Chapter 11

Resource conservation technologies in rice based cropping systems: A climate change mitigation option

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Rice based cropping systems accounts for more than half of the total acreage in South Asia, where rice is grown in sequence with rice or upland crops like wheat, maize or legumes. Rice based cropping systems occupy 13.5 m ha in the Indo-Gangetic Plains (IGP) of South Asia (Gupta & Seth, 2007) which provides food security and livelihoods for millions. The productivity and sustainability of the rice based systems are threatened because of (1) inefficient use of inputs such as fertilizer, water and labor; (2) increasing scarcity of resources, especially water and labor; (3) changing climate; (4) changes in land use (cropping practices and cropping systems) driven by a shortage of water and labor; (5) socio-economic changes (urbanization, labor migration, changing attitude of people to shun away from farm work); and (6) increasing farm pollution (Ladha et al., 2009). Countries with a large population like China and India face the challenge of maintaining and increasing high yield levels in a scenario of increasing climatic variability. Over the last few decades, the growth in agricultural production has come mainly from yield increase and to a lesser extent from area expansion. Now the agricultural land available per capita is expected to decline (FAO, 2002). Furthermore, in high intensity agricultural production areas, yield increase seems to have reached a ceiling despite higher input use. Crop yields even decline in some cases, for example in the grain producing areas of Punjab in India (Aulakh, 2005). Water is one of the most precious natural resources for agricultural production and agriculture accounts for 70 percent of water use (FAO, 2002). In the Indian state of Punjab, characterized by intensive irrigated agriculture, the groundwater table is falling at a rate of 0.7 m per year (Aulakh, 2005). Agriculture contributes to the problem by pumping excess water and by sealing and compacting the soils so that excess rain water can not infiltrate and recharge the aquifer; one of the causes of the growing number of flood catastrophes (DBU, 2002).

Reduced recycling of crop residue, minimal and unbalanced fertilizer addition, limited options for crop rotation and the regular intensive tillage are some of the factors responsible for the soil degradation over time. Tillage primarily helps in weed management and to create a seed bed with a fine soil tilth suitable for germination and seedling establishment. Additional reasons for practicing conventional tillage by manual, animal powered or mechanized means, include mineralization of nutrients, incorporation of fertilizers, crop residues and soil amendments, temporary alleviation of compaction, and management of some soil-borne diseases and insects (Hobbs et al., 2008; Kassam et al., 2009). However, regular tillage breaks down soil organic matter through mineralization, more so in warmer climates (Kirschbaum, 1995), thus contributing to deteriorating soil physical, chemical and biological properties (Wall, 2007). Tillage also adversely affects soil structure, with consequences for water infiltration and soil erosion through runoff, and create hardpans below the plough layer (Thierfelder & Wall, 2009). These adverse effects of tillage have been addressed over recent decades by the development of conservation agriculture

(CA) (Garcia-Torres et al., 2003). Conservation agriculture is defined as cropping systems based on minimal soil disturbance, permanent surface cover through crop residue retention and diverse crop rotations and associations (Hobbs et al., 2008; Kassam et al., 2009).

Soil quality is governed primarily by the tillage practices used to fulfill the contrasting soil physical and hydrological requirements of the rice and subsequent crop (Mohanty et al., 2007). Current crop cultivation practices in these systems degrade the soil and water resources thereby threatening the sustainability of the system (Fujisaka et al., 1994; Byerlee & Siddiq, 1994; Hobbs and Morris, 1996; Ali and Byerlee, 2000; Duxbury et al., 2000; Kumar and Yadav, 2001; Gupta et al., 2003; Ladha et al., 2003a). Evidence from long-term experiments shows that crop yields are stagnating and sometimes declining (Duxbury et al., 2000; Ladha et al., 2003a,b). Agricultural technologies that can save resources reduce production costs and improve production while sustaining environmental quality are therefore becoming increasingly important (Gupta et al., 2002; Hobbs & Gupta, 2003).

Soil affects not only production, but also the management of other natural resources, such as water. Soil structure is strongly correlated with the organic matter content and the soil life. Organic matter stabilizes soil aggregates, provides feed to soil life and acts as a sponge for soil water. With intensive tillage-based agriculture, the organic matter of soil is steadily decreasing, leading to a decline in productivity (Shaxon & Barber, 2003). World soils play an important role in carbon (C) cycling. Being a principal terrestrial C pool, soils contain more than twice the C than in the atmospheric, in the land plant or biotic pool. It is apparent, however, that atmospheric C pool has increased at the expense of soil pool since the beginning of agriculture. Agricultural practices with drastic impact on increasing C efflux include deforestation, burning, plowing, and continuous cropping (Houghton et al., 1983; Lal & Logan, 1995). In general, intensive cultivation or continuous cropping leads to decline in soil organic matter content (Post et al., 1990), and release of soil organic carbon (SOC) to the atmosphere. Agricultural practices affect soil C reserve by influencing at least two processes: (i) increasing rate of biomass decomposition and mineralization releasing carbon dioxide (CO_2) into the atmosphere, and (ii) exposing SOC in the soil surface to the climatic elements thereby increasing mineralization of C.

Over the past decades, extreme climatic events such as extreme precipitation as well as extended drought periods or extreme temperatures have become more frequent and stronger (Met Office, 2005). Agricultural production systems are highly vulnerable to those changes. Resource conservation technologies (RCTs) can assist in the adaptation to climate change by improving the resilience of agricultural cropping systems and hence making them less vulnerable to abnormal climatic situations. Better soil structure and higher water infiltration rates reduce the danger of flooding and erosion catastrophes after high intensity rainstorms. Yield variations by adopting combinations of RCTs in extreme years, under either dry or wet conditions, are less pronounced than under conventional agriculture (Shaxon & Barber, 2003; Bot & Benites, 2005). Conservation agriculture can also help to mitigate climate change by reducing emission of green house gases. By adopting suitable RCTs, soils can retain C from CO_2 and store it safely for long periods of time. It is becoming increasingly difficult to achieve additional gains in productivity, profit, and product quality by using the single-technology-centric approach. Therefore, a systems approach is needed to adapt to emerging challenges and to enhance the productivity, profitability, and resource-use efficiency of the system on a sustainable basis (Ladha et al., 2003, Gupta & Seth, 2007).

Resource conservation technologies in rice based cropping system

Irrigated rice is increasingly subject to (i) the high fuel costs of puddling and the reduced availability of labor, (ii) the water consumption of traditionally puddled rice is too high in many regions. Hence alternatives must be found. Also the release of greenhouse gases such as methane is high in traditionally flooded rice (Gao, 2006). Rice cultivation has therefore been adapted to conservation agriculture in several countries. Rice can be cultivated without puddling or permanent flooding by adopting RCTs. Several efforts have been done in this regard (Gupta & Seth, 2007; Humphreys & Roth, 2008). Cropping systems involving residue retention and zero tillage perform better in terms of profitability, yields and resource conservation, while conventional systems and zero tillage systems without residue retention are inferior. Most RCTs have been aiming at the two most crucial natural resources, water and soil. However, some of them would also affect the efficiency of other production resources and inputs such as labor and farm power or fertilizer. Some of the more popular RCTs, particularly in irrigated or rice based cropping systems, are the following:

Direct seeding

Direct seeding of rice compared with transplanted rice saves water as there is no puddling. There are huge savings of labor and fuel. Further, the total growing period from seed to seed is reduced by about 10 days and yields and water efficiency of the following rotation crops other than rice are increased (PDCSR, 2005). However, weed management is more difficult in dry direct-seeded rice. Direct seeding is another complement to conservation agriculture. Although transplanting of crops, including paddy rice, is possible under zero-tillage, direct seeding is preferable for the reasons mentioned above. In addition, direct seeding results in less soil movement than transplanting, which often involves some sort of strip tillage. At the same time, CA facilitates direct seeding by reducing several problems, such as surface crusting or weed control, encountered when direct seeding is applied in isolation.

Bed planting

Bed planting refers to a cropping system where the crop is grown on beds and irrigation water is applied in furrows between the beds. This is a common practice for row crops, but not for small grain crops such as wheat and rice. The advantages are saving of irrigation water, improved fertilizer efficiency, better weed control, and a reduced seed rate. The most important one as an RCT is the saving of irrigation water because of reduced evaporation surface and efficiency in distribution. In addition, the rooting environment is changed and aeration of the bed zone is better than with flat planting. Water savings compared to flat surfaces of 26% for wheat and 42% for transplanted rice have been reported, with yield increases at the same time of 6.4% for wheat and 6.2% for rice (RWC-CIMMYT, 2003). Different type of bed plantings can be used under different situations which are:

Raised-bed transplanted rice: A bed former-cum-drill seeder is used to form 37-cm-wide raised beds and 30-cm-wide furrows in well-prepared, pulverized soil. Then, 21-days old seedlings are planted on both sides of moist beds. Furrows are kept flooded for up to 21 days after transplanting.

Raised-bed drill-seeded rice: A bed former-cum-zero-till drill is used to form 37-cm-wide raised beds and 30-cm-wide furrows in well-prepared and pulverized soil, and dry rice seeds are sown in rows on both sides of moist beds. Frequent light irrigations are applied for quick germination and crop establishment. Yields of raised bed-dry-direct seeded rice were lower by 29% than conventional tilled transplanted rice (Kumar & Ladha, 2011).

Permanent (double) bed-planted rice: Drill seeding on raised beds is practiced for both rice and wheat in a sequence. It helps in good drainage, saves irrigation water and facilitates mechanical weeding. Permanent-bed-planting with double zero tillage for rice and wheat can significantly increase rice and wheat yield. Compared with the traditional cropping technique, wheat yield increased by 6.7%~9.7%, and rice yield by 5.1~6.7% (YongLu et al., 2005).

Reduced and zero tillage

Intensive soil tillage is the main cause for the reduction in soil organic matter and hence degradation of soils. Tillage accelerates the mineralization of organic matter and destroys the habitat of soil life. In addition to this, zero tillage results in water savings and improved water-use efficiency. Since the soil is not exposed through tillage, the unproductive evaporation of water decreases and water infiltration is facilitated (DBU, 2002). The possible water savings through zero tillage vary depending on the cropping system and climatic conditions and about 15–20% water saving can be expected (PDCSR, 2005). Various combinations of RCTs involving reduced tillage are as follows (Ladha et al., 2009).

Reduced-till (non puddled) transplanted rice: 2–3 dry tillages followed by planking/leveling and ponding water but without puddling; 21–30 days old seedlings are transplanted at random or in rows. Good soil structure is maintained due to reduced tillage and no puddling.

Reduced-till (non puddled) dry drill-seeded rice: Dry seeds are drilled in rows by a zero cum ferti-seed-drill at 2–3 cm depth in a well-prepared leveled and moist soil, followed by one light irrigation applied for good germination.

Reduced-till drill-seeded rice with a power tiller–operated seeder: The power tiller–operated seeder (PTOS) is a tiller with an attached seeder and a soil-compacting roller. The PTOS is used to till shallow (4–5 cm depth), sow seeds in rows at adjustable distance, and cover seed and compact the soil at the same time in a single pass.

Reduced-till (non-puddled) dry drill-seeded rice + Sesbania: Rice is drill-seeded, *Sesbania* seeds either drill-seeded or broadcast on the same day rice is sown in reduced-till plots followed by *Sesbania* knocked down at 25–30 days after sowing (DAS) with 2-4,D.

Zero-till (nonpuddled) transplanted rice: Transplanting rice seedlings in flooded field at optimum soil moisture without tillage and seedbed preparation.

Zero-till drill-seeded rice: Fields are flush-irrigated to moisten the soil and allow weeds to germinate. After about 2 weeks, glyphosate is applied to kill all weeds. A zero-till drill seeder is used to drill rice seeds at shallow depth, followed by a light irrigation to have a quick and uniform germination.

Zero-till drill-seeded rice and Sesbania: Rice is drill-seeded; *Sesbania* seeds either drill-seeded or broadcast in zero-till plots. *Sesbania* knocked down at 25–30 DAS with 2-4,D.

Double zero-till drillseeded rice: Rice is zero-till drill-seeded at optimum moisture in the presence of residues, along with need-based preplant herbicide for weed control. In winter, wheat is similarly zerotill drill-seeded in the same field. Compared with conventional tillage systems, double zero tillage consumed 12–20% less water with almost equal system productivity and demonstrated higher water productivity in rice wheat system (Jat et al., 2009).

Mulching and green manuring

The supply of organic matter to the soil through mulching and green manure is an important factor for maintaining and enhancing soil fertility. The mulching material can result from crop residues or green manure crops. This provides feed for the soil life and mineral nutrients for plants. If legume crops are used as green manure, they can supply up to 200 kg ha^{-1} nitrogen to the soil. This can result in savings of 50–75% mineral fertilizer for rice (RWC-CIMMYT, 2003). Left on the soil surface, the mulch reduces evaporation, saves water, protects soil from wind and water erosion, and suppresses weed growth.

Crop residue burning is a problem, particularly rice straw after combine harvesting in the north-west Indo-Gangetic Plain (Ladha et al., 2003). The development of zero-till drill seeding of wheat and rice under crop residue mulch provides an option to reduce residue burning, thereby reducing greenhouse gas emissions (Iqbal & Goheer, 2008). A soil amendment with residue may also improve soil quality.

Inclusion of grain legumes, green-manure crops, or *Sesbania* can add some biologically fixed N (BNF) and organic matter to soils, thereby building up soil fertility in the long run (Peoples et al., 1995, Ladha et al., 1996). Simultaneous sowing of rice and *Sesbania* and killing of young *Sesbania* plants at 30–45 days after sowing by selective herbicides (commonly referred to as brown manuring) could help build up soil fertility in the RW system (Singh et al., 2007).

Laser-assisted land leveling

For surface-irrigated areas, a properly leveled surface with the required inclination according to the irrigation method is absolutely essential. Traditional farmers' methods for leveling by eyesight, particularly on larger plots, are not accurate enough and lead to extended irrigation times, unnecessary water consumption, and inefficient water use. With laser leveling, the unevenness of the field is reduced to about ± 2 cm, resulting in better water application and distribution efficiency, improved water productivity, better fertilizer efficiency, and reduced weed pressure. Water savings of up to 50% have been reported in wheat and 68% in rice (Jat et al., 2006).

Controlled traffic farming

Controlled traffic farming restricts any traffic in the field always to the same tracks. Although these tracks are heavily compacted, the rooting zone never receives any compaction, resulting in better soil structure and higher yields. Through border effects, the area lost in the traffic zones is easily compensated for by better growth of plants adjacent to the tracks so that overall yields are usually higher than in conventional systems with random traffic (Kerr, 2001). Obviously, controlled traffic farming is the ideal complement to zero-tillage or bed-planting systems.

Sustainable and resource-conserving crop management technologies offer several major benefits under changing climate. These include:

1. Practices such as reduced tillage in combination with crop residue retention can buffer crops against severe climatic events, for example, by increasing water harvest and thereby offsetting water shortages that will intensify as global temperatures rise.
2. Improving the overall environment for root growth, such practices permit the genetic potential of improved cultivars to be more optimally expressed helping to close yield gaps that may already exist.
3. Diversification of cropping systems helps to control soil borne diseases.

Resource conservation technologies and greenhouse gases emissions

Inter governmental Panel on Climate Change (1995) estimated that 20% of the greenhouse effect is related to agricultural activities. Therefore, the management of soil resources, in general, and that of the SOC, in particular, is extremely important. Soil resources of the world may be the key factor in the creation of an effective carbon sink and mitigation of the greenhouse effect.

Conservation agriculture helps to mitigate the effects of climate change, by sequestering soil organic carbon and reducing emission of greenhouse gases (GHGs). With the increasing soil organic matter, soils under CA can retain carbon from carbon dioxide and store it safely for long periods of time. This carbon sequestration continues for 25 to 50 years before reaching a new plateau of saturation (Reicosky, 2001). The consumption of fossil fuel for agricultural production is significantly reduced under CA and burning of crop residues is completely eliminated, which also contributes to a reduction in greenhouse gas release. Depending on the type of management, soils under zero tillage might also emit less nitrous oxide (Izaurralde, 2004). With paddy rice in particular, the change to zero tillage systems combined with adequate water management can positively influence the release of other greenhouse gases, such as methane and nitrous oxides (Belder, 2005; Gao, 2006).

Carbon dioxide emission: Atmospheric CO_2 concentration is increasing at the rate of 5% a year. Burning fuel and changing land use are two major human activities that result in this increase (Lal & Kimbel, 1995). Organic carbon in the soil is the main source of GHG emissions from the soil (Post & Kwon, 2000). In rice based agricultural lands, organic carbon is supplied to the soil as root exudates, dead roots and stubble of crops. Some other additional organic carbon is also supplied by organic matter incorporation (Nishimura et al., 2008). The amount of organic carbon stored in paddy soils is greater than in upland soils because of different biochemical processes and mechanisms specifically caused by the presence of flooded water in paddy soils (Liping & Erda, 2001). The dynamics of carbon in paddy fields significantly differs from that in fields with upland crop cultivation in which the aerobic decomposition process is dominant. During the submerged period of paddy rice cultivation, CO_2 production in the soil is severely restricted under anaerobic conditions. Chen et al. (2001) has reported continuous rice cultivation has a tendency to increase CO_2 emission from soil. On the other hand, researchers also reported that paddy field acts as net sink of atmospheric CO_2 (Yin et al., 2008). Liu et al (2007) has reported that the optimum/high moisture condition in the paddy fields reduces the CO_2 flux by increasing the gross primary productivity (GPP) over net ecosystem respiration (NER).

Nitrous oxide emission: Nitrous oxide (N_2O) is an important greenhouse gas, accounting for about 5% of total global warming (Robertson et al., 2000). The emission of N_2O occurs as a result of nitrification and denitrification processes occurring in aerobic and anaerobic soil conditions, respectively. Total emissions of N_2O-N were lower (0.002 kg ha^{-1}) under continuous submergence than under alternate wetting and drying (0.050 to 0.054 kg ha^{-1}). Over a period of 12 days, approximately 0.12% of applied N was emitted as N_2O from soil under alternate wetting and drying (AWD), whereas this value was negligible under continuous submergence (Mohanty et al., 2009). Thus, growing rice in unpuddled soil under aerobic conditions will have implications for the emission of GHG N_2O (Pathak et al., 2007). However, emissions of methane (CH_4), another greenhouse gas, are less under aerobic conditions than under flooded rice cultivation (Gupta-Vandana et al., 2009). In rice, it has been observed that strategies to reduce emissions of N_2O often lead to an increase in emissions of CH_4. There is tradeoff between these two gases. Both of these gases have different global warming potential (GWP), hence the RCTs with lesser GWP need to be recommended for rice based systems.

Methane emission: The regional distribution of the rice–wheat system warrants a comparative assessment of CH_4 emissions in Central China and Northern India, because these two regions collectively account for more than 75% of the global rice–wheat area. The available CH_4 emission records from rice fields in Central China showed a relatively high background level of CH_4 emissions ranging from 200 to 900 kg CH_4 ha^{-1} under mineral fertilization (Zheng et al., 1997; Wassmann et al., 1993) and up to 1100 kg CH_4 ha^{-1} following organic amendments (Khalil et al., 1998). Emission records from Northern India were consistently lower and did not exceed 30 kg CH_4 ha^{-1} under mineral fertilization (Mitra et al., 1999) and 50 kg CH_4 ha^{-1} under organic treatment (Debnath et al., 1996). Methane is mainly generated from organic material that is recently formed or added during the growing season of the rice itself. Moreover, the post-wheat fallow period until the transplanting of rice crop should result in converging soil conditions. Wheat straw only slightly deviates from rice straw in its C content, so that an impact deriving from distinct residues is rather unlikely even under high doses of straw application. The composition of organic residues, however, could become a factor when rice–wheat system is compared to rice–legume rotations. In rice fields applied with residues from the preceding season, CH_4 emissions were reduced by approximately 50% when cowpea was grown instead of wheat (Abao et al., 2000).

Resource conservation technologies to enhance carbon sequestration

Resource conservation technologies involving no or minimum tillage with direct seeding, bed planting and crop residue management are now being advocated as alternatives to the conventional rice based cropping system for improving the input-use efficiency, productivity, and sustainability of the system (Gupta et al., 2003, Bhushan et al., 2007). The SOC content depends on the type of conservation tillage and amount of crop residues returned to the soil surface, and may be linearly related to crop residue returned to the soil. Crop residues produced in the world are estimated at 2962 million Mg yr^{-1}. Even a fraction of these residues returned to the soil through conservation tillage can increase SOC content and lead to C sequestration.

Tillage effects on soil organic matter: While thorough tillage of the soil has immediate advantages for controlling weeds and creation of a fine soil tilth for sowing seed and for seedling emergence, there are adverse consequences of regular tillage on soil quality which become more apparent over the longer term. Soil quality is largely determined by soil organic matter (SOM) status and there is much accumulated evidence in temperate and tropical soils of declining SOM with tillage as compared to relatively undisturbed soil (Ogle et al., 2005). There is a range of soil physical, chemical and biological consequences to declining SOM caused by tillage. A decline in SOM reduces soil particle aggregation (Chaney & Swift, 1984), which slows water infiltration (Thierfelder & Wall, 2010), reduces aeration and increases bulk density, thereby restricting root distribution and function. With reduced SOM, soil water holding capacity is decreased and susceptibility to water erosion increased through increased runoff (Thierfelder & Wall, 2010). Declining SOM also diminishes the ability of the soil to release nutrients in approximate synchrony with crop demand (Drinkwater & Snapp, 2007). Soil organic matter provides exchange sites for nutrient ions, minimizing their leaching or sorption on clay minerals, but increases their availability for plant uptake through slow release to the soil solution. A decline in SOM results in an inevitable decline in soil biological activity (Soon & Arshad, 2005). Depending on soil type, frequent tillage may cause the development of a hardpan at the bottom of the ploughed or hoe cultivated layer which can impede water infiltration and root penetration (Thierfelder & Wall, 2009).

Conservation tillage and carbon cycling: Conservation tillage, a generic term denoting a range of tillage practices that reduce soil and water losses in comparison with conventional or plow-based tillage method and use crop residue mulch to provide a protection against raindrop impact, increases SOC through enhancement of soil aggrading processes and reversal of soil degrading processes (Lal, 1989; Carter, 1993). The SOC content also depends on the type of conservation tillage and amount of crop residues returned to the soil. Several experiments conducted in temperate and tropical regions have demonstrated the beneficial effects of conservation tillage on SOC (Juo and Lal, 1978; Lal, 1979; Dalal, 1989; 1992; Lal et al., 1989; Carter, 1993). On an Ultisol in Eastern Nigeria, Ohiri and Ezumah (1990) observed about 8% higher SOC in conservation tillage compared with conventional tillage systems. Conservation tillage is known to enhance SOC in the surface soil horizons through several mechanisms (e.g., alterations of soil temperature and moisture regimes, and erosion control) (Lal, 1989; Kern & Johnson, 1993).

Crop residue and its role in soil organic carbon management: Crop residue management, quantity and quality of biomass applied to the soil, has a significant impact on soil quality and resilience, agronomic productivity, and carbon sequestration. Crop residue is an important and a renewable resource. Developing techniques for effective utilization of this vast resource is a major challenge. Improper use of crop residues (e.g. removal and burning) can accelerate erosion, deplete soil fertility, and pollute environment through burning and eutrophication of surface and contamination of groundwater. If managed properly, residue management may save energy, recycle nutrients, enhance soil fertility, improve soil structure and sequester carbon.

The quantity of crop residue produced depends on the arable land area, crops and cropping systems, and soil and crop management. The global arable land area is about 1.4 billion ha with about 31% in Asia (FAO, 1993). Based on the mean residue:grain ratio for different crops, annual production of crop residue is estimated at 3.4 Pg in the world (Lal, 1997). The amount of residue produced by cereals is usually high because of a high straw:grain ratio, low decomposition rate, and high C:N ratio. Residue production by all grain cereals is estimated at 2.5 Pg for the world. Assuming the mean carbon content of 45%, total carbon assimilated annually in the crop residue is about 1.5 Pg in the world. If 15% of the carbon assimilated in the residue can be converted to humus fraction, it may lead to carbon sequestration at the rate of 0.2 Pg yr^{-1} or 5.0 Pg of cumulative C sequestration in the world by the year 2020. Application of 50% NPK + 50% N through FYM in rice and 100% NPK in wheat, sequestered 0.39 to 0.62 Mg C ha^{-1} yr^{-1} over control (no N–P–K fertilizers or organics) in IGP of India (Nayak et al., 2012). Application of NPK either through inorganic fertilizers or through combination of inorganic fertilizer and organics such as farm yard manure or crop residue or green manure improved the SOC, particulate organic carbon, microbial biomass carbon concentration and their sequestration rate.

Conclusions

Locally adopted RCTs appropriate to resource endowments of farmers and the biophysical environment hold potential to improve management of natural resources and provide sustainable increases in productivity. The long-term trials, set up at the beginning of the green revolution era to understand nutrient mining in the system and to develop nutrient management strategies have provided valuable information to develop future strategies. Appropriate long-term monitoring must continue, and be relevant to future changes in tillage and water management practices. In addition, benefits of changes in the tillage system and stubble management to the soil ecosystem need to be better understood. Zero-till, permanent bed-planting systems and new nonpuddled rice establishment techniques coupled with laser land levelling can go a long way to increasing the use efficiency of these vital natural resources. Resource conservation technologies applied in isolation have advantages and disadvantages. They are not universally applicable as the problems can sometimes outweigh the benefits. However, by combining different resource conservation technologies, synergies can be created to eliminate the disadvantages of single technologies and accumulate the benefits. Different RCTs are successfully applied under the concept of conservation agriculture in different cropping systems around the world, allowing stable agricultural production without the known negative environmental impact.

Mitigation options in the rice based cropping system may individually be of limited scope, but they may achieve a discernable composite effect when implemented in coordinated fashion. Mitigation programs will rely on win–win opportunities when emissions can be reduced with another concomitant benefit such as higher yields, less fertilizer, water needs, etc. Targeting one individual gas alone seems inappropriate due to tradeoff effects in the emissions of CH_4, N_2O, and CO_2. More research is needed to combine geographic information, emission models, yield models and socio-economic information to devise site-specific packages of mitigation technologies.

References

Abao, E.B. Jr., Bronson, K.F., Wassmann, R., & Singh, U. (2000). Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rain fed conditions. *Nutrient Cycling in Agroecosystems,* 58, 131-139.

Ali, M., & Byerlee, D. (2000). Productivity growth and resource degradation in Pakistan's Punjab: A decomposition analysis. *Policy Economics Working Paper*, World Bank.

Aulakh, K.S. (2005). *Punjab Agricultural University, accomplishments and challenges*. Ludhiana. p.23.

Belder, P. (2005). Water saving in lowland rice production: An experimental and modelling study. Wageningen University, Netherlands. (Ph.D. thesis with English and Dutch summaries).

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y.S., Gathala, M., & Pathak, H. (2007). Saving of water and labor in rice-wheat system with no-tillage and direct-seeding technologies. *Agronomy Journal,* 99, 1288-1296.

Bot, A., & Benites, J. (2005). The importance of soil organic matter, key to drought-resistant soil and sustained food production. *FAO Soils Bulletin* 80. Rome (Italy): FAO.

Byerlee, D. & Siddiq, A. (1994). Has the green revolution been sustained? The quantitative impacts of the seed-fertilizer technology in Pakistan revisited. *World Development*, 22(9), 1345-1361.

Carter, M.R. (Ed.). (1993). *Conservation tillage in temperate agroecosystems*. (pp. 390). Boca Raton, Fl: Lewis Publishers.

Chaney, K., & Swift, R.S. (1984). The influence of organic matter on aggregate stability in some British soils. *J.Soil Sci.*, 37, 329-335.

Chen, H.W., Yen, J.H., Chung, R.S., Lai, C.M., Yang, S.S., & Wang, S.S. (2001). Carbon dioxide flux densities in cultivated rice paddy fields. *Proceedings of the National Science Council, Republic of China,* 25(4), 239-247.

Dalal, R.C. (1989). Long-term effects of no-tillage, crop residue and nitrogen application on properties of a *vertisol*. *Soil Science Society of America Journal,* 53, 1511-1515.

Dalal, R.C. (1992). Long-term trends in total nitrogen of a *vertisol* subjected to zero-tillage, nitrogen application and stubble retention. *Australian Journal of Soil Research,* 30, 223-231.

DBU. (2002). Innovativer Ansatz eines vorbeugenden Hochwasserschutzes durch dezentrale Maßnahmen im Bereich der Siedlungswassserwirtschaft sowei der Landwirtschaft im Einzugsgebiet der Lausitzer Neiße. Project report DBU-project AZ 15877, Deutsche Bundesstiftung Umwelt (German Federal Environment Foundation), Osnabrück, Germany.

Debnath, G., Jain, M.C., Kumar, S., Sarkar, K., & Sinha, S.K. (1996). Methane emissions from rice fields amended with biogas slurry and farm yard manure. *Climatic Change,* 33, 97-109.

Drinkwater, L.E., & Snapp, S.S. (2007). Nutrients in agroecosystems: Re-thinking the management paradigm. *Advances in Agronomy,* 92, 163-186.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., & Bronson, K.F. (2000). Summary analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In I.P. Abrol et al (Eds.), *Long-term soil fertility experiments in rice-wheat cropping systems.* New Delhi, India: Rice-wheat consortium for the Indo-Gangetic Plains.

FAO. (1993). *Production yearbook*. (pp. 254). Rome, Italy: FAO.

FAO. (2002). *Agriculture: Towards 2015/2030*. (p.420). Rome, Italy: FAO.

Fujisaka, S., Harrington, L.W., & Hobbs, P.R. (1994). Rice-wheat in South Asia: System and long-term priorities established through diagnostic research. *Agricultural Systems,* 46, 169-187.

Gao Huanwen. (2006). *The impact of conservation agriculture on soil emissions of nitrous oxide*. Draft report. Beijing, China: Asian and Pacific Centre for Agricultural Engineering and Machinery.

Garcia-Torres, L., Benites, J., Martinez-Vilela, A., Holgado-Cabrera, A. (Eds.). (2003). *Conservation agriculture: Environment, farmers experiences, innovations, socio-economy, policy*. Dordrecht, The Netherlands; Boston, Germany; London, UK: Kluwer Academia Publishers.

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

Gupta, R.K. et al. (2003). In J.K. Ladha et al. (Eds.), *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication No. 65. (pp. 1-25). Madison, Wisconsin, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Gupta, R.K., & Rickman, J. (2002). Design improvements in existing zero-till machines for residue conditions. Traveling Seminar Report Series 3. New Delhi, India: Rice-Wheat Consortium for the Indo- Gangetic Plains.

Gupta-Vandana, Singh, S., Chandna Parvesh, Tewari, A., Kumar, K., Ladha, J.K., Gupta, R.K., & Gupta, P.K. (2009). Mitigating methane emission in rice with resource conserving technologies. In *Conservation agriculture: Innovations for improving efficiency, equity and environment.* Proceedings of 4th World Congress on Conservation Agriculture, 4-7 February 2009. New Delhi, India: Indian Council of Agriculture Research.

Hobbs, P.R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B,* 363(1491), 543-555.

Hobbs, P.R., & Morris, M. (1996). Meeting South Asia's future food requirements from rice-wheat cropping systems: Priority issues facing researchers in the post green revolution era. NRG paper 96-01. CIMMYT, Mexico.

Hobbs, P.R., & Gupta, R.K. (2003). Rice-wheat cropping systems in the Indo-Gangetic Plains: Issues of water productivity in relation to new resource-conserving technologies. In J.W. Kijne, R. Barker, D. Molden (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement.* Wallingford, UK: CABI Publications.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R., & Woodwell, G.M. (1983). Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecological Monographs,* 53, 235-262.

Humphreys, E., Roth, C.H. (Eds.). (2008). Proceedings of the workshop on permanent beds and rice-residue management for rice–wheat systems in the Indo-Gangetic Plains, Ludhiana, India, September 7–9, 2006. ACIAR No. 127. Australian Centre for International Agricultural Research, Canberra, Australia, in press.

Intergovernmental Panel on Climate Change. (1995). Agricultural options for mitigation of greenhouse gas emissions. IPCC Workgroup II, Chapter 23, Washington, D.C.

Iqbal Mohsin, M., & Goheer Arif, A. (2008). Greenhouse gas emissions from agro-ecosystems and their contribution to environmental change in the Indus basin of Pakistan. *Advances in Atmospheric Sciences,* 25(6), 71.

Izaurralde, R.C., Lemke, R.L., Goddard, T.W., McConkey, B., & Zhang, Z. (2004). Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Science Society of America Journal*, 68, 1285-1294.

Jat, M.L., Chandna, P., Gupta, R., Sharma, S.K., & Gill, M.A. (2006). Laser land levelling: A precursor technology for resource conservation. Rice-Wheat Consortium Technical Bulletin Series 7. (p. 48). New Delhi, India: Rice-Wheat Consortium for the Indo Gangetic Plains.

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, Vipin., Sharma, S.K., Kumar, V., & Gupta, R. (2009). Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. *Soil and Tillage Research*, 105(1), 112-121.

Juo, A.S.R., & Lal, R. (1978). Nutrient profile in a tropical *alfisol* under conventional and no-till systems. *Soil Science,* 127, 168-173.

Kassam, A.H. (2009). Sustainability of farming in Europe: Is there a role for conservation agriculture? *Journal of Farm Management*, 10, 717-728.

Kern, J.S., & Johnson, M.G. (1993). Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal,* 57, 200-210.

Kerr, P. (2001). Controlled traffic farming at the farm level. GRDC Research Update, Finley NSW, Australia.

Khalil, M.A.K., Rasmussen, R.A., Shearer, M.J., Chen, Z.L., Yao, H., & Yang, J. (1998). Emissions of methane, nitrous oxide, and other trace gases from rice fields in China. *Journal Geophysical Research - Atmosphere,* 103, 25241-25250.

Kirschbaum, M.U.F. (1995). The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic carbon storage. *Soil Biology and Biochemistry,* 27, 753-760.

Kumar Virender & Ladha, J.K. (2011). Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy*, 111, 297-413.

Kumar, A., & Yadav, D.S. (2001). Long-term effects of fertilizers on the soil fertility and productivity of a rice-wheat system. *Journal of Agronomy and Crop Science,* 86, 47-54.

Ladha, J.K., Kundu, D.K., Angelo-Van Coppenolle, M.G., Carangal, V.R., Peoples, M.B., Dart, P.J. (1996). Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. *Soil Science Society of America Journal,* 60, 183-192.

Ladha, J.K., Kumar, V., Alam, M.M., Sharma, S., Gathala, M., Chandna, P., Saharawat, Y.S., & Balasubramanian, V. (2009). Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In J.K. Ladha, Y. Singh, O. Erenstein, B. Hardy (Eds.), *Integrated crop and resource management in the rice–wheat system of South Asia.* (pp. 69-108). Los Banos, Philippines: International Rice Research Institute.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Bijay-Singh, Yadvinder Singh, Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., & Hobbs, P.R. (2003a). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research,* 81, 159-180.

Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., & Gupta, R.K. (2003b). Productivity trends in intensive rice-wheat cropping systems in Asia. In J.K. Ladha, J.E. Hill, J.M. Duxbury, Raj K. Gupta, R.J. Buresh (Eds.), *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication 65. (pp. 45-76). Madison, USA: ASA-CSSA-SSSA.

Ladha, J.K., Hill, J.E., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.). (2003). *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication 65. (p. 211). Madison, USA: ASA-CSSA-SSSA.

Lal, R. (1997). Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2-enrichment. *Soil and Tillage Research,* 43, 81-107.

Lal, R., & Logan, T.J. (1995). Agricultural activities and greenhouse gas emissions from soils of the Tropics. In R. Lal, J. Kimble, E.Levine, B.A. Stewart (Eds.), *Soil management and greenhouse effect.* (pp. 293-307). Boca Raton, Fl: CRC/Lewis Publishers.

Lal, R. (1979). Influence of six years of no-tillage and conventional plowing on fertilizer response of maize on an *alfisol* in the Tropics. *Soil Science Society of America Journal*, 43, 399-403.

Lal, R. (1989). Conservation tillage for sustainable agriculture: Tropics vs. Temperate environments. *Advances in Agronomy,* 42, 85-197.

Lal, R., & Kimble, J. (1995). Soils and global change. In *Advances in Soil Sciences* (1th ed.). (pp. 1-2). FL Boca Raton, USA: CRC Press.

Liping, G., & Erda, L. (2001). Carbon sink in cropland soils and the emission of greenhouse gasses from paddy soils: A review of work in China. *Chemosphere-Global Change Science,* 3, 413-461.

Liu, H., Zhao, P., Sun, G.C., Lin, Y.B., Rao, X.Q., & Wang, Y.S. (2007). Characteristics of CO_2, CH_4 and N_2O emission from winter fallowed paddy soils in hilly areas of South China. *Ying Yong Sheng Tai Xue Bao* (in Chinese), 18, 57-62.

Met Office. (2005). *Climate change, rivers and rainfall*. Recent research on climate change science from the Hadley Centre, Exeter, UK.

Mitra, S., Jain, M.C., Kumar, S., Bandyopadhyay, S.K., & Kalra, N. (1999). Effect of rice cultivars on methane emission. *Agriculture Ecosystems Environment,* 73, 177-183.

Mohanty, M., Painuli, D.K., Misra, A.K., & Ghosh, P.K. (2007). Soil quality effects of tillage and residue under rice–wheat cropping on a *vertisol* in India. *Soil and Tillage Research,* 92, 243-250.

Mohanty, S., Ladha, J.K., Gathala, M., Pathak, H., Jain, N., & Sharma, S. (2009). Emission of N_2O from soil with different resource conserving technologies. In *Conservation agriculture: Innovations for improving efficiency, equity and environment*. Proceedings of the 4th World Congress on Conservation Agriculture, 4-7 February 2009. New Delhi (India): Indian Council of Agricultural Research.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar Sonali, P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research,* 127, 129-139.

Nishimura, S., Yonemura, S., Sawamoto, T., Shirato, Y., Akiyama, H., Sudo, S., & Yagi, K. (2008). Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. *Agriculture, Ecosystems and Environment,* 125, 9-20.

Ogle, S.M., Breidt, F.J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry,* 72, 87-121.

Ohiri, A.C., & Ezumah, H.C. (1990). Tillage effects on cassava production and some soil properties. *Soil and Tillage Research*, 17, 221-229.

Pathak, H., Ladha, J.K., Saharawat, Y.S., & Gathala, M. (2007). Impact, productivity, income and environmental impact assessment of RCTs in RW system using modeling tool. In Proceedings of the 94th Indian Science Congress, 3-7 January 2007, Chidambaram, India. p. 32.

PDCSR. (2005). Annual report 2004-05. (p.143). Modipuram, Meerut, India: Project Directorate for Cropping Systems Research.

Peoples, M.B., Herridge, D.F., & Ladha, J.K. (1995). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant Soil*, 174, 3-28.

Post, W.M., Peng, T.H., Emaniel, W.R., King, A.W., Dale, V.H., & DeAngelis, D.I. (1990). The global carbon cycle. *American Scientist*, 78, 310-326.

Post, W.M., & Kwon, K.C. (2000). Soil carbon sequestration and land use change: Processes and potential. *Global Change Biology*, 6, 317-327.

Reicosky, D. (2001). Conservation Agriculture: Global environmental benefits of soil carbon management. In L. Garcia-Torres, J. Benites, A. Martínez-Vilela (Eds.), *Conservation Agriculture - A World-wide Challenge*. (p. 3-12).

Robertson, G.P., Paul, E.A., & Harwood, R.R. (2000). Greenhouse gases in intensive agriculture: Contribution of individual gases to the radiative forcing of the atmosphere. *Science*, 289, 1922-1925.

RWC-CIMMYT. (2003). Addressing resource conservation issues in rice-wheat systems of South Asia: A resource book. (p. 305). New Delhi, India: Rice-Wheat Consortium for the Indo-Gangetic Plains/ International Maize and Wheat Improvement Centre.

Shaxon, T.F., & Barber, R.G. (2003). Optimizing soil moisture for plant production: The significance of soil porosity. *FAO Soils Bulletin* No. 79. Rome, Italy: FAO.

Singh, S., Ladha, J.K., Gupta, R.K., Bhushan, L., Rao, A.N., Sivaprasad, B., & Singh, P.P. (2007). Evaluation of mulching, intercropping with *Sesbania* and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). *Crop Protection*, 26, 518-524.

Soon, Y.K., & Arshad, M.A. (2005). Tillage and liming effects on crop and labile soil nitrogen in an acid soil. *Soil and Tillage Research*, 80, 23-33.

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

Thierfelder, C., & Wall, P.C. (2010). Investigating Conservation Agriculture (CA) systems in Zambia and Zimbabwe to mitigate future effects of climate change. *Journal of Crop Improvement*, 24, 113-121.

Wall, P.C. (2007). Tailoring conservation agriculture to the needs of small farmers in developing countries: An analysis of issues. *Journal of Crop Improvement*, 19, 137-155.

Wassmann, R., Sch¨utz, H., Papen, H., Rennenberg, H., Seiler, W., Dai, A.G., Shen, R.X., Shangguan, X.J., & Wang, M.X. (1993). Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment. *Biogeochemistry*, 11, 83-101.

Yin, C.M., Xie, X.L., & Wang, K.R. (2008). Effect of straw mulching on CO_2 flux on winter fallow paddy field. *Ying Yong Sheng Tai Xue Bao* (in Chinese), 19, 115-119.

YongLu, T., JiaGuo, Z., & Gang, H. (2005). Studies on permanent-bed-planting with double zero tillage for rice and wheat in Sichuan basin. *Southwest China Journal of Agricultural Sciences*, 18(1), 25-28.

Zheng, X.H., Wang, M.X., Wang, Y.S., Heyer, J., Kogge, M., Papen, H., Jin, J.S., & Li, L.T. (1997). N_2O and CH_4 emissions from rice paddies in Southeast China. *Chinese Journal of Atmospheric Sciences*, 21, 167-174.

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