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Long-Term Sustainability of the Tropical and Subtropical Rice–Wheat System: An Environmental Perspective

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ABSTRACT

Arable lands in the Indo-Gangetic Plains are already intensively cropped with little scope for expansion because of the competing end uses of land for urbanization and industry. Evidence from long-term experiments in the region indicates that cereal yields are declining, which is in stark contrast to the needed increases in production to meet population demand in the future. The intensification of rice–wheat rotations has resulted in a heavy reliance on irrigation, increased fertilizer usage, and crop residue burning, which all have a direct effect on the variable that most affects global climate change—emissions of greenhouse gases. We estimate that the CO_2 equivalent emissions from a high-input conventionally tilled cropping system with residue burning and organic amendments would equal 8 Mg C or 29 Mg CO_2 yr^{-1} if applied to 1 million hectares of the Indo-Gangetic Plains. In a no-till, residue-retained system, with 50% of the recommended NPK application, the total emissions would equal 3.7 Mg C, or 14 Mg CO_2 yr^{-1}, an effective halving of emissions as we move from a high- to low-input system with improved nutrient use and environmental efficiency. The transition to intensified no-tillage systems, with recommended fertilizer levels, can be both productive and environmentally sound in a world that is rapidly becoming aware of the significant effects of global climate change in both the short and long term.

The need to increase production in rice- and wheat-growing regions of the tropics and subtropics is well recognized. Expected population growth will put enormous

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stress on existing production systems and is likely to lead to pressure to expand cropping systems into areas that are now either agronomically marginal or protected for environmental reasons. The long-term sustainability of these systems—their ability to provide food and fiber in a manner that is economically and socially viable without environmental harm (Robertson & Harwood, 2001)—will be stretched very thin.

Environmental problems are primarily associated with damage to the natural capital of the land, which often is not recognized until well after very serious and, in many cases, irreversible degradation of the natural resource base has occurred. Feedback in the system can either decelerate or accelerate this process, with the direction of this change depending on the type of agronomic management used in the system. For example, losses in soil organic matter under conventional tillage and residue removal may reduce yields, which can lead to further environmental damage as the land is farmed more intensively in an effort to recover yield that has been lost. If crop residues are retained and tillage is reduced in concert with legume rotations, stores of organic matter can be maintained or even increased under intensive agriculture.

Examples of this pattern are beginning to emerge across wheat–rice regions of the tropics and subtropics. A good example of this trend is in the Indo-Gangetic Plains (IGP), where serious questions about both the sustainability and potential environmental consequences of current and future production systems have been raised.

Concerns about the impact of current agronomic practices have been heightened by the evidence from long-term experiments that cereal yields in the region are generally declining (Ladha et al., 2002). A detailed assessment of 11 long-term rice–wheat experiments (ranging from 7 to 25 yr in duration) from the region (Duxbury et al., 2000) (Table 2–1) indicates a marked yield decline of up to 500 kg ha^{-1} yr^{-1} in rice in nine of the experiments (Fig. 2–1), while wheat yields have tended to stabilize (Fig. 2–2). There is evidence that decreases in solar radiation over the past decade across the IGP (Pathak et al., 2002) may have played a role in the overall decline. Higher genetic improvement in wheat relative to rice may also partly explain the anomaly between the trends in rice and wheat yields (Ladha et al., 2003, Chapter 3 of this publication). Strong evidence suggests that the main reasons for this overall decline are soil-based and include the ineffective use of N inputs; soil organic matter decline; soil structural decline; micronutrient deficiencies, particularly S, K, and Zn; and the buildup of pests and diseases.

The soil organic matter decline is of particular importance because it affects both nutrient availability and soil structural stability. In Fig. 2–3, rapid declines of 200 to 624 kg ha^{-1} yr^{-1} are evident in representative growing areas, even with recommended NPK levels, which indicates that tillage practices need to be reviewed.

The addition of organic inputs (both farmyard and legume green manures) has been promoted as a possible solution to the yield decline, but no clear evidence exists from the long-term experiments that the sustainability of crop yields is increased. The addition of 15 Mg ha^{-1} yr^{-1} of farmyard manure (FYM) before wheat in conjunction with NPK fertilizer consistently increased yields of rice in a 20-yr experiment in Uttar Pradesh (Ram, 2000) compared with fertilizer alone, but rice yields declined regardless. Only small effects of FYM have been observed in ex-

Table 2–1. Researchers and location of long-term rice–wheat experiments in South Asia (Duxbury et al., 2000).

Researchers	Location	Approx. duration
		yr
Prasad and Sinha	Samastipur, Bihar	7
Sakal	Pusa, Bihar	9
P. Singh and Khan	Jabulpar, Madya Pradesh	9
Kundu and Samui	Mohanpur Nadia, West Bengal	9
Yadvinder Singh et al.	Ludhiana, Punjab	10
Y. Singh et al.	Pantnagar, Uttar Pradesh	14
Regmi et al.	Bhairawaha, Nepal	18
Chhabra and Thakur	Karnal, Haryana	19
Ram	Pantnagar, UP	20
K. Singh and Swarup	Karnal, Haryana	20
Saha et al.	Barrackpore, West Bengal	25

periments in Bangladesh and West Bengal. It is possible that more emphasis needs to be given to the supply of nutrients such as K and S.

ENVIRONMENTAL CONSEQUENCES OF INTENSIFICATION

From a biophysical perspective, increases in production in the IGP have come from intensification (expressed as increasing production per hectare). This has been achieved by using several management options either singly or in combination. The major options lie in the degree of land preparation (tillage), the choice of germplasm (crop species or cultivar), the time of sowing, the use of appropriate nutrients to enhance growth, the use of irrigation where water is available, and the method of pest and weed control.

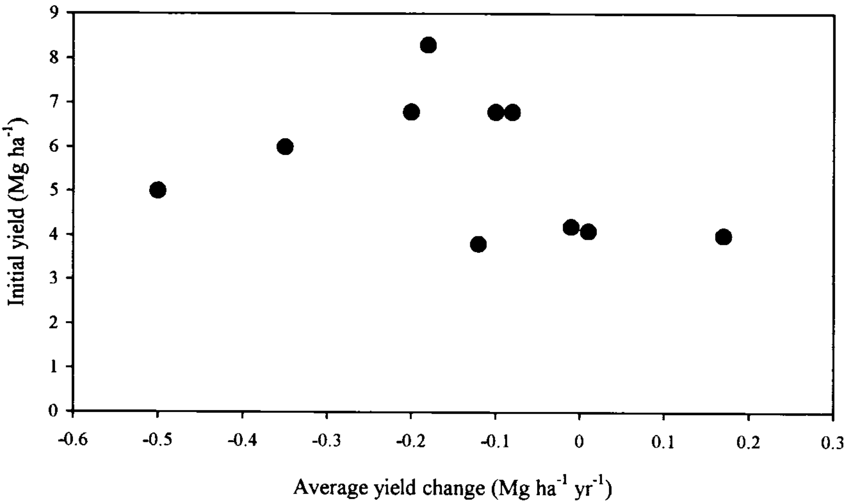

Fig. 2–1. Average annual yield change in rice in long-term experiments in the Indo-Gangetic Plains.

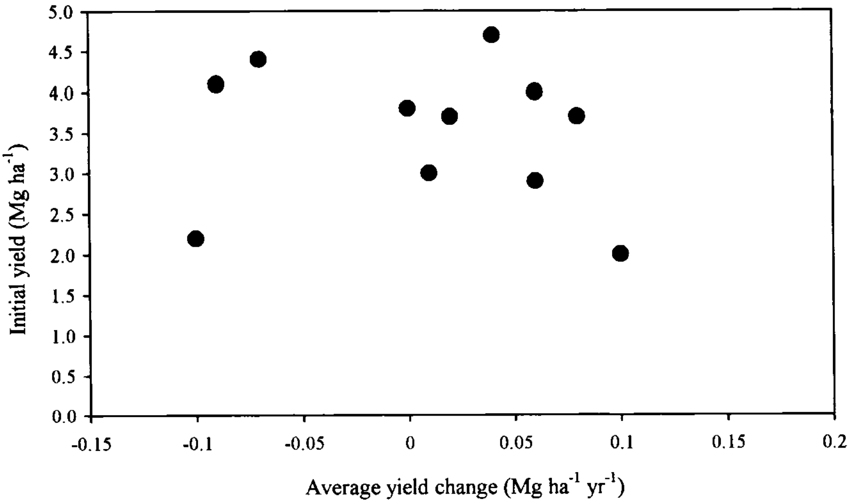

Fig. 2–2. Average annual yield change in wheat in long-term experiments in the Indo-Gangetic Plains.

Current production systems now occupy a continuum in a spectrum of intensification, governed, for a given climate and soils, by the level of inputs and crop management. For convenience, three types of intensification can be specified (Gregory et al., 2002), each with characteristic features (Table 2–2). Productivity may vary widely, however, within a given type.

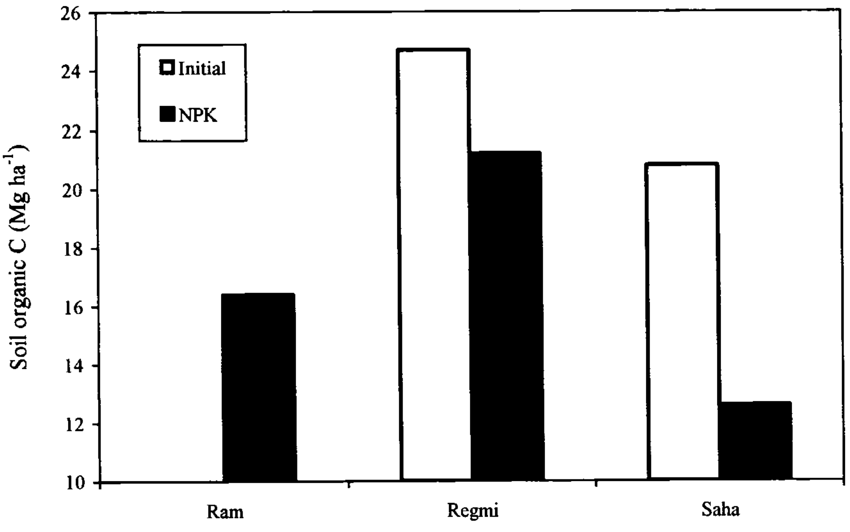

Fig. 2–3. Topsoil soil organic C levels for three long-term experiments in the Indo-Gangetic Plains by stated authors (after 20, 18, and 25 yr, respectively). Data from Duxbury et al. (2000). Assumes a bulk density of 1.3 g cm^{-3}.

Table 2–2. Categories of farming systems in the rice–wheat region of the Indo-Gangetic Plains and their characteristics.†

	Farming system		
Characteristic	Type I Low external inputs Pre-Green Revolution	Type II Conventional Green Revolution	Type III Alternative Doubly Green Revolution
Main objective	Minimizing food shortage	Maximizing food production	Maximizing profit and other land functions
Rural population density	Increasing	High	Reduced
Access to market and technology	Low	High	High
Environmental concerns	Medium	Low	High
Land efficiency	Increasing/declining	High	Reduced
Labor/energy efficiency	High or declining	Low	Reduced
Capital efficiency	No capital	Low or medium	High
Fallow time	Declining	Zero	Increasing
Technological package	Zero or limited	High	Reduced (minimum tillage, IPM)
Credit, land tenure	Zero	High	High
"Mining" agriculture	Yes or no	Yes	No
Example	Sahel	Indo-Gangetic Plains	South American "success" stories

† Reprinted from Gregory et al. (2002).

Type I intensification occurs when available management inputs are limited (pre-Green Revolution). Type II intensification is largely dominated by the technological features of the Green Revolution and has been widely adopted from about 1960. It involves the introduction of new cultivars coupled with large increases in the use of fertilizers, herbicides, pesticides, irrigation, and mechanization. The adoption of this technology successfully achieved its primary aim of substantially increasing food production in the IGP, but concern about the environment was, and still remains, low in this type. Type III intensification ("doubly" Green Revolution) necessitates a production system that is both high-yielding and more environmentally benign than Type II systems. Affluent populations are pressing for this type of system but demonstrated examples are rare, leading to the absence of comparative data sets in terms of production and environmental externalities.

All three intensification strategies result in detrimental environmental consequences to some extent, but their nature and magnitude differ markedly among types and particularly in whether the major consequences are on- or off-site. Type I is viewed as the most environmentally benign, while Type II has been the subject of most recent concern. This is because of its on-site effects in relation to sustainability and soil degradation and its off-site effects in relation to water pollution and climate forcing (mainly via greenhouse gas emissions to the atmosphere), leading to regional climate change. Any change in farming system results in changed environmental consequences, but the difficulty lies in assessing which changes are nonreversible and have the most deleterious effect. The advent of genetically modified technologies is becoming important in the development of Type III systems, bringing both potential environmental benefits and problems.

In the IGP, the intensification of rice–wheat rotations has resulted in the following changes in production systems: seasonal wet and dry crop cycles, a heavy reliance on irrigation, increased fertilizer usage, crop residue burning, asymmetry of planting schedule, and a uniformity in cultivar selection. Of these activities, irrigation, fertilizer application, and residue burning have a direct effect on the variables that most affect global climate change—emissions of the greenhouse gases (GHGs) CO_2, CH_4, and N_2O. While agricultural enterprises are normally local in scale (i.e., at the farm level), widespread changes in production practices in large high-input regions such as the IGP are of global consequence.

In a recent summary of the effects of climate change on wheat and rice production systems of the Indo-Gangetic region, Gregory et al. (1999) concluded:

1. Under optimal field conditions, wheat yields are unlikely to increase by more than about 10% for double preindustrial CO_2; a 5 to 7% increase is more likely for average management conditions. This estimate is lower than previously suggested by the Intergovernmental Panel on Climate Change (1996) because it allows for decreased crop duration (and hence yield) as a consequence of warming and the many factors that reduce yield from potential to actual levels.
2. Major rice models are consistent across a wide range of potential yields and indicate a reduction in yield of about 5% per °C rise above 32°C. This would largely offset any increase in yield as a consequence of increased CO_2. Rice yields are reduced when temperatures exceed 32°C at flowering because of spikelet sterility. This finding is unaffected by elevated CO_2 but might differ among genotypes.
3. Elevated CO_2 is likely to enhance yields of rice more than wheat because rice is usually grown intensively with inputs of water and nutrients, whereas wheat is grown extensively in drier areas.
4. For mid-latitude regions such as the IGP, an average warming of 1 to 3.5°C over the next 100 yr would be equivalent to a poleward shift of the present geographic bands of similar temperatures (or isotherms) of approximately 150 to 550 km, or an altitude shift of about 150 to 550 m.

SOURCES OF GREENHOUSE GASES IN THE RICE–WHEAT SYSTEM

The direct cause of climate change is primarily the enhanced greenhouse effect. Different gases persist for different lengths of time in the atmosphere, and they also trap heat to different degrees. The global warming potential (GWP) is used to compare the effectiveness of each greenhouse gas to trap heat in the atmosphere relative to some standard gas, by convention CO_2. The GWP for CH_4 (based on a 100-yr time horizon) is 21, while that for N_2O is 310. Although present in lower concentrations than either CO_2 or CH_4, N_2O is a very potent greenhouse gas, accounting for about 6% of the enhanced greenhouse effect.

By using GWP values for CH_4 and N_2O emissions as stated above (21 and 310, respectively), we can convert all our emission estimates to either a CO_2 or carbon equivalent (CE) basis. Carbon dioxide equivalents can be calculated by multiplying the CE values by 3.7.

Carbon Dioxide

The main source of CO_2 to the atmosphere in the rice–wheat system is through tillage. Two on-site tillage sources exist: the biological decomposition of soil organic matter and the production of CO_2 as a byproduct of machinery fuel usage. The burning of crop residues is not considered a CO_2 source to the atmosphere because an amount of CO_2 equivalent to the amount released will be taken up by the following crop; in other words, on an annual basis, there will be no change in standing C stock. Carbon dioxide from this source is therefore not counted in the accounting procedures adopted by the Intergovernmental Panel on Climate Change (IPCC).

During tillage, soil aggregates are broken, thus increasing oxygen supply and surface area exposure of organic material. This promotes the decomposition of organic matter. An example of the effect of three to four cultivations per year on soil organic C (SOC) content can be drawn from CIMMYT's long-term wheat–maize trial at El Batán in central Mexico (P. Grace, unpublished data, 2000). Initial levels of SOC in the top 20 cm were 1.37%. After 8 yr of continuous wheat, with residue retention and conventional tillage, SOC had declined to 1.12%, a total decline of nearly 6.5 Mg C ha^{-1}, or 800 kg ha^{-1} yr^{-1}. In the adjacent no-till treatment, where yields were similar, the total decline was only 3.6 Mg C ha^{-1}, or 450 kg ha^{-1} yr^{-1}, a savings of 350 kg ha^{-1} yr^{-1}. The rate of decline (or accumulation) of SOC therefore depends on several interacting factors: the amount of residue retained, the quality of residue retained, soil temperature and moisture interactions, tillage, and a reduction in fallow periods.

For residue quality, high-quality (i.e., high N) residues from grain legumes or fodders can accelerate the decomposition of soil organic matter because of the additional N being available to the microbial population. Usually, the additional N being released will also be taken up by the following crop, thereby enhancing yields and biomass production; however, where high temperatures coincide with high water-holding capacity, the conditions are ideal for the promotion of SOC decomposition and the emission of CO_2. Soils therefore are generally considered to be a source of CO_2, unless the inputs outweigh the outputs, which is not usually the case in conventionally tilled low- to medium-input production systems.

Heavy use of diesel fuel occurs with current land preparation practices. For every liter of diesel fuel consumed, 2.6 kg of CO_2 are released to the atmosphere. Assuming that 150 L ha^{-1} yr^{-1} of fuel are used for tractor usage and irrigation pumping in conventional systems, this would amount to nearly 400 kg of CO_2 being emitted. For the entire 12 million hectares under rice–wheat in the IGP, this would amount to 4.8 Mg CO_2 yr^{-1} or 1.3 million metric tonnes C equivalents (MMTCE). To put this in perspective, this value is approximately one-third of the CH_4 emissions (expressed as MMTCE) from rice paddy fields in the entire IGP (see section on methane below); therefore, diesel use is a greatly underestimated source of GHGs.

An off-site source that is often neglected is the production of CO_2 in the manufacture of fertilizers (Schlesinger, 2000). Although this is not relevant to our discussions of on-farm environmental effects, 0.58 mol of C is produced per mole of N fixed in fertilizer production, resulting in 1.8 kg CO_2 produced per kilogram of N fertilizer manufactured. The full cost of accounting (including transportation and application) would raise this value to 1.4 mol. In a no-till cropping system, this cost can significantly negate the mitigation gain by soil C sequestration.

A further source of CO_2 usually neglected is agricultural lime (usually calcium carbonate or dolomite) added to noncalcareous soils to counteract the acidity produced by N fertilizer use and by base cation removal during harvest (Robertson et al., 2000). Between lime applications, the lime previously applied dissolves to HCO_3^- or CO_2 depending on the acid–base balance of the soil solution; any CO_2 formed will be released to the atmosphere. For N fertilizer manufacture, the CO_2 cost of lime can significantly negate any mitigation achieved by soil C storage.

Methane

Methane is produced in soil during microbial decomposition of organic matter and reduction of CO_2 under strictly anaerobic conditions. Methane emissions are controlled by two microbial processes: CH_4 production by methanogenic bacteria and CH_4 oxidation by methanotrophic bacteria. Continuously flooded rice fields are a source of CH_4 because anoxic conditions that favor methanogenesis predominate, and rice plants serve as conduits for its release to the atmosphere once it is formed in sediments (Neue et al., 1997).

Under the UNDP-IRRI Inter-Regional Programme, CH_4 emissions from rice fields were measured at eight locations in five rice-producing countries covering the main rice ecosystems—irrigated, rainfed, and deepwater systems (Wassmann et al., 2000a,b). Irrigated rice fields had the highest emission rates. Seasonal emissions varied from 1 to 50 g m^{-2}, with continuously flooded fields emitting the most (Wassmann et al., 2000a). Depending upon local precipitation, emissions from rainfed rice fields may be less than one-half of the emissions from irrigated fields and may be less than 5 g m^{-2}.

On the basis of results obtained by various rice-growing countries, the IPCC has suggested that emission reduction factors under single and multiple aeration are 0.5 and 0.2 of those in continuously flooded fields. Using the IPCC accounting methodology and the country default value of 10 g m^{-2}, CH_4 emissions from rice cultivation in India (45 million ha) should not exceed 2.5 Mg yr^{-1} (or 14.3 MMTCE). In the 12 million ha of rice–wheat in the IGP, this would equal about 0.7 Mg CH_4 yr^{-1} (or 4 MMTCE yr^{-1}). The main reason for low CH_4 emissions from rice fields in India is that the soils of major portions of rice-growing areas have very low organic C or receive very little in the way of organic amendments (Jain et al., 2000). Incubation studies have shown that large differences in CH_4 production potential are related to organic C content (Majumdar et al., 1998). The use of organic manuring is also not very common in India, although where it occurs it can affect methane emissions (Debnath et al., 1996).

The burning of crop residues also contributes to the global CH_4 budget. For each tonne of crop residue burned, 2.3 kg CH_4 are emitted, equivalent to 48.3 kg CO_2 (using a GWP of 21). If we assume average annual residue production for rice and wheat on the IGP to be 10 Mg ha^{-1}, then, if one-half of the 12 million ha under rice–wheat is burned, a total flux of 0.14 Mg CH_4 is emitted. This is equivalent to 20% of the total CH_4 emitted from paddy rice fields in the IGP (total 0.7 Mg CH_4 as outlined above).

Nitrous Oxide

Both fertilized and unfertilized soils emit N_2O. Although nitrogenous fertilizer is a source in the case of fertilized soils, the built-in N of the soil itself also contributes to the release of this GHG. It has long been recognized that both soil water content and the availability of C enhance the production of N_2O provided a suitable NO_3 source is available. The total fluxes of N_2O have been reported to be many times higher in organic soils and mineral soils with higher contents of soil organic matter (Terry et al., 1981). The primary effect of water on N_2O production in aerobic and partially aerobic soils is the restriction of oxygen levels, which produces anaerobic conditions. Because of the relatively slow diffusion of oxygen through water (10 000 times slower than through air), denitrification in soil is highly affected by the relative amount of air- and water-filled porosity (Robertson, 2000; Burton & Beauchamp, 1985).

Generally, an increase in denitrification and potential N_2O losses is observed following irrigation and precipitation. However, rice paddies are not considered an important source of atmospheric N_2O because N_2O, as the intermediary product of denitrification, would be further reduced to N_2 under strong anaerobic conditions (Granli & Bockman, 1994). The exception is in irrigated rice grown in upland conditions with frequent natural drainage of standing water, in which N_2O production is possible. Nitrous oxide is also not usually detectable during the normal growing season of flooded rice (Bronson et al., 1997a,b) but is significant after N fertilizer applications. During the dry season, Bronson et al. (1997a,b) reported N_2O fluxes that were 2.5 times higher with ammonium sulfate than with urea. The N_2O flux also increased sharply during the drainage period at mid-tillering until reflooding, when it dropped back to near zero. Experiments in rice fields conducted at the Indian Agricultural Research Institute (IARI) have shown that, as the redox potential becomes positive, CH_4 emissions decrease, but N_2O emissions increase. It has also been shown that the use of the nitrification inhibitor DCD along with urea and ammonium sulfate reduces both CH_4 and N_2O emissions (Ghosh, 1998). There is much uncertainty about the amount of N_2O released; however, it is suspected that 0.1 to 6% of applied N is lost as N_2O. Intergovernmental Panel on Climate Change (1994) methodology assumes that 1.25% of fertilizer N is lost as N_2O. Crops such as wheat and maize, which receive nitrogenous fertilizers, are expected to release more N_2O than crops grown in flooded environments.

The burning of crop residues also contributes to the global N_2O budget. For each tonne of crop residue that is burned, 40 g N_2O are emitted, equivalent to 12.4 kg CO_2 (using a GWP of 310). If we assume that the average annual residue (rice and wheat) production on the IGP is 10 Mg ha^{-1}, then, if one-half of the 12 million ha under rice–wheat is burned, a total flux of 2400 tonnes of N_2O is possible; that is, about 0.74 Mt CO_2 (equivalent) is emitted.

MITIGATION MECHANISMS

Carbon Dioxide

Current land preparation practices for wheat after rice involve as many as 12 tractor passes. Changing to a zero-till system on 1 ha of land would save 98 L of diesel and approximately 1 million L of irrigation water; this represents about a quarter tonne less emission per hectare of CO_2, the principal contributor to global warming. These benefits increase dramatically if extended across even a portion of the region's 12 million ha. Adoption of zero-till on only 5 million ha would represent a savings of 5 billion m^3 of water each year. That would fill a lake 10 km long, 5 km wide, and 100 m deep. In addition, annual diesel fuel savings would come to 0.5 billion L, equivalent to a reduction of nearly 1.3 million Mg in CO_2 emissions each year.

Methane

Experiments at IARI during 1994 to 1998 have shown that intermittent irrigation, which is the usual practice, reduces CH_4 emissions up to about 28% (Jain et al., 2000). At Pantnagar, the reduction in CH_4 emissions because of intermittent irrigation was 30% compared with continuously flooded conditions. Experiments have also shown that the addition of organic manures (legume green manure, FYM, biogas slurry, and rice straw) enhances methane emissions from rice fields. The experiments conducted at IARI have also shown wide variations in CH_4 emissions because of the variety of organic amendments. However, it is apparent that CH_4 emissions from rice fields amended with biogas slurry are significantly less than with other organic amendments (Debnath et al., 1996). Experiments have also shown that there is no significant increase in CH_4 emissions if neem-coated urea is used in place of urea, whereas grain yields increase significantly (Sarkar, 1997). Methane emissions have been reported to depend on the cultivar sown (Mitra et al., 1999), and efforts are needed to identify a few suitable cultivars in different regions with high yield potential but low CH_4 emission potential.

In summary, methane emissions can be reduced significantly by adopting the following mitigation practices: water management through intermittent irrigation or drainage, the use of digested manure instead of fresh manure, and the selection of suitable cultivars that emit less methane. Varietal differences have been shown to affect CH_4 emissions (Neue et al., 1994; Wang et al., 1997), with differences usually becoming evident in the middle and late growth stages (Wang & Adachi, 2000). Indications are that roots and their relative size play a significant role in CH_4 production as they provide a source of C through exudation and upon their death.

Nitrous Oxide

Strategies that increase N-fertilizer efficiency (Robertson, 1997) reduce emissions of N_2O (Mosier et al., 1996; Majumdar et al., 2001). Plant uptake of N can be improved and total N losses can be reduced by deep fertilizer placement (Youngdahl et al., 1986) and by banding fertilizer within the crop rows. Nitrogen use efficiency can also be improved by applying fertilizer close to the time that it is needed by the crop, and by using soil and plant tests before fertilization to tailor the amount of fertilizer applied to that needed by the plant. Cover crops can also keep available soil N away from the microbes responsible for N_2O production.

Nitrous oxide emissions from soil can also be reduced by nitrification inhibitors (Mosier et al., 1998; Majumdar et al., 2000; Pathak & Nedwell, 2001; Kumar et al., 2000). Compounds such as nitrapyrin, $HgCl_2$, toluene, CS_2, DCD, thiosulfate, and acetylene retard the conversion of NH_4^+–N into NO_3^-–N. This results in the reduction of direct N_2O emissions from nitrifiers and reduces the availability of NO_3^- necessary for denitrification. Low emissions of N_2O have been observed through the use of used encapsulated calcium carbide (a source of acetylene) and nitrapyrin (Bronson et al., 1992). These authors reported losses of 1.5 to 3.1 kg N_2O ha^{-1} from urea alone compared with 0.87 to 1.0 kg N_2O ha^{-1} from urea plus nitrapyrin. Other biocidal inhibitors, such as neem and karanja seed extracts, have been found to retard nitrification by 60 to 70% (Sahrawat, 1996); however, the general lack of availability of inhibitors in the developing world and cost-ineffectiveness in broad-area situations usually prohibit their use.

We therefore propose three feasible, cost-effective agronomic interventions that would have an immediate effect by reducing GHG production in the IGP: (i) a reduction in residue burning, (ii) a reduction in flood irrigation frequency for rice, and (iii) the use of minimum or no-tillage for wheat.

Based on the calculations in the sections above, we can make an estimate of the total savings in CO_2 equivalent emissions (kg ha^{-1} yr^{-1}) if we

Reduce burning	60
Reduce irrigation frequency	1000
No-tillage (diesel savings)	260
No-tillage (soil C), based on 100 kg C ha^{-1} increase	360
Total CO_2 saved (kg ha^{-1})	1680

These estimates also assume no change in basic nutrient management, only tillage and reduced irrigation. If these measures were in place on one-half of the IGP, a conservative estimate would be a savings of 10 Mg CO_2. To put this in perspective, during the 30 yr of the Green Revolution, 45 million ha of land were cleared in all of Asia, resulting in 360 Mg being lost to the atmosphere as CO_2 on average every year (Grace et al., 2000).

COMPARATIVE GREENHOUSE GAS BUDGETS FOR FARMING SYSTEMS

The management of the rice–wheat system in the IGP is extremely diverse in terms of the amount of N applied and the rotation and tillage options that exist. It is therefore instructive to look at the GHG emission potential of some parts of this system and, in line with the need for poverty alleviation, assess their potential in terms of overall productivity in relation to the amount of GHG emissions from each system. Emissions usually depend on both inputs (inorganic N, organic manure) and tillage. To make this comparison, a carbon/productivity ratio (CPR)

Table 2–3. Agronomic details of 20-yr irrigated rice–wheat–cowpea treatments and average yields at Pantnagar, Uttar Pradesh (Ram, 2000).

System	Rice	Wheat	Fodder	N fert. per crop	Manure	Soil organic C
	Mg ha^{-1}			kg ha^{-1}	Mg ha^{-1}	%
Control	3.74	1.71	1.86	0	0	0.49
Trt 1: 50%	5.02	3.13	1.93	60	0	0.64†
Trt 2: 100%	5.67	3.97	2.36	120	0	0.84
Trt 3: 150%	5.92	4.38	2.32	180	0	1.06†
Trt 8: FYM	6.41	4.6	2.47	120	15	1.48

† Estimated for 0–15 cm based on published measurements in other treatments.

(Grace et al., 2000) is used to assess how environmentally inefficient various production systems are with respect to GHG emissions and how much food is actually placed on the table. Systems with higher CPRs are more inefficient at producing food with respect to the damage to the global environment. The CPR for Latin America, Africa, and Asia for the 30 yr of the Green Revolution was 0.52 (Grace et al., 2000).

To make this comparison more realistic, we have chosen data from a long-term trial in northern India at Pantnagar (Ram, 2000). This trial started in 1971 and its objective was to assess the effects of nutrient management (NPK) on productivity and soil fertility. The rice–wheat–cowpea trial consisted of 12 treatments with 50, 100, or 150% of the recommended dose of NPK fertilizer. The recommended dose of N was 120 kg ha^{-1} for each crop of rice and wheat. In our assessment, we constructed annual GHG budgets for individual gases (CO_2, CH_4, N_2O) for 5 of the 12 treatments (Table 2–3) on the basis of the activities outlined in the earlier part of this chapter. We included one treatment that incorporated farmyard manure. In all budgets, we then converted this information to C equivalents to give an overall assessment of C lost to the atmosphere in relation to total edible product.

Table 2–4 outlines the conventional tillage budget with all crop residues being retained, which we assume represents the experiment most closely. The highest total emissions in terms of C equivalents were found in Treatment 8 (7 Mg C ha^{-1}), which included FYM. Treatment 2, which received the recommended dosage of fertilizer only, had emissions of 4.7 Mg C ha^{-1}, but it had the lowest CPR, which meant that it was the most efficient of all the nutrient management systems in this analysis of conventional tillage with residue retention. However, Treatments 1 and 3, which supplied 50 and 150% of the recommended dosage, respectively, had similar CPRs. In Treatment 3, the higher fertilizer N input may also result in leaching of excess fertilizer, so this treatment is not recommended if we are considering other environmental problems other than GHG emissions. In terms of recommendations, obviously Treatment 1, with the reduced N input (and hence reduced cost), would be the most suitable, particularly if we consider the off-site environmental costs (i.e., fertilizer production) discussed earlier.

Tables 2–5 and 2–6 outline the respective budgets where burning of all residues and no-tillage are alternative managements. The no-till scenario assumes complete retention of all crop residues and a hypothetical two-thirds reduction in on-site fuel use (cultivation only). Both scenarios exhibit the same trend as the earlier conventional residue-retained scenario in the final treatment analysis. The

Table 2–4. Estimated annual (on-site) emissions of greenhouse gases (GHG) from the irrigated rice–wheat system in the Indo-Gangetic Plains based on 20-yr long-term trial data of Ram (2000). This example assumes conventional tillage with all crop residues being retained.

	GHG emissions				
GHG source	Control	Trt. 1	Trt. 2	Trt. 3	Trt. 8
			kg ha^{-1}		
CO_2: Soil tillage	3539	3003	2288	1502	0
CO_2: Diesel†	260	260	260	260	260
N_2O: Burning residues	0	0	0	0	0
N_2O: Manure application‡	0	0	0	0	3
N_2O: N fertilizer application‡	0	2.4	4.7	7.1	4.7
N_2O: Cereal residues retained§	0.1	0.1	0.1	0.1	0.1
N_2O: N-fixing crops§	1.1	1.1	1.4	1.4	1.5
CH_4: Burning residues	0	0	0	0	0
CH_4: Rice cultivation	100	100	100	100	200
kg CE ha^{-1}#	3496	4103	4721	5232	7137
CPR††	0.64	0.50	0.49	0.51	0.64

† 2.6 kg CO_2 L^{-1} of diesel consumed and 100 L yr^{-1}.

‡ 1.25% of applied N.

§ 1.25% of fixed or residue N.

¶ 10 g CH_4 m^{-2}, doubled if manure added.

\# Carbon equivalents, global warming potentials (GWPs) of 21 and 310 used for CH_4 and N_2O, respectively.

†† Carbon/productivity ratio, kg C emitted (equivalents) per kg of edible dry product (cereals).

Table 2–5. Estimated annual (on-site) emissions of greenhouse gases (GHG) from the irrigated rice–wheat system in the Indo-Gangetic Plains based on 20-yr long-term trial data of Ram (2000). This example assumes conventional tillage with all crop residues being burned.

	GHG emissions				
GHG source	Control	Trt. 1	Trt. 2	Trt. 3	Trt. 8
			kg ha^{-1}		
CO_2: Soil tillage	3539	3003	2288	1502	0
CO_2: Diesel†	260	260	260	260	260
N_2O: Burning residues	0.4	0.6	0.6	0.7	0.7
N_2O: Manure application‡	0	0	0	0	3
N_2O: N fertilizer application‡	0	2.4	4.7	7.1	4.7
N_2O: Cereal residues retained§	0	0	0	0	0
N_2O: N-fixing crops§	1.1	1.1	1.4	1.4	1.5
CH_4: Burning residues	17	25.3	29.9	31.1	34.1
CH_4: Rice cultivation¶	100	100	100	100	200
kg CE ha^{-1}#	3953	4774	5510	6086	8032
CPR††	0.73	0.59	0.57	0.59	0.73

† 2.6 kg CO_2 L^{-1} of diesel consumed and 100 L yr^{-1}.

‡ 1.25% of applied N.

§ 1.25% of fixed or residue N.

¶ 10 g CH_4 m^{-2}, doubled if manure added.

\# Carbon equivalents, global warming potentials (GWPs) of 21 and 310 used for CH_4 and N_2O, respectively.

†† Carbon/productivity ratio, kg C emitted (equivalents) per kg of edible dry product (cereals).

Table 2–6. Estimated annual (on-site) emissions of greenhouse gases (GHG) from the irrigated rice–wheat systems in the Indo-Gangetic Plains based on 20-yr long-term trial data of Ram (2000). Assuming no-tillage† and all crop residues being retained in this example.

GHG source	GHG emissions				
	Control	Trt. 1	Trt. 2	Trt. 3	Trt. 8
	kg ha^{-1}				
CO_2: Soil tillage	1769	1501	1144	751	+366‡‡‡
CO_2: Diesel‡	86	86	86	86	86
N_2O: Burning residues	0	0	0	0	0
N_2O: Manure application§	0	0	0	0	3
N_2O: N fertilizer application§	0	2.4	4.7	7.1	4.7
N_2O: Cereal residues retained¶	0.1	0.1	0.1	0.1	0.1
N_2O: N-fixing crops¶	1.1	1.1	1.4	1.4	1.5
CH_4: Burning residues	0	0	0	0	0
CH_4: Rice cultivation#	100	100	100	100	200
kg CE ha^{-1}††	2966	3646	4362	4981	6724
CPR‡‡	0.54	0.45	0.45	0.48	0.61

† Assuming 66% fuel savings and soil organic C levels decrease only by 50% compared with conventional till.

‡ 2.6 kg CO_2 L^{-1} of diesel consumed and 33 L yr^{-1}.

§ 1.25% of applied N.

¶ 1.25% of fixed or residue N.

10 g CH_4 m^{-2}, doubled if manure added.

†† Carbon equivalents, global warming potentials (GWPs) of 21 and 310 used for CH_4 and N_2O, respectively.

‡‡ Carbon/productivity ratio, kg C emitted (equivalents) per kg of edible dry product (cereals).

‡‡‡ Assuming a C accumulation of 100 kg yr^{-1} in the topsoil.

seemingly small amount of N_2O and CH_4 being emitted from residue burning in fact contributed an additional 15% to the overall C emission budgets of all treatments (ranging from 457 to 895 kg C ha^{-1} yr^{-1}). These increased emissions with residue burning exceed any benefit of moving from conventional to no-tillage, which showed only a 9% reduction in the C emission budget. In other words, no-till must be complemented by residue retention. The use of FYM is not recommended as it increases GHG emissions, and Treatments 1 through 3 all showed similar CPRs. Again, the tendency to use a less N-intensive system would be desirable, but it is not essential provided N losses through leaching can be minimized, perhaps through better timing and placement of fertilizers.

Many experiments exist in the literatures that demonstrate that the judicial use of fertilizers can produce results similar to the application of greater amounts. Also, crop simulation models such as CERES-Wheat and Rice can mimic these systems very well in terms of water, N movement, and yield responses. A version of CERES-Rice also gives CH_4 emissions (Matthews et al., 2000) and has shown conclusively the significant effect of irrigation frequency on reducing emissions.

CONCLUSIONS

The summary in Table 2–7 compares the total annual emissions in terms of CEs and CPRs of three different systems. The most inefficient systems, expressed

Table 2–7. Estimated total annual (on-site) emissions of greenhouse gases (GHG) from the irrigated rice–wheat system in the Indo-Gangetic Plains in terms of C equivalents (CE) and the C/productivity ratio (CPR).

	GHG emissions				
GHG source	Control	Trt. 1	Trt. 2	Trt. 3	Trt. 8
	kg ha^{-1}				
	CE (kg C emitted)				
Conventional/retain residues	3496	4103	4721	5232	7137
Conventional/burn residues	3953	4774	5510	6086	8032
No-till/retain residues	2966	3646	4362	4981	6724
	CPR (kg C emitted per kg grain yield)				
Conventional/retain residues	0.64	0.50	0.49	0.51	0.64
Conventional/burn residues	0.73	0.59	0.57	0.59	0.73
No-till/retain residues	0.54	0.45	0.45	0.48	0.61

in terms of the CPR, were the control and FYM treatments in conventionally tilled systems with residue burning. Even with conventional tillage and residue retention, both these treatments had high CPRs.

If we applied these scenarios to 1 million ha of the IGP, the CE emissions from a high-input conventionally tilled system with residue burning with FYM (the lowest environmental efficiency, i.e., high CPR) would be equivalent to 8 Mt C or 29 Mt CO_2 yr^{-1}. In a no-till, residue-retained system with 50% NPK (the highest environmental efficiency, i.e., low CPR), the total CE emissions would be equivalent to 3.7 Mt C or 14 Mt CO_2 yr^{-1}, an effective halving of emissions as we move from a high- to low-input system with improved nutrient-use and environmental efficiency.

We must recognize that these values are for reasonably high production systems within the IGP; the overall magnitude may be reduced in terms of C loss from soil in the sandier soils of the Punjab. Nevertheless, it is obvious that, even though a vast combination of management practices exists on the IGP, the transition to intensified no-tillage systems, with recommended fertilizer levels, can be both productive and environmentally sound in a world that is rapidly becoming aware of the significant effects of global climate change in both the short and long term.

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