productivity of cereal systems to meet the growing demand. Projections indicate that production of rice, wheat, and maize will have to increase by about 1.1%, 1.7%, and 2.9% per annum, respectively, over the next four decades to ensure food security in South Asia (O. Erenstein, pers. comm.). National mean yields of all three cereals in South Asia are below global averages (except for maize in Bangladesh) and yield gaps of 50% or more exist in all the three crops (Table 3) (Aggarwal et al., 2008; Lobel et al., 2009). Thus, there is a

Table 3. Yields (t/ha) and yield gaps (t/ha) for rice, wheat, and maize in sub-regions of the Indo-Gangetic Plains (IGP).

Yield and	North-west			Central	Eastern	
yield gaps	Pak. Punjab	Indian Punjab	Haryana	Uttar Pradesh	Bihar	Bangladesh
Rice (Paddy)						
Potential yield	5.2(M); 3.8(F)	8.8(M); 6.5(E)	6.6(E); 5.9(F)	6.1(M); 6.6(E)	5.5(M); 6.1(E)	5.4(E); 7.1(E)
Average yield	3.6(M); 1.6(F)	5.0(M); 5.0(E)	5.0(E); 4.7(F)	3.1(M); 2.9(E)	2.0(M); 1.8(E)	4.6(E); 6.3(E)
Yield gap	1.6(M); 2.2(F)	3.8(M); 1.5(E)	1.6(E); 1.2(F)	3.0(M); 3.7(E)	3.5(M); 4.3(E)	0.8 (E); 0.8(E)
Wheat						
Potential yield	6.8(M); 4.6(F)	5.5(M); 4.6(E)	4.0(M); 5.4(E)	5.0(M); 3.8(E)	3.8(M)	4.2(F); 3.4(E)
Average yield	2.7(M); 2.5(F)	4.1(M); 4.1(E)	3.8(M); 4.2(E)	2.5(M); 2.5(E)	2.2(M)	2.9(F); 2.5(E)
Yield gap	4.1(M); 2.1(F)	1.4(M); 0.5(E)	0.2(M); 1.2(E)	2.5(M); 1.3(E)	1.6(M)	1.3(F); 0.9(E)
Maize						
Potential yield	9.2(M); 6.9(F)	5.1(M)	–	3.0(E)	5.7(E)	9.0(M)
Average yield	3.5(M); 1.9(F)	2.6(M)	–	1.3(E)	1.7(E)	5.7(M)
Yield gap	5.7(M); 5.0(F)	2.5(M)	–	1.7(E)	4.0(E)	3.3(M)

(M): Model-based; (E): Experimental on-station or on-farm; (F): Farmers' best yield.

great potential to increase the yields of major cereals in South Asia (Ladha et al., 2009; Timsina et al., 2011).

Economic and environmental concerns

Energy use is generally high in intensive cereal production systems. Of the total energy used for crop production, fertilizer and chemical energy inputs comprise 47% for wheat, 43% for rice (Khan et al., 2009b), and 45% for maize (Kraatz et al., 2008). About 60% of this is due to nitrogen (N) fertilizers alone. In the R–W system in northwest IGP most of the energy is used for land preparation—wet tillage and puddling for rice and preparatory tillage operations for wheat, pump irrigation, and combine harvesting. Conventional tillage is not only fuel- and cost-inefficient, it also contributes to a larger carbon footprint through increased emission of CO_2 (Grace et al., 2003).

The liberal or excessive use of natural resources and external inputs such as N fertilizers and other agrochemicals in the western and central regions of IGP has caused environmental and ecological degradation—soil degradation (salinity and alkalinity, soil erosion), depletion of soil organic matter due to oxidation of soil carbon under conventional tillage, depletion of groundwater in large areas, pollution of surface and groundwater, and leakage of reactive N into the environment (Bijay-Singh et al., 2008).

Power subsidy to farms leads to inefficient use of electricity, particularly for pumping water. For example, in 2007, 7.5 billion units of electricity (28% of total power consumed in the state) were used for tube-wells in Punjab alone, in addition to the diesel consumed (Anonymous, 2008).

As a result of excessive exploitation of groundwater, the depth to water table has increased steadily in many areas (Hira and Khera, 2000; Hira, 2009; Rodell et al., 2009), for example, by 0.2 m/year between 1973 and 2001 and by 1 m/year between 2000 and 2006 in Punjab (Humphreys et al., 2010). The rates of groundwater depletion were greatest in the northwest Indian IGP: in 2009 groundwater was overexploited in 103 out of 138 administrative blocks in Punjab and 55 out of 108 in Haryana (Humphreys et al., 2010). With the continued decline in water table, power consumption for tube-well irrigation will double by 2023 and the cost to farmers of maintaining pump infrastructure and replacing failed pumps will escalate. Moreover, saline groundwater is intruding into fresh groundwater aquifers (Humphreys et al., 2010). Fluoride and arsenic contamination of groundwater is also a problem in some areas of the IGP. Fluoride in groundwater above the safe limit of 1.5 mg/liter has been recorded in five districts of Bihar, two districts of Chhattisgarh, four districts of Jharkhand, and seven districts each of Uttar Pradesh and West Bengal. Similarly, occurrence of arsenic above the safe limit of 0.01 mg/liter in groundwater from the intermediate aquifer at a depth of 20 to 100 m has been observed in 12 districts of Bihar, five districts of Uttar Pradesh, and one district each of Chhattisgarh and Assam (Anonymous, 2008; Hira, 2009).

Agricultural systems in northwest and central IGP also produce large amounts of greenhouse gases (GHGs), particularly from flooded rice fields (Pathak et al., 2002; Pathak et al., 2003; Bhatia et al., 2010; Pathak et al., 2011). While emission of methane (CH_4) from flooded rice systems can be reduced by adopting different water and crop management strategies (Adhya et al., 2009; Gupta-Vandana et al., 2009), such changes, plus increased N fertilizer use, in intensive cereal systems would be likely to increase production of nitrous oxide (N_2O), another GHG (Pathak et al., 2007; Wassmann et al., 2009). This trade-off between CH_4 and N_2O emissions is a major limitation in devising an effective strategy for mitigating GHG emissions from the R–W system (Ladha et al., 2009). Burning of rice residues to clear the land for wheat also releases large amounts of CO_2 into the atmosphere (Ladha et al., 2003). Farm machinery, including the pumps used for irrigation, emitted 283–437 kg CO_2-C/ha of rice and 33–58 kg CO_2-C/ha of wheat in a R–W system (Pathak et al., 2011).

Clearly, new approaches are needed to develop agricultural production systems that are productive and sustainable, both economically and ecologically. Eco-efficient agriculture offers such an approach.

Eco-Efficient Agriculture

Eco-efficiency is concerned with the efficient and sustainable use of resources in farm production and land management. It can be increased either by altering the management of individual crop and livestock enterprises or by altering the land-use system. Conceptually the eco-efficiency seems to be similar to the concepts of ecological intensification (Cassman, 1999; Dobermann et al., 2008) and conservation agriculture (CA) (Hobbs et al., 2008), while encompassing both the ecological and economic dimensions of sustainable agriculture. In addition to the economic aspect, evolving social, institutional, market, and policy-related pressures will determine the extent of development of eco-efficient agriculture (Keating et al., 2010).

At the farm level, eco-efficiency might be represented in terms as diverse as food output per unit labor, the biodiversity benefits provided by retention of natural habitat per unit food production, or the aggregate food output per unit water or fertilizer applied (Keating et al., 2010). Production increases of the last 50 years were achieved at significant cost to the natural resource base (degraded soils and ecosystem impacts, including habitat fragmentation threatening biodiversity) as well as the global environment. Future production increases must come from stabilizing yields in areas where yields are already high and increases in production in areas where yields are currently low, while promoting ecological sustainability. The agricultural revolution over the next 40 years has to be the eco-efficiency revolution, with 50 to 100% increases in the efficiency with which scarce resources of land, water, nutrients, and energy are used. Importantly, this greater output and efficiency has to be achieved while maintaining or restoring land, water, biodiversity, and agroecosystems.

Practices that have been shown to increase the productivity and eco-efficiency of agriculture at the farm level include resource-conserving technologies (RCTs) such as laser land leveling and direct seeding (Hobbs and Gupta, 2003; Ladha et al., 2003; Sharma et al., 2005; Gupta and Seth, 2007; Harington and Hobbs, 2009; Ladha et al., 2009), integrated crop management (ICM) (Nguyen, 2002; Balasubramanian et al., 2005), integrated crop and resource management (Ladha et al., 2009), integrated farming systems (Hesterman and Thorburn, 1994), and integrated soil–crop system management (Chen et al., 2011).

These and other components of eco-efficient agriculture are discussed in more detail below.

Key Components of Eco-Efficient Agriculture in the IGP

Laser leveling and land preparation

Integrating laser-leveling with other best management practices has been shown to increase productivity of R–W systems by 7–19% and reduce water consumption for irrigation by 12–30% in on-station and farmer-participatory trials in India, increasing net returns by US$113–US$300/ha per year (Jat et al., 2009). This has been reflected in a rapid increase in the number of laser units employed in the northwest Indian IGP between 2001 and 2008, from zero to 925 and in the laser-leveled area from zero to 0.2 m ha (Jat et al., 2009; Ladha et al., 2009). The laser-leveled area in Pakistan increased from zero to 0.18 m ha during the same period (Harrington and Hobbs, 2009; M. Ahmed, pers. comm.).

Reduced/zero tillage and direct/drill seeding

Zero-tillage (ZT) wheat has been the most successful technology for reducing resource use in R–W systems, particularly in the Indian IGP. The prevailing ZT technology in the IGP uses a tractor-drawn zero-till seed drill to drill wheat directly into unplowed fields with a single pass of the tractor. The ZT drills are made domestically at a cost of around US$400 (Thakur, 2005). Alternatively, wheat seed can be broadcast on a saturated soil surface before or after the rice harvest (Erenstein and Laxmi, 2008). This is ideal for resource-poor farmers, requiring no land preparation or machinery, but its use is still largely confined to low-lying fields that remain too moist for tractors to enter, particularly in the eastern IGP.

ZT as applied to the R–W systems in the IGP has three characteristic features that separate it from related systems elsewhere (Erenstein, 2003). First, ZT is typically applied only to the wheat crop in the double-cropped system, with the subsequent rice crop still intensively tilled. Second, ZT wheat after rice does not necessarily entail an increased reliance on herbicide, as the paddy rice fields are relatively weed-free at harvest time. Third, ZT wheat does not necessarily imply the retention of crop residues as mulch. In fact, the prevailing Indian ZT seed drills are relatively poor in trash handling, but this has not been a major issue in view of the limited biomass remaining in R–W systems after the rice crop (Erenstein et al., 2007).

Combining precision land-leveling, ZT, and drill seeding wheat with leaving crop residues on the soil surface quadrupled farmer income compared with reduced-till or conventional-till wheat, mainly due to higher yields resulting from timely planting and reduced tillage cost (Gupta and Seth, 2007; Jat et al., 2011). Smallholders in the eastern IGP have also increased yields and reduced costs by adopting ZT for broadcast seeding of wheat (Gupta et al., 2003). It is estimated that 20–25% of the wheat area in northwest IGP is now under zero- or reduced tillage, with or without crop residues left on the soil surface (Erenstein, 2009).

Similarly, direct seeding of rice has the potential to provide several benefits to farmers and the environment over conventional practices of land preparation such as puddling and transplanting. Recently, Kumar and Ladha (2011) reviewed the benefits of direct seeding compared with transplanting into puddled soil, which typically include reduction in irrigation water use (12–35%), labor (0–46%), and cultivation costs (2–32%); higher net economic returns, and reduced methane emissions. However, yields are lower in some cases, especially with dry seeding combined with reduced/zero tillage, as a result of uneven and poor crop stand, poor weed control, higher spikelet sterility, crop lodging, and poor knowledge of water and nutrient management. Most rice varieties are bred and selected for transplantation into puddled land. Risks associated with a shift from puddle transplanting to direct seeding include a shift toward hard-to-control weed flora; development of herbicide resistance in weeds; evolution of weedy rice; increases in soil-borne pathogens and pests such as nematodes; higher emissions of nitrous oxide—a potent greenhouse gas; and nutrient disorders, especially N and micronutrients. Grain yields and net income were lower from reduced-till and zero-till direct-seeded or bed-planted rice than from conventional rice, despite significant savings in water use (Ladha et al., 2009; Gathala et al., 2011; Jat et al., 2011). This was because of increased weed infestation. Further research is needed to develop suitable weed control technologies for direct seeded rice systems (Kumar and Ladha, 2011).

Thus, direct seeding of rice will be adopted only once an integrated package of technologies has been developed, including improved weed control and cultivars that perform well under these conditions.

Water management

As already noted, water consumption can be significantly reduced by directly seeding rice into dry soil instead of transplanting into puddled soil (Bhuiyan et al., 1995; Bouman, 2001; Cabangon et al., 2002; Sharma et al., 2002), and by growing rice on raised beds (Borrel et al., 1997). However, yields on raised beds may be reduced by 15% or more compared with traditionally-grown rice (Sharma et al., 2002; Vories et al., 2002; Gathala et al., 2011). Similarly, other water conservation techniques, such as crop-need-based water application, alternate wetting and drying (AWD), aerobic rice culture, etc. would both increase water use efficiency and irrigated crop area (Cabangon et al., 2002; Bouman et al., 2005; Bhushan et al., 2007; Gathala et al., 2011). For example, AWD irrigation of rice transplanted into puddled soil reduced water use by 25% with little impact on yield (7-year average of 7.8 t/ha compared with 8.1 t/ha) (Gathala et al., 2011).

Some of the water conservation technologies have positive impacts on resource use and the environment, such as increased water infiltration leading to groundwater recharge, lower energy use due to less pumping of water, enhanced soil quality, reduced methane emissions, and short-term carbon sequestration in soil due to retention of crop residues instead of burning (Jat et al., 2011).

Crop diversification

Farmers in the IGP are being encouraged to grow high value crops, such as vegetables, fruits, and cut flowers, and to expand production of fodder crops and livestock/dairy farming for both local and export markets. In the central and eastern IGP, farmers following the R–W system leave land fallow for about 60–70 days in the pre-monsoon (pre-*kharif*) season, after the wheat harvest. Growing short-season pulses such as mung bean (green gram), black gram, green manure crops such as sesbania, vegetables, or other high-value crops during this period would diversify the R–W cropping system, improve soil quality, and increase farmers' income (Gupta and Seth, 2007; Singh et al., 2007).

Integrated crop–fish/poultry/duck/livestock systems also would diversify farm income, improve food and nutritional security, enhance land and water productivity, and preserve ecosystems (Ayyappan et al., 2009).

Plant nutrition management

Nitrogen sources and nitrogen-use efficiency in eco-efficient farming

Efficient N use is central to eco-efficiency in agriculture (Keating et al., 2010). The term nitrogen-use efficiency (NUE) relates only to applied fertilizer N, although crops absorb N from other sources. Four agronomic indices are commonly used to measure NUE in crops and cropping systems: (a) partial factor productivity (PFP_N), expressed as the total grain yield per unit of N applied; (b) agronomic efficiency (AE_N), expressed as the increase in grain yield over that of the zero-N control per unit of N applied; (c) apparent recovery efficiency (RE_N), defined as the percentage of applied N absorbed by the crop in aboveground biomass; and (d) internal or physiological efficiency (PE_N), defined as the increase in grain yield over that of the zero-N control per unit of N acquired by the crop (Novoa and Loomis, 1981; Ladha et al., 2005).

Two key factors that influence crop yields and RE_N in cereal cropping systems are the spatial and temporal synchronization of applied N with crop demand and use of N-efficient crop cultivars (Tilman, 1998; Balasubramanian et al., 2004; Ladha et al., 2005; Balasubramanian, 2010). For example, application of N transplanted rice in the

IGP (551 farms) based on need indicated by a leaf-color chart (LCC) increased grain yield by 0.24 to 0.75 t/ha and net income by US$41 to US$49/ha (Regmi and Ladha, 2005; Varinderpal-Singh et al., 2007; Ladha et al., 2009). Takebe et al. (2006) demonstrated that applying the correct N dose at full heading stage increased the wheat protein content to more than 120 g/kg.

Balanced fertilizer use is also critical. For example, Norse (2003) has shown that application of fertilizer with unbalanced N–P_2O_5–K_2O ratios (e.g., 100–36–19 in China, 100–37–12 in India, and 100–35–45 in USA) may diminish plant utilization of applied N and thus reduce NUE. Deficiency of calcium, magnesium, sulfur, and micronutrients reduce plant response to N and hence reduce NUE (Aulakh and Bahl, 2001; Aulakh and Malhi, 2004; Mosier, 2002). Thus, deficiency of nutrients other than N must be corrected to get an optimal response to N (Ladha et al 2005).

Soil and soil organic matter

Soil organic matter (SOM) is a key component of soil health and acts as a temporary storehouse of nutrients. It is reported that more than 50% of crop N is obtained from SOM in most soils except coarse textured sandy soils (Dourado-Neto et al., 2010). Crops use applied N more efficiently in organic-matter-rich soils than in organic-matter-poor soils.

Maintenance of SOM is critical for increasing eco-efficiency in farming, especially in tropical soils. Fertilizer N added to soil plays both a constructive and a destructive role in the maintenance of SOM (Ladha et al., 2011). Application of fertilizer N increases production of biomass, part of which is added to soil to enrich SOM (Sisti et al., 2004). However, fertilizer N also increases mineralization of SOM. Oxidization of SOM is also promoted by conventional tillage, removal of vegetation cover, and exposure of the soil to the sun's radiation (Khan et al., 2007; Powlson et al., 2010).

Overall, practices such as ZT, maintenance of permanent groundcover, and crop rotation help increase SOM levels and thus maintain soil health and crop productivity (Ladha et al., 2009; Jat et al., 2011).

SOM levels can also be increased by applying organic materials, including crop residues, green manure, and animal manure, and biowaste such as byproducts from food-processing and city/municipal biowastes (Yadvinder-Singh et al., 2005; Sidhu et al., 2008), as can crop productivity and fertilizer use efficiency (Ladha et al., 2011). However, organic materials such as crop residues and animal manures have competing uses (fodder, fuel, roofing material) and thus their availability for use as a soil amendment is limited (Erenstein, 2009). Also conventional practices of organic amendment such as incorporation and composting are labor-intensive. Therefore, in-field cycling of available crop residues is likely to be the most effective and least expensive option for the farmers (Yadvinder-Singh et al., 2011).

Integrated nutrient management

The ideal approach for eco-efficient agriculture is integrated nutrient management (INM), or optimum use of all available nutrient sources—SOM, BNF, crop residues, manures, and mineral fertilizers. The integrated soil fertility management in Africa (Vanlauwe et al., 2004), site-specific nutrient management in Asia (Dobermann and White, 1999; Dobermann et al., 2004; Buresh, 2010), and integrated plant nutrient systems (Bruinsma, 2003) are some of the efforts to promote the efficient use various nutrient sources. INM can save 5–30% of fertilizer N and increase grain yield by 10–15% (Vanlauwe et al., 2002; Balasubramanian et al., 2004; Dobermann and Cassman, 2004; Ladha et al., 2005; Bijay-Singh et al., 2008; Buresh, 2010). Stress tolerant crop varieties when combined with INM systems and ICM increase grain yields and NUE even under stressful conditions (Havlin, 2004; Ortiz et al., 2008; Ribaut et al., 2009; Ali-Jauhar and Santlaguel, 2011).

Intensive Eco-Efficient Agricultural Systems

Globally, the demand for food and agricultural products is projected to double by 2050 (Keating et al., 2010). Given that only 7 to 12% of the projected increase in food production between 2010 and 2050 is likely to come from expansion of arable land area (Fischer et al., 2005), most of the increase will have to come from intensification of existing production systems —13–15% from increased cropping intensity and 75–76% from increased yields (Fischer et al., 2005, 2007). This can be achieved sustainably only through eco-efficient agriculture. Here we present three examples of eco-efficient agricultural systems operating successfully in the IGP that could be replicated in other similar agroecological zones.

Intensive eco-efficient cereal production systems in the northwest and central IGP

Intensive irrigated cereal production systems of the northwest and central IGP combine CA practices with efficient water, nutrient, and pest management. Land management, crop establishment, and crop management practices employed include land leveling, ZT, direct/drill seeding, deep placement of fertilizer N, residue mulch, and diverse crop sequences/rotations. The systems achieve land productivity of 70–90% of site yield potential for major crops; water productivity of 0.8 to 1.0 kg grain/m^3 water for rice and 2.0–2.5 kg grain/m^3 water for maize and wheat; agronomic N use efficiency of 20–25 kg additional grain/kg N applied for rice and wheat and 25–30 kg additional grain/kg N applied for maize; crop N recovery efficiency of significantly more than 50%; reduce farm energy use by 40–50%; reduce methane and N_2O emission by 40–50%; and increase soil organic matter to 2–3% in most soils except in sandy soils. The systems are thus highly productive and profitable, efficient in resource use and conservation, enhance ecological efficiency and climatic resilience, improve soil quality, preserve biodiversity, and have minimal environmental footprints (Gupta et al., 2003; Byerlee et al., 2003; Gupta and Seth, 2007; Harrington and Hobbs, 2009; Ladha et al., 2009). Such systems currently occupy some 4 million hectares of land in the IGP.

Integrated farming systems for rainfed lowlands

Integrated farming systems (IFSs) are a natural resource management strategy advocated by the Central Rice Research Institute (CRRI), Cuttack, India. The objective is to achieve economic and sustainable production of diverse products to meet farm families' needs and to cater to local market demands, while preserving the resource base and maintaining environmental quality (Hesterman and Thorburn, 1994). Generic IFS models developed by CRRI integrate cropping with horticulture, fish, poultry, ducks, pigs, sericulture, mushroom culture, bee-keeping, farm woodlots, depending on agroclimatic and socio-economic conditions (Table 4). A micro watershed (15–18% of the farm area) is used to drain excess water from rice fields during floods in deepwater ecosystems, and to provide one or two supplementary irrigations for field crops during periods of drought. All crop residues and other farm wastes including animal droppings are recycled or composted and returned to the land. Initial cost of earth works for land shaping ranges between US$2900 and US$3300/ha.

IFSs have been shown to stabilize crop production (especially in rainfed ecosystems); enhance resource recycling; ensure efficient use of all inputs; generate year-round employment; improve farm income, cash flow, and family nutrition; and maintaine healthy ecosystem services in the face of biotic, abiotic, and environmental stresses and climate-change-induced extreme weather events in the lowlands (Srivastava et al., 2004; Mangala, 2008). The benefit/cost ratio increased from 1.89 for rice alone to 2.27 for rice plus horticultural crops, 2.80 for rice plus horticultural crops and fish, and to more than 3.00 if ducks were added to the system (Srivastava et al., 2004). The IFS model for rainfed medium lowland has been adopted on 100 ha of land in Orissa State, India, and the model for deepwater areas on 40 ha. These IFS systems could be expanded to the eastern IGP, but this would require financial assistance to help with the costs of initial land shaping, training of and technical support to farmers during the first year of adaptation and adoption, and development of market access for the multiple products produced in the IFS.

Integrating grain legumes in the rice–wheat system in Bangladesh

Incorporating grain legumes in the R–W system has the potential to increase farm income,

Table 4. Characteristics, land-shaping cost, productivity, employment generation and income of integrated farming systems (IFSs) developed for irrigated, rainfed medium lowland, and deepwater areas.

Rice–fish–multicrop IFS model for irrigated lowland	Rice–fish–horticulture–farm animals IFS model for rainfed medium lowland	Multistorey rice–fish–farm animals–agroforestry IFS model for deepwater ecology
		
Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, ducks, poultry, mushroom, bee-keeping Irrigated lowland rice (50% of area): rice–pulse/oil seed/vegetable crops Micro watershed (15% of area): fish refuge, aquaculture, irrigation during droughts	Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, goats tethered, rabbits in cages, ducks, poultry Rainfed lowland rice (40% of area): rice–pulse/oil seed/vegetable crops Micro watershed (18% of area): fish refuge, aquaculture, irrigation during droughts Fish nursery (7% of area): fingerlings	Upland (15% of area) + 2–3-m-wide bunds (20% of area): perennial & seasonal fruit crops & trees; tubers, vegetables, goats tethered, rabbits in cages, ducks, poultry Rainfed lowland rice (20% of area): rice–pulse/oil seed/vegetable crops Deep-water rice (20% of area): Deep-water rice–summer/boro rice Micro watershed (18% of area): fish refuge, aquaculture, irrigation during droughts Fish nursery (7% of area): fingerlings
Initial investment: US$2900 to 3300/ha		
Productivity in t/ha per year: Food crops: 16–18 Fish + prawns: 0.4–0.5 Bird meat: 0.5–0.7 Animal fodder/feed: 5–6 Flowers, fuel wood, etc.	Productivity in t/ha per year: Food crops: 16–18 Fish + prawns: 0.5–0.6 Meat: 0.5–0.8 Animal fodder/feed: 5–6 Eggs (number): 8,000 Pearl, flowers, wood, etc.	Productivity in t/ha per year: Food crops: 14–15 Fish + prawns: 1 Meat: 0.5–0.8 Animal fodder/feed: 3–5 Fuel wood: 10–12
Additional employment: 250–300 person days/ha per year	Additional employment: 400–450 person days/ha per year	Additional employment: 400–500 person days/ha per year
Income per ha per year: US$1300–US$1600	Income per ha per year: US$1800–US$2900	Income/ha per year: US$2200–US$3300
Teak trees on bunds can be sold at maturity (30+ years) to meet large family expenses		

SOURCE: Central Rice Research Institute, Cuttack, India.

improve soil fertility, and thus enhance the sustainability of the farming system. For example, farmers in Bangladesh planting mungbean during the short fallow period between winter wheat and monsoon rice earned more than US$600/ha more than those who left the land fallow (A. Sarkar, pers. comm.). Improved short-duration, salt-tolerant crop varieties (e.g., BARI mung-6 in Bangladesh, hybrid pigeonpea in India) could intensify or diversify crop production in the IGP (Dahiya et al., 2002; Khan et al., 2009a).

Summary and Conclusions

Intensive eco-efficient farming has an important role to play in addressing existing and emerging problems of intensive cereal production systems in the IGP.

In the water-poor northwest IGP, changes envisaged include enhancing eco-efficiency in intensive cereal production systems and replacing rice with crops with lower water requirements. In the rainfall- and groundwater-rich eastern IGP, viable options include integration of irrigated winter (*boro*) rice, maize, and annual crops such as sugarcane and banana, inclusion of grain or green manure legumes in the R–W cropping system, and intensification of rice-based cropping systems and crop–livestock systems. Generic IFS models have been developed that employ land-leveling and micro watershed to grow rice, upland crops, fruit trees, timber trees, produce fish and poultry, and support bee-keeping and sericulture. However, although the system has been shown to stabilize crop production, enhance resource use efficiency and recycling, generate year-round employment, improve income, cash flow and family nutrition, and maintain healthy environment, farmer adoption is still limited.

Improving the productivity of farm-scale eco-efficient agriculture to the level achieved on research plots will be a challenge as it requires transfer of complex and knowledge-intensive principles and practices to millions of smallholder farmers. This will require massive concerted efforts in six areas:

- Large-scale training or technical mentoring programs in eco-efficient agriculture for agricultural scientists, extension workers, and farmers.
- Development of appropriate machinery and farm machinery rental services to allow farmers to adopt conservation agriculture practices and integrated soil, water, and crop management technologies.
- Research and development based on farmers' feedback to solve practical problems in the adoption of CA and related integrated crop management technologies.
- Development of local champions to showcase and promote the best management practices and other technologies to farmers in their respective areas.
- Development of price support and markets for new agricultural products produced in integrated farming systems.
- Focused institutional and policy support, including appropriate incentives and crop insurance to reduce risks for the widespread dissemination and adoption by farmers of intensive eco-efficient agricultural practices in the IGP of South Asia.

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