Proc Indian Natn Sci Acad **80** No. 1 March 2014 pp. 95-114

10.16943/ptinsa/2014/v80i1/55089

Review Article

Management of Cereal Crop Residues for Sustainable Rice-Wheat Production System in the Indo-Gangetic Plains of India

Y SINGH[1*] and H S SIDHU[2]
[1]*Department of Soil Science, Punjab Agricultural University, Ludhiana 141 004, India*
[2]*Borlaug Institute for South Asia (BISA), Ladhowal, Punjab Agricultural University, Ludhiana 141 008, India*

(Received 03 August 2013; Revised 10 October 2013; Accepted 24 October 2013)

Rice-wheat (RW) cropping system of the Indo-Gangetic Plains has played a significant role in the food security of India. However, sustainability of this important cropping system is at risk due to the deterioration of soil health, mounting pressure on natural resources and emerging challenges of climate change. Conservation agriculture involving zero- or minimum-tillage and innovations in crop residue management (CRM) to avoid straw burning should assist in achieving sustainable productivity and allow farmers to reduce nutrient and water inputs, and reduce risk due to climate change. High yields of the irrigated RW system have resulted in production of huge quantities of crop residues (CRs). Burning of rice straw is common in north-western parts of India causing nutrient losses, and serious air quality problems affecting human health and safety. Mulch is a good option for rice residue management during the wheat crop, especially with no tillage. Mulch can increase yield, water use efficiency, and profitability, while decreasing weed pressure. Surplus residue from the previous wheat crop can be incorporated into the paddy fields with no adverse effect on rice yield. Residue decomposition in anaerobic flooded soil substantially increases methane emission relative to residue removal. Long-term studies of the residue recycling have indicated improvements in physical, chemical and biological health of soil. Since CRs contain significant quantities of plant nutrients; their continuous application will have positive effect on fertilizer management in RW system. Other plausible option of CRM lies in utilizing a potion of surplus residue for producing biochar (and co-production of bioenegy) for using as soil amendment to improve soil health, increase nutrient use efficiency and minimize air pollution. In this review authors have discussed current concerns and possible options for with efficient management of CRs in the RW cropping system.

Key Words : Bioenergy; Crop Residues; Decomposition; Rice-Wheat System; Straw Management; Straw Mulch; Soil Health

Introduction

Rice (*Oryza sativa* L.) - wheat (*Triticum aestivum* L.) (RW) cropping system has been developed through the introduction of rice in the traditional wheat-growing areas and vice versa in India (Paroda *et al*., 1994). In the mid-1960s, Green Revolution technologies led to the emergence of RW as the major production system covering an area of 10 million hectares spread over the Indo-Gangetic Plains (IGP) of India. About one-third of the total cereals of India are produced in this region. The two northwestern (NW) states of Punjab and Haryana now constitute a highly productive RW zone in the IGP contributing about 69% of the total food output in the country (about 84% wheat and 54% rice) and this region is called the "food bowl of India." A number of problems have cropped up in the region with the spread of the RW system for the last four decades, threatening the sustainability of the system. Low levels of soil organic matter, appearance of multiple nutrient deficiencies due to their over mining from soils and poor management of crop residues (CRs), leading to their burning are some of the major reasons for declining

**Author for Correspondence: E-mail: yadvinder16@rediffmail.com*

RW productivity in the region (Ladha *et al*. 2000). To feed India's projected population of 1.35 billion in 2025, agricultural production, especially that of rice and wheat (staple foods of India), would have to increase by approximately 25%. Furthermore, agricultural production in Punjab, Haryana, and western Uttar Pradesh might not be sustainable unless major steps are taken to improve management of groundwater and increase water use efficiency (Hira 2009). Adopting the principles of conservation agriculture together with better bet crop management practices would improve system productivity and overall resource-use efficiency, resulting in a higher profitability as well as sustainability of RW system.

Availability of Crop Residues

In India, over 500 million tons (Mt) of agricultural residues are produced every year (MNRE, 2009; www.nicra.iari.res.in/Data/FinalCRM.doc). With increased production of rice and wheat, residue production has also increased substantially. There is a large variability in production of CRs, and their use depends on the crops grown, cropping intensity, and productivity in different regions of India. Cereal crops (rice, wheat, maize, millets) contribute 70% of the total CRs (352 Mt) comprising 34% by rice and 22% by wheat crops. The RW system accounts for nearly one-fourth of the total CRs produced in India (Sarkar *et al*., 1999). The surplus CRs (i.e., total residues produced minus the amount used for various purposes) are typically burned on-farm. The amount of surplus CRs available in India is estimated between 84 and 141 Mt year^{-1} where cereals crops contribute 58%. Of the 82 Mt of surplus CRs nearly 70 MTs (44.5 Mt rice straws and 24.5 Mt wheat straws) are burned annually.

Crop Residues as Source of Plant Nutrients

CRs are good sources of plant nutrients, are the primary source of organic matter (as C constitutes about 40% of the total dry biomass) added to the soil, and are important components for the stability of agricultural ecosystems. About 40% of the N, 30-35% of the P, 80-85% of the K, and 40-50% of the S absorbed by rice remain in the vegetative parts at maturity (Dobermann and Fairhurst 2000). Similarly, about 25-30% of N and P, 35-40% of S, and 70-75% of K uptake are retained in wheat residue. Typical amounts of nutrients in rice straw at harvest are 5-8 kg N, 0.7-1.2 kg P, 12-17 kg K, 0.5-1 kg S, 3-4 kg Ca, 1-3 kg Mg, and 40-70 kg Si per ton of straw on a dry weight basis (Dobermann and Witt, 2000). One ton of wheat residue contains 4-5 kg N, 0.7-0.9 kg P, and 9-11kgK (Yadvinder-Singh, personal communication). Based on several observations, van Duivenbooden (1992) reported mean N, P and K amounts in rice straw as 6.2 kg N, 1.1 kg P and 18.9 kgK per ton of straw. Potassium concentration is generally higher (up to 25 kg per ton) in rice straw of NW IGP than that from other regions of the India or other countries. Nutrient concentration in CRs depends on the soil conditions, crop management, variety, season etc. The amount of NPK contained in rice and wheat residues produced (197 Mt) is about 4.1x 10^6Mt in India. Considering 90% of rice straw and 30% of wheat straw are surplus in Punjab, the amount of NPK recycled annually would be about 0.54 MT. Besides NPK, one ton of rice and wheat residues contain about 9-11 kg S, 100 g Zn, 777 g Fe and 745g Mn. CRs still play an important role in the cycling of nutrients despite the dominant role of chemical fertilizers in crop production. Continuous removal and burning of CRs can lead to net losses of nutrients under standard fertilization practices, which ultimately will lead to higher nutrient cost input in the short term and reduction in soil quality and productivity in the long term.

Management Options for Crop Residues

In NW India, RW cropping system generates huge quantities of CRs. Majority of rice and wheat in NW India is harvested by combine leaving residues in the field. While about 75% of wheat straw is collected as fodder for animals with the help of special cutting machine though this requires additional operation and investment, rice straw is considered poor feed for animals due to its high silica content. Rice straw differs from other straws in having a higher content of silica (12-16 vs. 3-5%) and a lower content of lignin (6-7 vs. 10-12%). Rice straw stems are more digestible than leaves because their silica content is lower; therefore the rice crop should be cut as close to the ground as possible if the straw is to be fed to livestock. Management of rice straw, rather than wheat straw is a serious problem, because there is very little turn-around time between rice harvest and wheat sowing and due to the lack of proper technology for recycling. Among options available to farmers for the CRM (including burning), important are baling/removal for use as feed and bedding for animals, *in situ* incorporation in the soil with tillage, and complete/partial retention on the surface as mulch using zero or reduced tillage systems. After bailing CRs can also be used for paper and ethanol production, bioconversion, and engineering applications. Since rice straw has no economic value and there is a scarcity of labour, farmers hesitate to invest in cleaning the field by using a chopper. This practice also requires another operation and increases cost. Farmers in NW India have discovered burning as the cheapest and easiest way of removing large loads of residues produced by rice to establish the wheat crop rapidly after rice. Presently, more than 80% of total rice straw produced annually is being burnt by the famers in 3-4 weeks during October-November (Yadvinder-Singh *et al.* 2010b). Burning of rice straw causes gaseous emission of 70% CO_2, 7% CO, 0.66% CH_4, and 2.09% N_2O (Gupta et al. 2004). The field burning of CRs is a major contributor to reduced air quality (particulates, greenhouse gases), and impacts human and animal health both medically, and by traumatic road accidents due to restricted visibility in NW India. Besides, burning of CRs leads to a loss of organic matter and precious nutrients, especially N and S. The peak in asthmatic patients in hospitals in NW India coincides with the annual burning of rice residue in surrounding fields (Yadvinder-Singh *et al.* 2010b). In spite of the legal ban enforced by the district magistrates of the NW states of India, burning of CRs by the farmers has not subsided. In Punjab alone about 20 Mt of rice and wheat residues out of a total of 37 M tons of residues are being burned *in situ* annually, leading to a loss of about 8 Mt of C equivalent to a CO_2 load of about 29 Mt per year and a loss of about 1 x 10^5 tons of N, in addition to loss of S and the destruction of beneficial microflora of the soil (Yadvinder-Singh *et al.* 2010b). Removal of CRs for various off farm purposes (except for composting and use as fodder), potentially have adverse effects on nutrient supply representing an economic loss in the short term, but it will have a long-term negative effect on soil quality, water quality, and agriculture sustainability as demonstrated by many studies (Bijay-Singh *et al.* 2008 and references therein). In order to replace harvested residue nutrients lost due residue removal, additional nutrient (NPK) fertilization will be needed in the long term.

Decomposition and Release of Nitrogen from Crop Residues

Decomposition of CR releases nutrients into the mineral nutrient pool and C as CO_2. Using litter bags, Yadvinder-Singh *et al.* (2010a) showed that rice residue decomposition can be described by first-order exponential. Incorporated rice residue lost about 80% of its initial mass at the end of decomposition cycle (140 days), leading to a decomposition rate (k) of 0.21-0.24 day^{-1} that was about three times as fast as that in the surface-placed residue (0.078 day^{-1}). About 50-55% of the rice residue placed at the soil surface was not decomposed at the time of wheat harvest (Fig. 1). In another study, Yadvinder-Singh *et al.* (2004b) found that mass loss of incorporated rice residue was upto 51% by 40-day, 35 % for the 20-

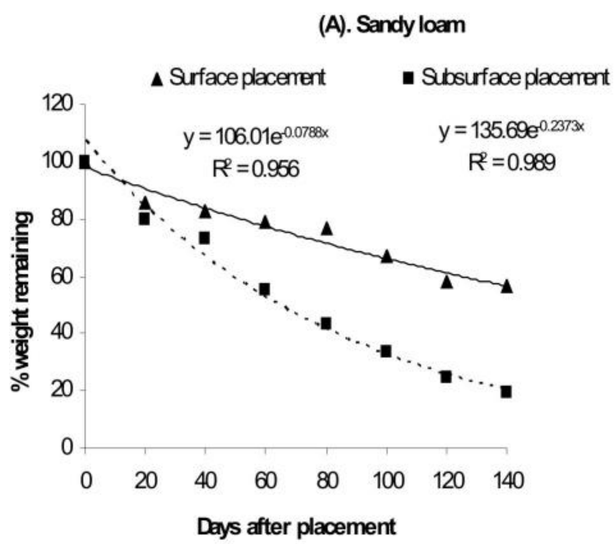

Fig. 1: Rice residue decomposition during wheat season as a function of time as affected by method of placement (Yadvinder-Singh *et al.*, 2010a)

day and 25% for 10-day decomposition treatment imposed before sowing of wheat.

Total N release from buried residue by maximum tillering stage was about 6 kg N ha^{-1} (15% of initial) in the sandy loam and 12 kg N ha^{-1} (27% of initial) in the silt loam (Yadvinder-Singh *et al*., 2010a). The amount of N released from the buried residue on the sandy loam increased to 12 kg ha^{-1} by the booting stage and to 26-28 kg ha^{-1} by maturity. Since N application after maximum tillering will have only a small effect on grain yield of wheat, the additional amount of N released after booting may not affect grain yield. In contrast, there was no release of N (rather N was immobilized) from the residues on the soil surface throughout the wheat growing season, with no N benefit to the growing wheat crop. From another study, Yadvinder-Singh *et al*. (2004b) reported that total amount of N released under different rice straw decomposition treatments during the life span of the wheat crop (~150 days) ranged from 6 to 9 kg N ha^{-1}. With such small amounts of N released from incorporated residue, a benefit of significant savings in fertilizer N is unlikely. Moreover, crops in the majority of experiments with incorporated residue receive recommended or adequate amounts of fertilizer N, P, and K, suggesting the increases in yield of crops with incorporated rice residue were most likely not related to the contribution of macronutrients contained in the residue (Bijay-Singh *et al*., 2008).

On-Farm Management of Crop Residues

Recycling of rice residue poses more problems to succeeding wheat than wheat straw to the following rice crop because of the shorter window between rice residue incorporation and wheat sowing, and the slow rate of decomposition of rice straw due to high silica content and low temperature.

In Situ Incorporation of Rice Straw

While soil incorporation of CRs is beneficial in recycling nutrients, ploughing under requires energy and time, leads to temporary immobilization of nutrients (e.g., N), and the high C:N ratio needs to be corrected by applying extra fertilizer N at the time of residue incorporation (Yadvinder-Singh *et al*. 2005, Bijay-Singh *et al*. 2008). A crop grown immediately after the incorporation of residues suffers from N deficiency caused by microbial immobilization of soil and fertilizer N in the short term. The duration of net N immobilization and the net supply of N from CRs to a subsequent crop depend upon decomposition period prior to planting next crop, residue quality, and soil environmental conditions (Yadvinder-Singh *et al*. 2005). In a long-term study, yields of rice and wheat crops decreased with the incorporation of CRs immediately before planting of the next crop over the residue removal treatment (Beri *et al*. 1995, Sidhu and Beri 1989). Rice straw can be managed successfully *in situ* by allowing sufficient time (10-20 days) between its incorporation and sowing of the wheat crop to avoid N deficiency due to N immobilisation (Yadvinder-Singh *et al*., 2004b). However, the practice of *in situ* rice straw incorporation as an alternate to burning has been adopted by only a few farmers because of high incorporation costs and energy and time intensive. Furthermore, incorporating rice residue before wheat planting results in 2-3 weeks delay in sowing (Thuy *et al*. 2008, Yadvinder-Singh *et al*. 2004b). Prasad *et al*. (1999) evaluated three practices of crop residue management, namely, residue removal, residue burning and residue incorporation in rice-wheat system. Results obtained showed that both rice and wheat residues can be safely incorporated without any detrimental effects on the crops of rice or wheat grown immediately after incorporation. Application of rice residue to wheat typically has a small effect on wheat yields during the short term of 1-3 years (Bijay-Singh *et al*. 2008, Yadvinder-Singh *et al*. 2005) but the effect appears in the fourth year with the incorporation of straw (Gupta *et al*. 2007).

Rice Straw Mulching in Wheat

Emerging CRM options in the IGP to avoid burning are to mulch with rice straw in no-till wheat and incorporate combine-harvested or even manually harvested (as in the Middle and Lower IGP) wheat straw and stubble (1-2 t ha^{-1}) in rice (Bijay-Singh *et al*., 2008; Sidhu *et al*. 2010). CRs retained on the soil surface provide soil and water conservation benefits, and increase subsequent crop yield. Conservation of soil and water resources is of paramount importance for sustaining cropland productivity in many semiarid environments. In these areas, as much as 50% of total evapotranspiration from a crop can be lost through evaporation from the soil surface (Unger and Stewart 1983). In fact, apart from adjusting the growing period of crops, as has been done for rice in Indian Punjab, mulching is the only practice that reduces the evapotranspiration by decreasing evaporation (Prihar *et al*. 2010). When all CRs are used as animal feed or removed for other purposes, the above benefits are lost. As a result, sustaining soil productivity becomes more difficult. However, it is possible to sustain crop production by using appropriate alternative practices, such as retaining partial residues, replacing the nutrients harvested in grain and CRs, growing forages that substitute for CRs, and adopting CA practices. Improvements in crop management, leading to greater CR production, may allow sufficient residues to be returned to fields and some to be removed without adversely affecting the soil environment.

Zero-till wheat has been adopted on a significant area in the RW system in the NW IGP with positive impacts on wheat yield, profitability, and resource-use efficiency (Erenstein and Laxmi 2008, Ladha *et al*. 2009). It has not been possible to manage CRs in no-till systems with tine-type openers. Loose straw accumulates in the seed drill furrow openers, the seed metering drive wheel loses traction due to the presence of loose straw and the depth of seed placement is non-uniform due to frequent lifting of the implement under heavy trash conditions. The potential benefits of no-till can be fully realized only when it is practiced continuously and the soil surface should remain covered at least 30% by previous CR. The use of new-generation planters (Happy seeder) will lead to wider adoption of conservation agriculture in the region (Sidhu *et al*., 2007). The Happy seeder works well for direct drilling in standing as well as loose residues, provided the residues are spread uniformly. Data from 154 on-farm trials conducted during 2007-10 in different districts of Punjab showed that weighted average wheat yield for HS sown plots was significantly more (3.24%) than the conventionally sown wheat (Table 1). Chakraborty *et al*. (2008, 2010) reported that rice straw mulch increased wheat grain yield, reduced crop water use by 3-11% and improved WUE by 25% compared with no mulch. Mulch produced 40% higher root length densities compared to no-mulch in lower layers (>0.15 m), probably due to greater retention of soil moisture in deeper layers. Combining the reduced tillage and in-situ incorporation of rice crop residues (5 Mg ha^{-1}) along with 150 kg N ha^{-1} were optimum to achieve high yields of wheat after rice in sandy loam soils of Indo-Gangetic plains of India (Gangwar *et al*. 2006). Wheat yield, however suffered under ZT due to soil compaction, possibly due to restricted oxygen supply to root zone, which adversely affected vigorous plant growth.

Fig. 2: Happy seeder sowing wheat into rice residue (8.5 t ha^{-1}) after uniform distribution of residue

Table 1: Performance of zero-till wheat sown into rice residue using Happy Seeder vis-à-vis conventional- till wheat on farmer's fields in Punjab during 2007-2010

Year	No. of expts	Grain yield (t/ha)		% increase in yield with HS over CT
		Happy seeder (HS)	Conventional till (CT)	
2007-08	46	4.59	4.50	2.0
2008-09	14	4.54	4.34	4.6
2009-10	94	4.42	4.30	2.8
Mean	(154)	4.56	4.42	3.24

Source: Sidhu *et al*. (2011)

Rice residue management in no-till systems (surface retention) provides multiple benefits, including soil moisture conservation, suppression of weeds, improvement in soil quality (Balwinder-Singh *et al*. 2011a, Ram *et al*. 2013; Kumar *et al*. 2013; Singh *et al*. 2005; Verhulst *et al*. 2011), reduction in greenhouse gas emissions equivalent to nearly 13 t ha^{-1} (Mandal *et al*. 2004), and regulates canopy temperature at the grain-filling stage to mitigate the terminal heat effects in wheat (Gupta *et al*. 2010; Jat *et al*. 2009), and significantly improves the C sustainability index (Jat *et al*. 2011). The suppression of weeds with straw mulch might help reduce herbicide requirements (Yadvinder-Singh *et al*. 2010b). The magnitude of the beneficial effects associated with returning CRs to fields depends on the quantity and quality of the residue, the subsequent crop to be grown, edaphic factors, topography, climate and soil management. Conservation of soil moisture by the mulch on the irrigation water input to wheat can be observed when irrigation is based on soil matric potential (SMP) instead of applications at critical growth stages without taking soil water status into account.

Balwinder-Singh *et al*. (2011a) found that, when wheat was irrigated based on SMP, mulch (8 t ha^{-1}) conserved soil water and delayed the need for irrigation, and resulted in a saving of 75 mm of irrigation water (one irrigation) compared with no mulch. The results of model simulations (Balwinder-Singh *et al*. 2011b) suggested that, with mulch, one-irrigation would be saved in about 50% of the years. From a three-year study, Ram *et al*. (2013) showed that under limited irrigation water conditions, rice straw mulching increased yield and water use efficiency in wheat. When wheat is sown with HS after rice harvest in the residual soil moisture eliminates the need for pre-sowing irrigation (Yadvinder-Singh *et al*. 2010b). Sowing wheat in the residual soil moisture without pre-sowing irrigation will save about 20% in irrigation water, which would help to save 80 kWh of electricity and reduce emission of 160 kg of CO_2. These limited studies suggest the need for more research to develop irrigation water scheduling based on SMP for ZT wheat with mulch conditions to reduce irrigation water requirement. Similar principle will apply when ZT direct seeded rice is sown with mulch. The major demerit of the Happy seeder is its inability to work in the early morning and late evening hours when straw is wet with dew, thus limiting its practical use to only a few hours of the day during the peak period of wheat sowing. Its high cost is another prohibitive factor. The work is in progress to reduce the power requirement and increase the working efficiency of the machine.

Wheat Straw Mulching in Rice

There are few reports of evaluation of mulching for rice in India and most of the studies are reported from China, where considerable input water savings of 20-90% occurred with straw mulch in combination with aerobic culture compared with continuously flooded transplanted rice (Shen and Yangchun 2003). Much of the water savings was probably due to higher percolation losses in the flooded systems (Lin *et al*. 2003). In Mulching system, soil is irrigated to approximately 80% of water-holding capacity. In residue retained fields direct seeded rice can be sown directly by using Happy Seeder machine to realize the potential benefits from mulching (Gathala *et al*. 2013). Residues must be carefully managed for obtaining positive effects on soil and crop production and avoiding negative effects such as interference with the planting of crops, N immobilization, and emission of greenhouse gases.

Management of Wheat Straw in Rice

Many farmers in NW states of the IGP after harvesting wheat grains, collect wheat straw with specially designed machine for using it as fodder leaving behind about 20 to 25% (1.5-2.0t/ha) wheat straw in the field. The wheat straw left on the field is also burned before preparing for rice transplanting. Farmers have the apprehension that wheat stubbles will adversely affect the rice yield. A 3-year field study conducted by the Department of Soil Science, PAU Ludhiana, however, showed no adverse of incorporating partial wheat residue on rice yield (HS Thind, personal communication). The role of green manure for improving the sustainability of soil N fertility in lowland rice has been established by

Yadvinder-Singh *et al*. (1991). A fallow period of about 60-65 days is available after the harvest of wheat, which can be utilized for raising pre-rice sole green manure crop or dual purpose short duration pulses like mungbean (*Vigna radiata*) for pulse grains and green manuring (Yadvinder-Singh *et al*. 1991). Aulakh *et al*. (2001) observed improved rice yield when wheat straw incorporation was combined with green manure (*Sesbania aculeata*). A long-term field study conducted on a loamy sand soil showed that integrating the incorporation of full load of wheat straw (high C:N ratio) with sesbania green manure (low C:N ratio) alleviated the adverse effect of wheat straw alone in rice in RW system (Yadvinder-Singh *et al*. 2004a). Consistent with the above study, Sharma and Prasad (2008) also reported that combining the application of wheat straw with *Sesbania* green manure or mungbean residues increased cereal grain yield and agronomic N efficiency and improved the generally negative apparent N balances. The combined use of wheat straw and mungbean produced an additional 0.5-0.6 t ha^{-1} protein-rich grain and thus appears to be the most promising residue-management option for rice–wheat cropping systems in South Asia. A study from China (Xu *et al*. 2009) showed that incorporation of wheat straw increased rice grain yield of rice by 2.65% compared with no straw.

Conservation Agriculture and Crop Residue Management

Conservation agriculture (CA) is recognized as agriculture of the future, the future of agriculture (Pretty *et al*. 2011). CA-based crop management technologies, such as no-till with residue retention and judicious crop rotation, are gaining more attention in recent years with the rising concern over degradation of natural resources, mainly soil and water, and to offset the production cost (Ladha *et al*. 2009, Saharawat *et al*. 2012). Furthermore, intensive tillage systems results to a decrease in soil organic matter due to acceleration of the oxidation and breakdown of organic matter and ultimately degradation of soil properties (Biamah *et al*. 2000, Gathala *et al*. 2011). To harness the full potential of CA, not only residue will have to be used as soil surface mulch but also rice will have to be brought under zero tillage.

Table 2: Effect of tillage and rice straw mulch on wheat yield (t/ha) in rice-wheat system (data average for two years) (HS Thind and associates, PAU Ludhiana)

Rice treatments	Wheat treatments		
	CT	ZT-rice straw removed	ZT + rice straw mulch (HS)
Conventional-till (CT) direct seeded rice (DSR)	5.05	4.03	5.17
Zero-till (ZT)-DSR	5.25	3.56	5.09
CT-Puddled trans-planted rice	4.98	4.48	5.25
Mean	5.09a*	4.02b	5.17a

*Values in the row followed by same letter not differ significantly $P \leq 0.05$

Ensuring good seed germination and crop stand establishment are major challenges to be addressed with CA and CRM. Agronomic productivity and profitability are high with use of CRs in conjunction with no tillage in CA. A two-year study on sandy loam soil at PAU Ludhiana showed that mean grain yield of wheat increased by 43% with straw mulching compared to no mulch under double ZT system (Table 2). On the other hand, the increase in wheat yield due to rice straw mulch in CT-puddled transplanted/ CT-direct seeded rice compared to no mulch was small (2.4-5.4%). Recently, Gathala *et al*. (2013) demonstrated the positive effects of managing wheat straw in direct seeded rice and the rice straw in wheat on system productivity and water use efficiency in the rice-wheat system under permanent zero-till system. However, Gangwar *et al*. (2006) demonstrated that reduced tillage resulted in significantly higher overall mean wheat yield compared to conventional and zero tillage.

Fertilizer Management Practices

Rice residue adds 35-45 kg N ha^{-1} and is a key consideration when attempting to optimize N fertility in conservation tillage systems. Nitrogen management for no till wheat with rice residue retained as mulch and following rice may differ from that where residue has either been removed or burned *in situ*, and is poorly documented in the irrigated RW systems of IGP. One factor that continues to be a problem in high residue no-till farming systems is N management. Studies in the literature (Yadvinder-Singh *et al*. 2005, and the references therein) suggest application of 20-40 kg ha^{-1} more N the first few years after residue incorporation due to tie-up and volatilization loss of N, especially with surface broadcasting of urea on fine- to medium-textured soils. Later on, recommended fertilizers may be needed to achieve higher yield productivity of RW systems. Previous results concerning the N fertilizer value of crop residues showed highly variable results; many studies suggested that it was not possible to substitute a part of fertilizer N without adverse effects on rice yield (Yadvinder-Singh *et al*. 2005). Results from a number of field experiments showed that wheat shown into rice residue generally responded to the application of N up to 120 kg N/ha similar to that recommended for conventionally sown wheat (Yadvinder-Singh *et al*. 2010b). Another 3-year study by Yadvinder-Singh *et al*. (2009) showed that response to N application was not influenced by straw and tillage treatments.

No-till systems with surface residue often exhibit suppressed yields due to lesser N availability because of slower soil N mineralization, greater N immobilization, denitrification and NH_3 volatilization, particularly in the early part of the growing season compared with conventional-till systems (Patra *et al*. 2004). Proper management of fertilizer N should reduce immobilization of N by CRs and produce higher N-use efficiency. Reducing fertilizer N contact with the straw by drilling the fertilizer below the soil surface (about 5 cm beside and/or below the seed row) to minimize immobilization and volatilization may increase N use efficiency in wheat.

Rahman *et al*. (2005) observed a significantly larger apparent recovery of fertilizer N under mulch than non mulch conditions possibly due to reduction in fertilizer N losses. The build up of soil organic matter and increase in readily mineralized organic soil N with residue recycling suggest the potential for reducing fertilizer N rates for optimal yield of following crop after several years of residue incorporation (Eagle *et al*. 2001, Thuy *et al*. 2008, Yadvinder-Singh *et al*., 2009). Therefore, adjustments in timing and rate of fertilizer N are likely necessary to optimally supply N to crops receiving residues. Greater immobilization in reduced and no-till systems can enhance the conservation of soil and fertilizer N in the long term, with higher initial N fertilizer requirements decreasing over time because of the build-up of a larger pool of readily mineralizable organic N. This transition period may vary from 4-6 years, during which band placement of nutrients below the residue-covered surfaces becomes very important. Studies conducted on two soil types in the IGP of NW India showed that grain yield of following rice increased by about 10% three years after continuous straw mulching in wheat compared to removal/burning of rice residue (Yadvinder-Singh, unpublished data). A 3-year study showed that fertilizer N required for rice to achieve the target agronomic efficiency of N was typically reduced when rice residue was incorporated before wheat. In a long-term field study on RW system at Ludhiana (H.S. Kalsi PAU Ludhiana, personal communication) it was found that the incorporation of rice straw in wheat for three years had no wheat yield advantage. However, the yield of following rice crop, with the application of 90 kg N/ha was found to be similar to the application of 120 kg N ha^{-1} on straw removed plots, thereby saving of 30 kg N/ha. Wall (2011) has reported that in Brazil, compared to 30 years ago, farmers have doubled the yield of maize and increased the yield of soybean by 50% with application of 30% less fertilizers by adopting CA.

In CA system, broadcasting N onto the residue covered surface is an inefficient method of application because of the potential for immobilization by surface residues and volatilization losses of N. This placement method quickly exposed volatilization problems. One obvious solution to the volatilization and N immobilization problems would be to place the fertilizer in bands below the C-enriched surface soil that results from surface placement of CRs. There is increasing interest in applying all needed nutrients in a one pass seeding and fertilizer operation involving placement of the fertilizer to the side and below the seed row or else mid-row banded between every second seed row (Yadvinder-Singh *et al*. 1994). One-pass seeding and fertilizing (as side band, or mid-row band) NT system is now regarded as a highly efficient way of managing N fertilizers for achieving high N use efficiencies by minimizing the nutrient loss and immobilization so common with broadcast application (Malhi *et al*. 2001). However, management of high rates of fertilizers applied along with seed, especially N, often discourage farmers from adopting a one-pass production system. This has prompted considerable research to determine how much fertilizer can be safely applied with the seed in ZT-wheat. For seed-row placement, application of DAP (130 kg ha^{-1}) along with 56 kg urea ha^{-1} showed no adverse effect on grain yield of wheat. Further increase in urea dose along with DAP adversely affected germination and grain yield of wheat (Sidhu HS and co-workers, unpublished data). Seeding openers adjustment was made in the Happy Seeder that allows placement of fertilizer in a separate band between two rows of wheat to avoid seed germination and emergence problems. Results from field trial evaluation of these openers indicates that up to 80% of fertilizer N dose recommended for wheat (120 kg N ha^{-1}) along with P and K fertilizers can be drilled at seeding with significant increase in grain yield over the recommended practice of broadcast application in two equal splits (H S Sidhu, personal communication). Factors that influence how much fertilizer can be safely applied with the seed include: row spacing, width of seed row, soil texture, moisture, organic matter, fertilizer placement, seed furrow opener, source, and crop.

The adjustments in the timing of inorganic fertilizers should be made to synchronize nutrient supply and crop demand under residue retention (Thuy *et al*. 2008). Allowing adequate time for decomposition of CRs before planting of the next crop has helped in alleviating adverse effects due to N immobilization (Yadvinder-Singh *et al*. 2004b). A 3-year field study showed that N application in 3 splits doses (25 kg N/ha as DAP drilled at sowing and top dressing 48 kg Nha^{-1} each before first irrigation and second irrigation) resulted in significantly higher grain yield (4.79 t ha^{-1}) and N use efficiency (56.7%) compared to recommended practice of two equal splits at sowing and with the first post-sowing irrigation (Yadvinder-Singh *et al*. 2010b).

In no-till system, as plant residues decompose, nutrients are released into the soil, with greater levels at the soil surface than conventional till systems. This cycle is repeated each season and is compounded by surface fertilization, creating a soil surface (0-5 cm) rich in nutrients, but depleted at depth. Certain nutrients, such as P, are less mobile than others (e.g. N) and tend to accumulate in surface layers due to lack of soil mixing. How the differences in soil P and K stratification between tillage systems will affect nutrient uptake by wheat is not yet studied in India? Mineralization of organic N, P, and S can be a major source of plant available nutrients near the surface of no-tilled soils.

Crop Residues as Surface Mulch in Other Crops

The rice straw can be used as mulch for other crops. The beneficial effects of this practice to improve crop yields at comparable irrigation regimes and saving of irrigation water and fertilizer nitrogen at comparable yields have been reported in several crops e.g. in forage maize, sugarcane, sunflower, soybean, potato and chillies by reducing the evaporation (E) component of the ET and acting as barrier to vapour flow, and moderating soil temperature (Arora *et al*. 2011, Jalota *et al*. 2007, Sekhon *et al*. 2008, Yadvinder-Singh *et al*. 2010b). The magnitude of yield gain in different crops ranged from 4 to 29% and saving of irrigation water from 7 to 40 cm. The variation in yield response to mulching depended upon the atmospheric temperature, frequency and amount of rainfall and soil texture. The response is more under high temperature, low rainfall year and on coarse texture soils. Higher soil water in the profile, especially the root zone, in the mulched plots caused better stand establishment, and early seedling vigour. Straw mulching economized fertilizer N for comparable crop yields amounting to 25 kg N ha^{-1} in Japanese mint, 50 kg in forage maize, and 30 kg N ha^{-1} in Chilli. More favourable soil temperature and higher water content under mulched than un-mulched soil increases mineralization of soil N. Due to the scarcity of labour and high cost involved in collection and applying straw mulch, this technology has not become popular with the farmers.

Crop Residues as Biochar

Biochar is produced via the burning of waste biomass at 300-600ºC in the partial or complete exclusion of oxygen, a process is known as pyrolysis. Due to the relatively stable biological state of biochar, its production for soil application has been proposed as a way of diverting waste biomass carbon from a rapid to a slow carbon-cycling pool in soil. In recent years, increased concerns for healthy food production and environmental quality and increased emphasis on sustaining the productive capacity of soils have raised interests in the maintenance and improvement of soil organic matter through appropriate land use and management practices (Whitbread *et al*. 2003, Puget and Lal 2005). In the past few years, there has been growing interest in the use of synthetic biochar as an amendment worldwide. Application of synthetic biochar in soil may provide a novel soil management practice because of its potential to improve soil fertility, enhance soil carbon, mitigate soil greenhouse gas emissions, reduce leaching of nutrients and chemicals, increase fertiliser use efficiency, and enhance agricultural productivity (Lehmann *et al*. 2006, Chan *et al*. 2007). Enormous quantities of rice straw, rice husk and other surplus residues available in the NW region of India could potentially be pyrolysed to produce bioenergy, thereby reducing field burning and the use of fossil fuels, and the biochar by-product could help to improve soils, avoid methane emissions, and sequester carbon in soils. However, if massive residue exports occurred without compensations, this could result in impoverished and eroded soils, and ultimately lower food crop yields.

Thind *et al*. (2012) showed that application of rice husk ash, and baggasse ash of sugar factory improved available nutrients and crop yields in RW system on a loamy sand soil of Punjab, India. Haefele *et al*. (2011) concluded that biochar from rice residues can be beneficial in rice-based systems but the actual effects on soil fertility, grain yield, and soil organic carbon will depend on site-specific conditions. The increase in crop yield with biochar application has been reported elsewhere for upland rice (Asai *et al*. 2009).

Because of its reactive surfaces and recalcitrant aromatic structure; soil biochar can influence a number of biogeochemical processes and serves as a sink for atmospheric CO_2. Upon pyrolysis of waste biomass; about 50% of carbon in biomass is immediately released which can be used for energy production to offset fossil fuel use, leaving a biochemically recalcitrant biochar residue (Lehmann *et al*. 2006). While 80-90% of biomass carbon in original form is emitted as CO_2 within 1-10 yrs, depending on the soil and climatic conditions, biochar offers significant prospects for sequestering about 40-50% of original biomass carbon in soil in a chemically altered form that is biologically stable and could last in soil for centuries, but remaining physically and chemically active. The recalcitrant nature of biochar makes it a suitable organic amendment with potential for large greenhouse mitigation benefits, but little research has been undertaken to document such benefits. Specifically, there is need to evaluate the decomposition and stability of biochars in soils, especially in field situation, where plant roots can make significant differences in soil conditions, as opposed to using sieved soil, or organic-matter free sand, under laboratory conditions. Due to its greater stability against microbial decomposition and its superior ability to retain nutrients compared to other forms of soil organic matter, applying biochar to soil also offers a significant potential for mitigating climate change and enhancing environmental quality. Biochar can stimulate native soil microbial activity (Hamer *et al*. 2004), provide favourable habitat for microbes, and encourage mycorrhizal fungal colonisation for improved plant water and nutrient supply (Warnock *et al*. 2007) and may promote rhizobia for N_2 fixation in leguminous plants. Currently, very little research has been done on various aspects of biochar application in different cropping systems in India. There is a need to evaluate and maximise the benefits of biochar application on soil health, carbon sequestration and nutrient use efficiency in different soils under different cropping systems. Evidence from limited research done in other parts of the world has shown that application of synthetic biochar can potentially resolve these issues (Lehmann *et al*. 2006; Liang *et al*. 2006; Bhupinderpal-Singh and Cowie, 2008; Chan *et al*., 2007). Long-term studies on biochar in field trials seem essential to better understand biochar effects and to investigate its behaviour in soils. Information regarding biochar function and its interactions with nutrients and crop roots may enable fertilizer use efficiency to be improved, with concomitant benefit to minimize air and water pollution. Quantification of the role of biochar with respect to soil physical properties (water infiltration, water retention, macroaggregation, and soil stability) would enable prediction of beneficial properties, and selection of biochar with particular properties for use in specific soil and climatic conditions. Published data for the effect on trace gas emission are extremely limited, but this could have an important effect in determining the long-term effect of biocharon net greenhouse gas balance.

Crop Residues and Bioenergy Options

An emerging issue in CRM is its potential use in the production of bioenergy. There are different ways in which CRS in RW cropping systems might be used as biofuel (i.e., the conversion of biomass to liquid fuel) or as source of biopower (i.e., the conversion of biomass to electricity) (Bijay-Singh *et al*. 2008). The main biofuel option for CRs is cellulosic ethanol production, which involves enzymatically breaking down the cellulose in the straw into its component sugars, which can then be fermented to ethanol. One of the biopower options is combustion - the burning of straw alone (direct-firing) or in combination with coal (co-firing) to produce steam to drive a turbine that turns an electricity generator. Other biopower options are gasification - in which straw is heated in the presence of limited O_2 to form a gas mixture of N_2, H_2, CO, and CO_2 known as producer gas or synthesis gas, and pyrolysis - in which straw is heated excluding O_2 to form a high-energy liquid. Either the gas produced by gasification or the liquid produced by pyrolysis can be burned to produce electricity. Anaerobic digestion of CRs produces biogas, in which straw is mixed with other wastes, such as manure, and allowed to decompose anaerobically and burned to produce electricity. In any of the biopower systems, some ash or slag made up of the straw components that do not readily burn or gasify such as Si, K, Cl, and small quantities of other mineral nutrients will remain after the thermal conversion process (Arvelakis and Koukios, 2002). Biomass densification represents a set of technologies for conversion of biomass into a fuel and briquetting is one of them (Yadvinder-Singh *et al*. 2010b). Majority of CRs, particularly rice straw as such is an inefficient fuel source when used in furnace or domestic cooking devices. The calorific value of rice straw is quite low (14-16 MJ kg^{-1}) compared to steam coal. Bailing of rice straw with the help of balers for use in the cardboard and paper industry seems to be another viable option in the future provided balers are available at an affordable price or custom hiring is encouraged. However, cereal straws have relatively high silica and potassium content. Wheat straw contains 4-8% silica, and rice straw has higher silica content of 9-14%. For using in paper and pulp production CRs are pre-treated with alkali for removal of ash/silica.

According to Bijay-Singh *et al*. (2008) the potential bioenergy applications have three serious implications for CRM if widely adopted: (1) residue would be removed rather than returned to the soil, (2) harvesting and threshing techniques would need to be considerably modified to make it feasible to collect the residue for transportation, and (3) it would become important to grow varieties with desirable straw characteristics. At present, total potential for rice straw utilization for bioenergy production may not be more than 10% of the total residues produced in the state. It would be better for the sustainability of RW cropping system if the residues are retained rather than removed for bioenergy conversion. The partial removal of residue in RW system might be feasible without jeopardizing sustainability provided inputs of K, S, and other nutrients are suitably adjusted to compensate for those removed with residue.

Other Uses of Crop Residues

Rice straw can be converted into high-value manure of better quality than FYM, and its use, along with chemical fertilizers, can help sustain or even increase the agronomic yield (Sidhu and Beri 2005). The potential of composting to turn on-farm waste materials into a farm resource makes it an attractive proposition. During composting rice straw can be fortified with P using indigenous cheap source of low grade rock phosphates to make it value added compost with 1.5% N, 2.3% P_2O_5 and 2.5% K_2O (Sidhu and Beri 2005). Small farmers without manual labour constraints are most likely to benefit from composting technology. The rice residue can be composted by using it as animal bedding and then heaping it in dung heaps. Each kg of straw can absorb about 2-3 kg of urine from animal shed. The residues of rice from one ha give about 3.2 tones of manure as rich in nutrients as FYM. But farmers do not appreciate the collection of the residues manually for the purpose.

Crop Residue Management and Soil Health

Soils in the IGP contain low organic matter content and are being consistently depleted of their finite reserve of nutrients by crops (Bijay-Singh *et al*. 2004). Excessive nutrient mining of soils is one of the major causes of fatigue experienced by soils under the RW system. The quantities of nutrients removed by rice and wheat are greater than the amount added through fertilizers and recycled. Removal of all the straw from crop fields leads to K mining at alarming rates because 80% to 85% of the K absorbed by the rice and wheat crops remains in the straw (Bijay-Singh *et al*. 2004). The long-term sustainability of RW cropping system depends on its carbon inputs, outputs, and carbon-use efficiency. Practices that increase organic matter addition to the soil through exogenous supply, or on-farm recycling improve soil fertility and crop productivity. There are numerous benefits of residue retention on cropland, especially if maintained as surface mulch and combined with direct seeding of crops without 'normal' tillage. Prasad *et al*. (1999) showed that incorporation of crop residue also improved soil fertility status as judged by organic carbon and available P and K contents. Residues retention improves soil physical (e.g., structure, infiltration rate, plant available water capacity), chemical (e.g., nutrient cycling, cation exchange capacity, soil reaction), and biological (e.g., SOC sequestration, microbial biomass C, activity and species diversity of soil biota) quality (Beri *et al*. 1992, 1995, Bijay-Singh *et al*. 2008, Power *et al*. 1986, Singh *et al*. 2005). CRs are also known to enhance dinitrogen fixation in soil by asymbiotic bacteria (*Azotobacter chroococcum* and *A. agilis*). There are few studies from India focusing on the changes in soil biological health under tillage and CRM systems. Data collected from 51 fields in Ludhiana and Sangrur districts of Punjab in 2011 showed that soil strength (kPa) in the 15-25 cm soil layer was 25% higher in conventional tillage (CT) fields compared to ZT wheat sown into rice residue using HS. Hydraulic conductivity and infiltration rate (final infiltration and the total infiltration) are higher in residue retention compared to CT due to the larger macropore conductivity as a result of the increased number of biopores that is commonly observed. The retention of rice residue in wheat may help reduce the adverse effects of hard pan in the RW system and benefit the wheat crop (Singh *et al*. 2005).

Long-term straw application will build soil organic matter level and N reserves, and also increase the availability of macro- and micro-nutrients (Yadvinder-Singh *et al*. 2000, 2005). Increase in rate of application of C in the form of CRs increases the SOC pool. The magnitude of increase in SOC pool, however, depends on other management options used in conjunction with CRs. On the basis of changes in soil C values and the amount of C applied, 12-25% of applied rice straw-C (incorporated into the soil) was sequestered by the loamy sand soil after 3-7 years (Yadvinder-Singh *et al*. 2004b, 2009). Carbon management index (CMI), a multiplicative function of carbon pool index (CPI) and lability index (LI) is more sensitive to changes in soil management than total organic carbon (Blair *et al*. 1995). Soils have a high C sink capacity, however, sink capacity and/or sequestration rate cannot continue indefinitely (Six *et al*. 2002). Rates of C sequestration are highly influenced by soil type and climate (West and Post 2002). Each ton of organic carbon in the plow layer is equivalent to 4.75 kg fertilizer N ha^{-1} (Benbi and Chand 2007). The critical level of C input requirement for maintaining SOC at the antecedent level has been calculated as 2.47 t ha^{-1} $year^{-1}$ for rice-based systems (Srinivasarao *et al*. 2013). Sequestration of soil organic carbon would: (1) help mitigate greenhouse gas emissions contributing to global warming and (2) increase soil productivity and avoid further environmental damage from the residue burning and unsustainable use of intensive tillage systems. Carbon credit trading will provide an economic opportunity for farmers to adopt these ecologically based approaches to farming.

Incorporation of residues of both crops in the RW cropping system for 11 years increased the total P, available P, and K contents in the soil over the removal of residues (Sidhu and Beri 2005). Besides a direct supply of P, CRs can lower the P sorption capacity and enhance nutrient availability. It is not surprising that crop residue retention can substitute a significant part of fertilizer K, as the rice straw at maturity contains over 80% of the total plant K (Bijay-Singh *et al*., 2008). As crop residues are poor with respect to P content, crop residue retention is unlikely to substitute significant amounts of fertilizer P (Yadvinder-Singh *et al*. 2005).

Gupta *et al*. (2007) calculated negative P balance in RW system when rice straw was removed but when the straws of both crops were incorporated, the P balance was positive, at the recommended P management of applying 26 kg P ha^{-1} to only wheat. Incorporation of residues increased inorganic and organic P, reduced P sorption, and increased P release. Data showed continuous incorporation of residues substituted for 13 kg inorganic P ha^{-1} $year^{-1}$. Rice and wheat residues are rich sources of K and releases about 70% of K within 10 days after incorporation into the soil (Yadvinder-Singh *et al*. 2004b, Yadvinder-Singh *et al*. 2010a). About 50-80% of micronutrient cations (Zn, Fe, Cu and Mn) taken up by rice and wheat crops can be recycled through incorporated residue. CRM influences availability of micronutrients such as zinc and iron in rice (Yadvinder-Singh *et al*. 2005 and references therein, Gupta *et al*. 2007). Studies conducted by Singh *et al*. (2011) showed that application of 2.5 kg Zn ha^{-1} once with first crop and 50% of crop residue of every crop was more effective than 10 kg Zn ha^{-1} application alone as starter dose which shows that substantial amount of Zn can be saved by the residue incorporation. Thus crop residue recycling might result in significant increases in their concentrations in edible plant products, contributing to consumers' health. Retention of CRs can also help to reduce soil salinity and sodicity. The crop residues also play an important role in amelioration of soil acidity through the release of hydroxyls especially during the decomposition of residues with higher C:N ratios.

Impact of Crop Residue Management on Pest and Disease Pressure

Crop residue mulch has the potential to control weed growth (Erenstien, 2002; Sidhu *et al*. 2007), thereby suppressing the possible negative effect of increased weed intensity in reduced and no tillage systems. Mulch controls weed growth by shading or through allelopathic effects (Erenstien, 2002; Kamara *et al*., 2000), and it might reduce herbicide requirements and weed competition for nutrients and water. Increasing the amount of rice residue as mulch in wheat can increase the suppression of weeds. Many others have also reported significant and sometimes very large reductions in weed biomass with mulch (Rahman *et al.* 2005; Sidhu *et al*. 2007). Gangwar *et al*. (2006) recorded the higher dry weight of weeds (0.22 Mg ha^{-1}) under residue incorporation compared with residue burning or removal. The weed dry weight at 30 days after sowing was 87.5 higher under zero tillage and lowest under conventional tillage.

The retention of plant residues on the soil surface has frequently been associated with an increased incidence of crop diseases (De Boer *et al*. 1993). Retaining residue as mulch in no-till systems can further exacerbate soil-borne diseases because of the lack of soil disturbance and retention of crop stubble on the soil surface. Periodic residue incorporation in a no-till system can inhibit pathogen growth by forcing it into a place with insufficient air and light, but residue incorporation is not considered as effective as crop rotation at controlling disease. In addition to residue-borne diseases, mulch can also favour the survival of some soil-borne pathogens because the pathogens are protected from microbial degradation by residence within the crop debris (Bijay-Singh *et al*. 2008). Their growth is aided by the lower soil temperature, increased soil water, and reduced soil disturbance associated with mulch. The crop residue can serve as an inoculums source and maintain favourable moisture and temperature conditions in the top 10-15 cm of soil where the pathogens are most active (Cook 2001). Highest infection percentage for the brown foot rot diseases has been observed when winter wheat was sown directly into the stubble (Sawinska *et al*. 2006). On the other hand, mulch may suppress other soil-borne pathogens, because it increases the population of soil micro- and meso-fauna, which offer potential for biological disease control as many of these species feed on pathogenic fungi. In one of the few studies of residue effects on disease in rice-based cropping systems, wheat planted into no-till rice residue had the lowest incidence of Tilletia indica (Karnal bunt) infection (Sharma *et al*. 2007). There are few reports of increased insect (pink stem borer) infestation in wheat sown into rice residue as mulch. The decomposition of residues along with several inter-related factors like climate, crop geometry, irrigation and fertilization, cultural practices and pesticides may affect the survival of insects in crop residues. Surekha *et al*. (2003) observed higher crop damage by yellow stem borer with straw + green manure in rice, apparently due to high quantity of N applied through crop residues and fertilisers in rice-rice system. Decisions on crop residue management should be made keeping in view the health of previous crops, the potential susceptibility of subsequent crops, cultivar selection, and planting date (Kumar and Goh 2000). It is possible that there would be fewer mulch-related disease problems in a rice-wheat crop rotation than in a rotation of two different upland crops (e.g. maize-wheat, cotton-wheat), because the flooded season might inhibit survival of the upland crop pathogens. If disease and insets can be adequately controlled by crop rotation and economic use of pesticides, mulching would become an attractive residue management option for mitigation of pest pressure in the wheat crop of rice-wheat cropping system. The effects of residue management and tillage on pests and diseases in rice-based cropping systems have not received much attention, and systematic work with different management options is needed.

Crop Residue Management and Green House Gas (GHG) Emission

Short-term effects of cereal residues (wheat straw) incorporation into paddy field include stimulation of CH_4 emissions, immobilisation of available N, suppression of rice growth, and accumulation of toxic materials (Yadvinder-Singh *et al*. 2005; Bijay-Singh *et al*. 2008). Incorporation of cereal residues into paddy fields at optimum time before rice transplanting can help in minimizing the adverse effect on rice growth and CH_4 emissions. The incorporation of wheat straw before transplanting of rice showed no significant effect on N_2O emission due to immobilization of mineral N by high C/N ratio of the straw incorporated (Ma *et al*. 2007). However, an increase in N_2O emission from fields with mulch compared to those with incorporated residue has been observed in subtropical Asian rice-based cropping systems (Baggs *et al*. 2003). This mulch effect is the result of higher water content under mulch, which leads to more anaerobic conditions, promoting denitrification (Aulakh *et al*. 1984). Baggs *et al*. (2000) speculated that timing residue return such that the N becomes available when needed by the upland crop should minimize N_2O emission as compared with residue return at the beginning of the preseason fallow. CRM is unlikely to have significant overall effects on CH_4 emission in upland crops like wheat. For any CH_4 to be produced, there must be at least a small number of anaerobic microsites for methanogenic bacteria to grow, so any treatment that makes the soil more anaerobic is likely to increase the risk of CH_4 emission, including a rainfall event or mulch application. As in flooded systems, any action that causes residue to decompose before becoming anaerobic will lessen the risk of CH_4 emission. From the perspective of mitigating GHG emissions from wheat crop in RW cropping system, residues are not the primary crop management concern. When soil is at or near field capacity, there would be such little CH_4 formation and N_2O emission and the effect of CRM would be negligible (Bijay-Singh *et al*. 2008). Neither mulch nor incorporation of rice residue into wheat crop would be expected to have very significant impact on CH_4 emission in the following rice crop, because the incorporated or mulched residue would decompose considerably during the upland crop season (Abao *et al*. 2000).

Summary and Conclusions

Conventional agronomic practices cannot meet the triple objectives of (i) producing enough food for the burgeoning population, (ii) minimizing agriculture-induced degradation of natural resources, and (c) maintaining environmental quality and ecosystem services. CRs offer sustainable and ecologically sound alternatives for meeting the nutrient requirements of crops, and improving soil and environmental quality. Rice residue can be incorporated into the soil at 10-20 days before sowing of following wheat using appropriate machinery without any adverse effect on the crop. The use of tillage to incorporate rice residue is, however costly and time consuming and exacerbates the risk of late wheat planting. Recent developments in machinery (Happy Seeder) allowing zero-till sowing of wheat with rice residue as surface mulch, while maintaining yield, reduces tillage costs and time savings, avoids the need for burning. The use of CR as a mulching material has been found beneficial as it reduces maximum soil temperature and conserves water. Direct drilling of wheat into rice residue using HS is a good agronomic practice for wheat, helping to limit the gradual depletion of soil organic matter and, at the same time, improving soil health. Residues decompose rather very slowly due to reduced contact with soil and also SOM decomposition is further reduced due to zero tillage in wheat. Limiting factor in adoption of CRM systems for some farmers include additional management skill requirements, apprehension of lower crop yields and/or economic returns, negative attitudes or perceptions, and institutional constraints. Nutrient management is more complex with CRM because of higher residue levels and reduced options with regard to method and timing of nutrient applications. The complexities with N fertilizer management in no-tillage with residue mulch systems indicate the need for more research for improved and efficient utilization of fertilizer N. In fact, there is a need to develop complete package of practices (fertilizer, irrigation, weed control, pest management, etc.) for CRM systems. Genetic variation in Si content in rice straw under different soil and water management situations needs investigation. Long term studies involving multidisciplinary approaches are needed to study different issues (genotypes with more root biomass, machinery, insects, diseases, weeds, phytotoxicity, soil health, and economics) associated with CRM. Further refinements in the HS are needed for fertilizer drilling, reducing its power requirement and improving its ability to work in moist straw. For large scale spreading of CR recycling, burning of CRs should be discouraged through incentive and punishment. Machinery need to be supplied on subsidized rates and providing soft loans. Subsidies have been an important component in helping make the technology affordable during the awareness raising phase.

The desired objectives of adopting a particular CRM option can be achieved only if the management option is feasible under a given set of soil, climate, and crop management conditions; is compatible with available machinery; and is socially and economically acceptable. Future research should address how above- and below-ground decomposition processes differ for a wider range of CRs and nutrients, emphasizing both short and long-term nutrient recycling. The effects of CRM on pests and diseases in RW cropping system have not received much attention, and systematic work with different management options is needed. It is possible that there would be fewer mulch-related disease problems in the RW rotation than in a rotation of two different upland crops, because the flooded season might inhibit survival of the upland crop pathogens. There is a need to support on-farm adaptation of CRM technologies in both large and scattered small fields, and developing focused institutional and policy support including appropriate incentives for the widespread dissemination and adoption of CRM practices in the IGP.

In intensive irrigated RW cropping system of north-western and central IGP, zero-till wheat planting under rice straw mulch is spreading, with significant savings on farm energy use, cost of cultivation, and irrigation water use; increased wheat productivity and profitability; and improved soil and environmental quality. Further improvements in Happy Seeder are needed to reduce its power requirement and increase its working efficiency. Modifying combine harvester to uniformly distribute the residue in the field. Large volume and transport is a major bottleneck in using the residues where those are required. Machinery for volume reduction would facilitate the process of residue use for CA.

Yield responses to residue retention were affected by both climate and soil conditions. Furthermore, agronomic practices, particularly N management, significantly influenced yield gains under crop residue retention. Therefore, site-specific fertilizer management practices should be developed to reduce inorganic fertilizer requirement without reducing crop yields under residue retention, thereby increasing the profitability of rice production (Bijay-Singh *et al*. 2008). In addition, appropriate simulation models should be developed to provide integrated and location-specific practices for crop residue management in order to achieve the multiple goals of increasing rice yield, improving fertilizer use efficiency, and enhancing the profitability of rice production. The rice yield benefits under crop residue retention increased with increasing experimental duration, which may be ascribed to the improvement in soil fertility (Yadvinder-Singh *et al*. 2005). Long-term experiments are needed to study the impacts on residue retention on soil health, water and nutrient use efficiency, C sequestration, GHG emissions and ecosystem services. Widespread adoption of CA in the IGP will tighten nutrient (N) cycling within farms and minimize N losses from the system. Further research is needed to improve N management in CA systems. There is a need to develop crop need-based, real-time N management strategies for apply N fertilizer in RW cropping system amended with CRs with tools such as SPAD meter, Green Seeker and leaf colour chart. Legislation to impose restrictions of on-field straw burning may greatly facilitate large scale adoption of this conservation agriculture practice (NAAS 2012). Supplying machineries for CA on subsidized rates and promoting custom hiring systems for agricultural implements will also be needed for increasing the area under direct seeding of wheat into rice residues so as to avoid large scale burning of the residues by the farmers. .

References

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

Arora V K, Singh C B, Sidhu A S and Thind S S Irrigation, tillage and mulching effects on soybean yield and water productivity in relation to soil texture. *Agric Water Manage* **98** (2011) 563-568

Arvelakis S and Koukios E C Physiochemical upgrading of agro-residues as feed stocks for energy production via thermo-chemical conversion methods. *Biomass Bioenergy* **22** (2002) 331-348

Asai H, Samson B K, Haefele M S, Songyikhangsuthor K, Homma K, Kiyono Y, Inoue Y, Shiraiwa T and Horie T Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Res* **111** (2009) 81-84

Aulakh M S, Rennie D A and Paul E A The influence of plant residues on denitrification rates in conventional and zero tilled soils. *Soil Sci Soc Am J* **48** (1984) 790-794

Aulakh M S, Khera T S, Doran J W and Bronson K F Managing crop residue with green manure, urea, and tillage in a rice–wheat rotation. *Soil Sci Soc Am J* **65** (2001) 820-827

Baggs E M, Rees R M, Smith K A and Vinten A J A Nitrous oxide emission from soils after incorporating crop residues. *Soil Use Manage* **16** (2000) 82-87

Baggs E M, Stevenson M, Pihlatie M, RegarA, Cook H and Cadisch G Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant Soil* **254** (2003) 361-370

Balwinder-Singh, Humphreys E, Eberbach P L, Katupitiya A, Yadvinder-Singh and Kukal S S Growth, yield and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule. *Field Crops Res* **121** (2011a) 209-225

Balwinder-Singh, Gaydon D S, Humphreys E and Eberbach P L The effects of mulch and irrigation management on wheat in Punjab, India. Evaluation of the APSIM Model. *Field Crops Res* (2011b) **124** 1-13

Benbi D K and Chand M Quantifying the effect of soil organic matter on indigenous soil N supply and wheat productivity in semiarid sub-tropical India. *Nutr Cycl Agroecosyst* **79** (2007) 103-112

Beri V, Sidhu B S, Bahl G S and Bhat A K Nitrogen and phosphorus transformations as affected by crop residue management practices and their influence on crop yield. *Soil Use Manage* **11** (1995) 51-54

Beri V, Sidhu B S, Bhat A K and Singh B P (1992) Nutrient balance and soil properties as affected by management of crop residues. In: Proceedings of the international symposium on nutrient management for sustained productivity. Vol II (Ed: Bajwa M S) pp. 133-135. Department of Soils, Punjab Agricultural University, Ludhiana, Punjab, India.

Bhagat R M and Verma T S Impact of rice straw management on soil physical properties and wheat yield. *Soil Sci* **152** (1991) 108-115

Bhupinderpal-Singh and Cowie A L (2008) A novel approach, using ^{13}C natural abundance, for measuring decomposition of biochars in soil. In: Carbon and nutrient management in agriculture, fertilizer and lime research centre workshop proceedings Occas. Report no. 21 (Eds: Currie L D and Yates L J) pp 549. Massey University, Palmerton North, New Zealand.

Biamah EK, Rockstrom J, Okwack G (2000) Conservation tillage for dryland farming: Technological options and experiences in Eastern and Southern Africa. Regional Land Management Unit, RELMA/Sida, ICRAF House, Gigiri. Nairobi, Kenya.

Bijay-Singh, Shan Y H, Johnson-beeebout S E, Yadvinder-Singh and Buresh R J Crop residue management for lowland rice-based cropping systems in Asia.*AdvAgron* **98** (2008) 118-199

Bijay-Singh, Yadvinder-Singh, Imas P and Xie Jian-Chang Potassium nutrition of rice-wheat cropping system *Adv Agron* **81** (2004) 203-259

Blair G J, Lefroy R D B and Lisle L Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Aus J Agric Res* **46** (1995) 1459-1466

Chakraborty D, Garg R N, Tomar R K, Singh R, Sharma S K., Singh R K, Trivedi S M, Mittal R B, Sharma P K, Kamble K H Synthetic and organic mulching and nitrogen effect on winter wheat (*Triticum aestivum* L.) in a semi-arid environment. *Agric Water Manage* **97** (2010) 738-748

Chakraborty D, Nagarajan S, Aggarwal P, Gupta V K, Tomar R K, Garg. R N, Sahoo R N, Sarkar A, Chopra U K, Sarma K S S and Kalra N Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. *Agric Water Manage* **95** (2008) 1323-1334

Chan K Y, Van Zwieten L, Meszaros I, Dowine A and Joseph S Agronomic value of green waste biochar as a soil amendment. *Aus J Soil Res* **45** (2007) 629-634

Cook R J Management of wheat and barley root diseases in modern farming systems. *Australasian Plant Pathol* **30** (2001) 119-126

De Boer R F, Steed G R, Kollmorgen J F and Mac Auley B G Effects of rotation, stubble retention and cultivation on take-all and eyespot of wheat in northern Victoria, Australia. *Soil Till Res* **25** (1993) 263-280

Dobermann A and Fairhurst T H Rice straw management. Better crops. Intern **16** (2002) (Sp. Supp. May), 7-9

Dobermann A and Witt C The potential impact of crop intensification on carbon and nitrogen cycling in intensive rice systems. In: Carbon and nitrogen dynamics in flooded soils (Kirk G J D, Olk D C eds) (2000) pp. 1-25. International Rice Research Institute, Los Baños, Philippines.

Eagle A J, Bird J A, Hill J E, Horwath W R and van Kessel C Nitrogen dynamics and fertilizer use efficiency in rice following straw incorporation and winter flooding. *Agron J* **93** (2001) 1346-1354

Erenstein O and Laxmi V Zero tillage impacts in India's rice-wheat systems: a review. *Soil Till Res* **100** (2008) 1-14

Gangwar K S, Singh K K, Sharma, S K and Tomar O K Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-Gangetic plains. *Soil Till Res* **88** (2006) 242-252

Gathala M K, Ladha J K, Saharawat Y S, Kumar V, Kumar V and Sharma P K Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. *Soil Sci Soc Am J* **75** (2011) 1851-1862

Gathala M K, Kumar V, Sharma P C, Saharawat Y S, Sharma P K, Jat H S, Singh M, Kumar A, Jat ML, Humphreys E, Sharma D K, Sharma S and Ladha J K Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic plains of India. *Agric Ecosys Environt* **177** (2013) 85-97

Gupta P K, Sahai S, Singh N, Dixit C K, Singh D P, Sharma C, Tiwari M K, Gupta R K and Garg S C Residue burning in rice–wheat cropping system: causes and implications. *Curr Sci* **87** (2004) 1713-1717

Gupta R, Gopal R, Jat M L, Jat R K, Sidhu H S, Minhas P S and Malik R K Wheat productivity in Indo-Gangetic plains of India: Terminal heat effects and mitigation strategies. *PACA Newsletter* **15** (2010) 1-3

Gupta R K,Yadvinder-Singh, Ladha J K, Bijay-Singh, Singh J, Singh G and Pathak H Yield and phosphorus transformations in a rice-wheat system with crop residue and phosphorus management. *Soil Sc Soc Am J* **71** (2007) 1500-1507

Haefele S M, Konboon Y, Wongboon W, Amarants S, Maarifat A A, Pfriffer E M and Knoblauch C Effects and fate of biochar from rice residues in rice-based systems. *Field Crops Res* **121** (2011) 430-440

Hamer U, Marschner B, Brodowski S and Amelung W Interactive priming of black carbon and glucose mineralisation. *Organic Geochemi* **35** (2004) 823-830

Hira G S Water management in northern states and the food security of India. *J Crop Improv* **23** (2009) 136-157

Jalota S K, Khera R, Arora V K and Beri V Benefits of straw mulching in crop production: A review. *J Res Punjab Agric Univ* **44** (2007) 104-117.

Jat M L, Singh R G, Saharawat Y S, Gathala M K, Kumar V, Sidhu H S and Gupta R (2009) Innovations through conservation agriculture: Progress and prospects of participatory approach in the Indo-Gangetic plains. In: Proceedings of the 4th World Congress on Conservation Agriculture.pp. 60-64, New Delhi, India.

Jat M L, Saharawat Y S and Gupta R Conservation agriculture in cereal systems of South Asia: Nutrient management perspectives. *Karnataka J Agric Sci* **24** (2011) 100-105

Kumar K and Goh K M Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yields, and nitrogen recovery. *Adv Agron* **68** (2000) 197-319

Kumar V, Singh S, Chhokar R S, Malik R K, Brainard D C and Ladha J K Weed management strategies to reduce herbicide use in zero-till rice-wheat cropping systems of the Indo-Gangetic Plains. *Weed Technol* **27** (2013) 241-254

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

Ladha J K, Fischer K S, Hossain M, Hobbs P R and Hardy B (2000) Improving the Productivity and Sustainability of Rice-Wheat Systems of the Indo-Gangetic Plains: A Synthesis of NARS-IRRI Partnership Research. Discussion Paper No. 40. International Rice Research Institute, Los Baños Philippines:

Lehmann J and Rondon M (2006) Bio-char soil management on highly-weathered soils in the humid tropics', In: Biological Approaches to Sustainable Soil Systems ((Eds: Uphoff N *et al.*) pp 517-530. Taylor & Francis, Boca Raton.

Lehmann J, Gaunt J and Rondo M Bio-char sequestration in terrestrial ecosystems—a review. *Mitig Adapt Strategies Global Change* **11** (2006) 403-427

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Nell B, Skjemstad J O, Thies J, Luizao FJ, Petersen J and Neves E G Black carbon increases cation exchange capacity in soils. *Soil Sci Soc Am J* **70** (2006) 1719-1730

Lin S, Dittert K, Tao H, Kreye C, Xu Y, Shen Q, Fan X and Sattelmacher B (2003) The ground-cover rice production system (GCRPS): A successful new approach to save water and increase nitrogen fertilizer efficiency. In: Water-Wise Rice Production (Eds: Bouman B A M, Hengsdijk H, Hardy B, Bindraban P S, Tuong T P and Ladha J K) pp 187-195. International Rice Research Institute, Los Ban˜ os, Philippines.

Ma J, Li X L, Xu H, Han Y, Cai Z C and Yagi K Effects of nitrogen fertiliser and wheat straw application on CH_4 and N_2O emissions from a paddy rice field. *Aus J Soil Res* **45** (2007) 359-367

Malhi S S, Grant C A, Johnston A M and Gill K S Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. *Soil and Till Res* **60** (2001) 101-122

Mandal K G, Misra A K, Kuntal M H, Bandyopadhyay K K, Ghosh P K and Mohanty M Rice residue: Management options and effects on soil properties and crop productivity. *Food Agric Environ* **2** (2004) 224-231

NAAS (2012) *Management of Crop Residues in the Context of Conservation Agriculture*. Policy Paper No. 58, National Academy of Agricultural Sciences, New Delhi, India. 12 p.

Paroda R S, Woodhead T and Singh R B (1994). Sustainability of rice-wheat production systems in Asia.RAPA Publication 1994/11.FAO Bangkok.

Patra A K, Chhonkar P K and Khan M A Nitrogen loss and wheat (*Triticum aestivum* L.) yields in response to zero tillage and sowing time in a semi-arid tropical environment. *J Agron Crop Sci* **190** (2004) 324-331

Power J F, Doran J W and Wilhelm W W Crop residue effects on soil environment and dryland maize and soybean production. *Soil Tillage Res* **8** (1986) 101-111

Prasad R, Gangaiah B and Aipe K C Effect of crop residue management in a rice–wheat cropping system on growth and yield of crops and on soil fertility. *Exp Agric* **35** (1999) 427-435

Prihar S S, Arora V K and Jalota S K Enhancing crop water productivity to ameliorate ground water fall. *Curr Sci* **99** (2010) 588-593

Puget P and Lal R Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. *Soil Tillage Res* **80** (2005) 201-213

Rahman M A, Chikushi J, Saifizzaman M and Lauren J G Rice straw mulching and nitrogen response of no-till wheat following rice in Bangladesh. *Field Crops Res* **91** (2005) 71-81

Ram H, Dadhwal V, Vashist K K, Kaur H Grain yield and water use efficiency of wheat (*Triticum aestivum* L.) in relation to irrigation levels and rice straw mulching in North West India. *Agric Water Manage* **128** (2013) 92-101

Saharawat Y S, Ladha J K, Pathak H, Gathala M, Chaudhary N and Jat M L Simulation of resource-conserving technologies on productivity, income and greenhouse gas (GHG) emission in rice-wheat system. *J Soil Sci Environ Manage* **3** (2012) 9-22

Sarkar A, Yadav R L, Gangwar B and Bhatia P C (1999) Crop Residues in India. Technical Bulletin. Directorate of Cropping System Research, Modipuram, India.

Sekhon N K, Singh C B, Sidhu A S, Thind S S, Hira G S and Khurana D S Effect of mulching, irrigation and fertilizer nitrogen levels on soil hydrothermal regime, water use and yield of hybrid chilli. *Arch Agron Soil Sci* **54** (2008) 163-174

Sharma A K, Babu K S, Sharma R K and Kumar K Effect of tillage practices on *Tilletia indica* Mitra (Karnal bunt disease of wheat) in a rice-wheat rotation of the Indo-Gangetic Plains. *Crop Prot* **26** (2007) 818-821

Shen Q and Yangchun X (2003) Cropping system N and water management: Aerobic barley in rotation with aerobic and waterlogged rice. Paper Presented at the FAO/IAEA Coordinated Research Project on Integrated Soil, Water and Nutrient Management for Sustainable Rice-Wheat Cropping System in Asia. IAEA Vienna, Austria.

Sidhu B S and Beri V Effect of crop residue management on the yields of different crops and soil properties. *Biol Waste* **27** (1989) 15-27

Sidhu B S and Beri V (2005) Experience with managing rice residue in intensive rice-wheat cropping system in Punjab. In: Conservation Agriculture-Status and Prospects (Eds: Abrol I P, Gupta R K and Malik R K) pp 55-63. Centre for Advancement of Sustainable Agriculture (CASA)., New Delhi.

Sharma S and Prasad R Effect of crop-residue management on the production and agronomic nitrogen efficiency in a rice-wheat cropping system. *J Plant Nutr Soil Sci* **171** (2008) 295-302

Sidhu H S, Manpreet-Singh, Humphreys E, Yadvinder-Singh, Balwinder-Singh, Dhillon S S, Blackwell J, Bector V, Malkeet-Singh and Sarbjeet-Singh The Happy Seeder enables direct drilling of wheat into rice stubble. *Aus J Exp Agric* **47** (2007) 844-854

Sidhu H S, Singh M., Yadvinder-Singh, Blackwell J, Singh V and Gupta N (2011) Machinery development for crop residue management under direct drilling. In: Resilient Food Systems for a Changing World pp 157-158. Proceedings of the 5th World Congress on Conservation Agriculture. Incorporating 3rd Farming Systems Design Conference, 25-29th September 2011, Brisbane, Australia.

Singh G, Jalota S K and Sidhu B S Soil physical and hydraulic properties in a rice-wheat cropping system in India: effects of rice-straw management. *Soil Use Manage* **21** (2005) 17-21

Singh S P, Singh A P, Singh M P, Singh V P, Singh M V, Kumar V and Singh S K (2011) Zinc and crop residue management under rice-wheat cropping system in calcareous soil. . Proceedings of the Third International Zinc Symposium- Improving crop production and human health. October 10-14, 2011, Hyderabad, India.

Singh U P, Singh Y, Kumar V and Ladha J K (2009) Evaluation and promotion of resource conserving tillage and crop establishment techniques in rice-wheat system in Eastern India. In: Integrated crop and resource management in the rice-wheat system of south Asia (Eds: Ladha J K, Yadvinder-Singh, Erenstein O and Hardy B) pp 151-176.International Rice Research Institute, Philippines.

Six J, Feller C and Denef K Soil organic matter, biota, and aggregation in temperate and tropical soils-effects of no-tillage.*Agronomie* **22** (2002) 755-775

Srinivasarao Ch, Venkateswarlu B, Lal R, Singh A K and Kundu S Sustainable management of soils of drylandecosystems of India for enhancing agronomic productivity and sequestering carbon. *Adv Agron* **121** (2013) 253-329

Surekha K, Padma Kumari A P, Narayana Reddy M, Satyanarayana K and Sta Cruz P C Crop residue management to sustain soil fertility and irrigated rice yields. *Nutr Cycl Agroecosys* **67** (2003) 145-154

Sawinska Z, Ma1ecka I and Blecharczyk A *Impact of Previous Crops and Tillage Systems on Health Status of Winter Wheat* EJPAU **9** (2006) 405-409

Thind H S, Yadvinder-Singh, Bijay-Singh, Varinderpal-Singh, Sharma S, Vashistha M and Gobinder-Singh Land application of rice husk ash, bagasse ash and coal fly ash: Effects on crop productivity and nutrient uptake in rice-wheat system on an alkaline loamy sand. *Field Crops Res* **135** (2012) 137-144.

Thuy N H, Yuhua S, Bijay-Singh, Wang K, Cai Z, Yadvinder-Singh and Buresh R J Nitrogen supply in rice-based cropping systems as affected by crop residue management. *Soil Sci Soc Am J* **72** (2008) 514-523

Unger P W and Stewart B A (1983) Soil management for efficientwater use: An overview. In: Limitations to efficient water use in crop production (Ed: Taylor H M *et al*.) pp.419-460. ASA, CSSSA and SSSA, Madison, WI

Van Duivenbooden N (1992) Sustainability in terms of nutrient elements with special reference to West Africa. Agrobiological Research Centre (CABODLO), Wageningen, The Netherlands.

Verhulst N, Sayre K D, Vargas M, Crossa J, Deckers J and Raes D Wheat yield and tillage-straw management system x year interaction explained by climatic co-variables for an irrigated bed planting system in northwestern Mexico. *Field Crops Res* **124** (2011) 347-356

Wall P (2011) What drives the conservation agriculture revolution? *Fert Agric* May Issue 12. *Int Fert Ind Assoc* (IFA), Paris, France. www.fert.org

Warnock D D, Lehmann J, Kuyper T W and Rillig M C Mycorrhizal responses to biochar in soil concepts and mechanisms. *Plant Soil* **300** (2007) 9-20

West T O and Post W M Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci Soc Am J* **66** (2002) 1930-1946

Whitbread A M, Blair G J, Konboon Y, Lefroy R D B and Naklang K Managing crop residues, fertilizers and leaf litters to improve soil C, nutrient balances and the grain yield of rice and wheat cropping systems in Thailand and Australia. *Agric Ecosyst Environ* **100** (2003) 251-263

Xu G W, Tan G L, Wang Z Q, Liu L J and Yang J C Effects of wheat residue application and site-specific nitrogen management on growth and development in direct-seeding rice. *Acta Agronomica Sinica* **35** (2009) 685-694

Yadvinder-Singh, Bijay-Singh, Ladha J K, Khind C S, Gupta RK, Meelu O P and Pasuquin E Long-term effects of organic inputs on yield and soil fertility in the rice–wheat rotation. *Soil Sci Soc Am J* **68** (2004a) 845-853

Yadvinder-Singh, Bijay-Singh, Ladha J K, Khind C S, Khera T S and Bueno C S Effects of residue decomposition on productivity and soil fertility in rice–wheat rotation. *Soil Sci Soc Am J* **68** (2004b) 854-864

Yadvinder-Singh, Bijay-Singh, Meelu O P and Khind C S (2000) Long-term effects of organic manuring and crop residues on the productivity and sustainability of rice-wheat cropping system in Northwest India. In: Long-term soil fertility experiments in rice-wheat cropping systems (Eds: Abrol I P, Bronson K F, Duxbury J M and Gupta R K) pp 149-162. Rice-wheat Consortium Paper Series 6. Rice-wheat Consortium for Indo-Gangetic Plains, New Delhi, India

Yadvinder-Singh, Bijay-Singh and Timsina J Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. *Adv Agron* **85** (2005) 269-407

Yadvinder-Singh, Gupta R K,Gurpreet-Singh, Jagmohan-Singh, Sidhu H S and Bijay-Singh Nitrogen and residue management effects on agronomic productivity and nitrogen use efficiency in rice-wheat system in Indian Punjab. *Nutr Cycl Agroecosyst* **84** (2009) 141-154

Yadvinder-Singh, Gupta R K, Jagmohan-Singh, Gurpreet-Singh, Gobinder-Singh and Ladha J K Placement effects on rice residue decomposition and nutrient dynamics on two soil types during wheat cropping in rice–wheat system in northwestern India. *Nutr Cycl Agroecosyst* **88** (2010a) 471-480

Yadvinder-Singh, Khind C S and Bijay-Singh Efficient management of leguminousgreen manures in wetland rice. *Adv Agron* **45** (1991) 135-189

Yadvinder-Singh, Malhi S S, Nyborg M and Beauchamp E G Large granules, nests or bands: Method of increasing efficiency of fall applied urea for small grains in North America. *Fertilizer Research* **38** (1994) 61-87

Yadvinder-Singh, Manpreet-Singh, Sidhu H S, Khanna P K, Kapoor S, Jain A K, Singh A K, Sidhu G K, Avtar-Singh, Chaudhary D P and Minhas P S (2010b) Options for effective utilization of crop residues. Directorate of Research, Punjab Agricultural University, Ludhiana, India.