Journal of Integrative Agriculture 2015, 14(8): 1524–1533

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RESEARCH ARTICLE

Climate change adaptation, greenhouse gas mitigation and economic profitability of conservation agriculture: Some examples from cereal systems of Indo-Gangetic Plains

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Abstract

Achieving sustainability of the cereal system in the Indo-Gangetic Plains (IGP) of India under progressive climate change and variability necessitates adoption of practices and technologies that increase food production, adaptation and mitigation in a sustainable way. This paper examines conservation agriculture (CA) from the perspective of: (i) increased yield and farm income, (ii) adaptation to heat and water stresses, and (iii) reduction in greenhouse gas (GHGs) emissions. The analyses and conclusions are based on the literature and evidences from a large number of on-station as well as farmers' field trials on CA in the cereal systems of IGP. Our analyses show that CA-based system substantially reduces the production cost (up to 23%) but produces equal or even higher than conventional system; thereby increasing economic profitability of production system. CA-based production systems also moderated the effect of high temperature (reduced canopy temperature by 1–4°C) and increased irrigation water productivity by 66–100% compared to traditional production systems thus well adapting to water and heat stress situations of IGP. Our continuous monitoring of soil flux of CO_2, N_2O and CH_4 revealed that CA-based rice-wheat systems emit 10–15% less GHGs than conventional systems. This is the first time that CA and its components are synthesized and analyzed from food security-climate change nexus. From this holistic analysis, we suggest that wide-scale promotion of suitable CA practices by integrating into national agriculture development strategy is a way forward to address food security, climate change adaptation and mitigation challenges faced by present agriculture.

Keywords: zero-tillage, residue retention, climate change, sustainability, conservation agriculture

1. Introduction

The Indo-Gangetic Plain (IGP) of India is an important region for agricultural production and food security contributing to 50% of the total food grain production and supporting food security of about 40% population (Pal *et al*. 2009). Green Revolution in IGP not only contributed to food security through increased production and reduced volatility of food-grain prices but also demonstrated that agricultural development affords an effective means for accelerating economic growth and reducing poverty. This remarkable achievement of Green Revolution was largely due to use of high-yielding varieties, chemical fertilizer, pesticides, ir-

Received 16 March, 2015 Accepted 22 June, 2015
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doi: 10.1016/S2095-3119(15)61093-0

rigation and mechanization. The unsustainable increase in agricultural production through indiscriminate use of external inputs gradually led to the deterioration of agri-environment and natural resources in the region (Erenstein *et al*. 2007). For example, the introduction of canal irrigation in India has increased salinity and water logging conditions in almost 7 million ha (Mha) of cultivated lands (Joshi and Tyagi 1994). The rapid increase in the number of tube wells during last four decades in north-western IGP has resulted in overexploitation of groundwater, leading to a rapid fall in water tables. Though the chemical fertilizer use over time has been increasing in the IGP, cereal production reportedly have removed more nutrients than the amounts externally added through fertilizers (Regmi *et al*. 2002). Despite these production challenges, production of rice (*Oryza sativa*), wheat (*Triticum aestium*) and maize (*Zea mays*) will have to increase in order to meet the increasing food demand in the region.

The growing threat of food insecurity and poverty in the region is further exacerbated by the risk of climate change and variability in agricultural production. Many studies in India including IGP region have predicted significant impact of change in temperatures and precipitations on agriculture (Parry *et al*. 2004; Aggarwal and Rani 2009; Aggarwal *et al*. 2010). These studies indicate that a moderate increase in temperature will have significant impact on rice, wheat and maize yields. The impact may be further worsen by increasing water scarcity, frequent floods and droughts, and declining soil carbon content (Singh and Pathak 2014). For example, there would be at least 10% increase in irrigation water demand in arid and semi-arid regions of Asia with a 1°C rise in temperature (Sivakumar and Stefanski 2011). Given these deleterious impacts of climate change on agricultural production and food security, adaptation of agriculture to climate change is not a choice, but a compulsion.

However, in agriculture sector, adaptation alone is not sufficient to sustainably overcome the challenges of climate change and variability. This is primarily due to the fact that agriculture is not only affected by climate change but it also contributes to climate change through the emission of large amount of greenhouse gas (GHGs). The input intensive cereal production system in the IGP is responsible for significant amount of GHG emissions. Grace *et al*. (2003) reported that the emissions of GHGs from rice-wheat system in IGP has a global warming potential of 13–26 Mg CO_2 ha^{-1} yr^{-1}. Business as usual production practices such as conventional tillage and farmers' nutrient and irrigation management systems are reported to be GHG intensive (Sapkota *et al*. 2014; Aryal *et al*. 2015). However, opportunities exist to mitigate GHG emission by adopting better agronomic and land management practices in the cereal production system of IGP.

Conservation agriculture (CA), mainly promoted for resource conservation and agricultural sustainability, has potential to improve crop productivity, enhance resource use efficiency and also help cope with some weather extremes. CA, defined as minimal soil disturbance and permanent soil cover combined with appropriate rotation, is being promoted during last few years to address some of the production challenges faced by cereal systems in South Asia. Various components of CA have been reported to increase crop growth and productivity (Jat *et al*. 2014), reduce production costs (Erenstein *et al*. 2012) and enhance resource-use-efficiency (Kumar *et al*. 2013). Farmers in IGP are adopting zero-tillage, one of the components of CA, primarily to lower cost of production and to increase profit (Erenstein *et al*. 2012). The focus of CA practices, so far, is to achieve agricultural sustainability by means of resource conservation and judicious use of external inputs while maintaining high yielding and profitable systems. Despite these agronomic and environmental benefits, CA has not been widely adopted in the region. Potential caveats for wide-scale adoption of CA include high initial cost of machinery, inability of simple ZT machine to handle loose straw left on the surface after combine harvesting of previous crop and lack of scale-appropriate and locally adapted machinery in some locations. With introduction of Turbo happy seeder capable of drilling seed and fertilizer directly through the residues at appropriate depth, farmers are gradually moving towards full CA-based rice-wheat system. However, CA is highly knowledge and skill intensive and therefore building capacity of various stakeholders including government service providers on principles and practices of CA is necessary for its wide-scale adoption.

CA may provide both adaptation and mitigation benefits and sustain agricultural production under the inevitable effects of climate change and variability. For example, CA contributes to build climate resilient agricultural system through improvement in soil properties, water and nutrient use efficiencies, and ecosystem services leading to more stable yields and reduction in GHGs emissions. Despite our general acceptance on the benefits of CA, holistic analysis of climate change adaptation and mitigation potential of CA technologies are still scanty and scattered. In this paper, we demonstrated climate change adaptation and mitigation potential of various CA practices by using field evidences from various long-term trials in the IGP. The impacts of different CA practices on the yield, income, water and energy use efficiencies and reduction in GHG emissions were analysed in order to examine their adaptation and mitigation potential. Demonstrating the adaptation and mitigation potential of CA, the paper also suggests scaling out a combination of CA practices that could minimize the potential impact of climate change and variability on agricultural production of the IGP.

2. Results and discussion

Based on the results of several on-station and -farm experiments, the benefits of CA in terms of food security, climate change adaptation and mitigation is summarized below. Increase in farm production and income is a proxy for household food security due to increased availability and access to food. Similarly, increase in crop production, increased water-, nutrition- and energy-use efficiencies and the minimum heat stress indicates adaptation to climate change and variability. Low GHG emission from the implementation of CA practices shows mitigation potential.

2.1. Economic benefits of CA

There are large 'management yield gaps' in the IGP ranging from 14 to 47% in wheat, 18 to 70% in rice and 36 to 77% in maize. These yield gaps are probably getting wider due to the sharp rise in the cost of energy, depleting water resources and the effects of soil degradation, including salinization. Such gaps can be narrowed down through appropriate and efficient crop management practices in a system perspective taking a range of challenges into consideration. Various researchers (e.g., Gathala *et al*. 2011; Saharawat *et al*. 2011; Sapkota *et al*. 2014) have demonstrated short- and long-term economic benefits of CA-based production systems from the IGP of South Asia. From participatory trials on 40 farmers' fields in Haryana for three consecutive years, we found that the average total cost of wheat production was 23% less in zero-tillage with (ZT+R) and without residue retention (ZT) than in conventional tillage (CT) system. The variable cost of wheat production in this agro-ecosystem was (278±5.36), (211±4.34) and (218±6.13) USD ha^{-1} under CT, ZT and ZT+R, respectively (*n*=120). This reduction was mainly due to reduction in the cost of preparatory tillage and irrigation (Fig. 1). With similar or slightly higher yield (5.9 Mg ha^{-1} in ZT *vs*. 5.7 Mg ha^{-1} in CT), the net return was significantly higher in ZT than in CT system of wheat production (Aryal *et al*. 2015).

Similarly, through six years of long-term trial on crop establishment methods in rice-wheat system of eastern IGP, we found that the productivity of rice-wheat was higher under ZT-based system (ZTR-ZTW) with and without residue retention as compared to CT systems (Fig. 2). The increased system productivity in this trial resulted mainly due to higher wheat yield under ZT system although rice yield was not statistically different among the tillage and residue management systems.

In this trial, we obtained lower rice yield under ZT than CT during initial four years which can be attributed to lack

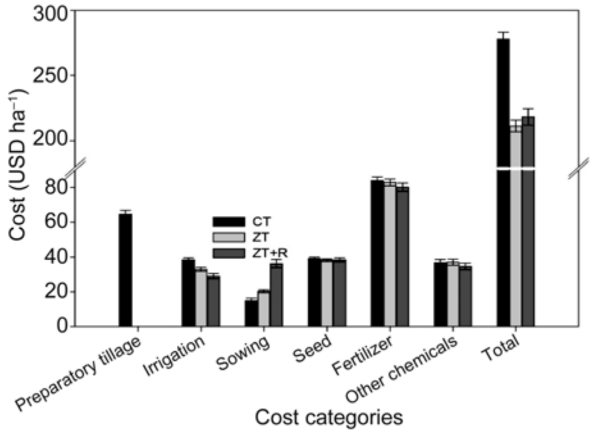

Fig. 1 Input cost for wheat production under various tillage and crop establishment method. CT, conventional tillage; ZT, zero-tillage; ZT+R, zero-tillage with residue retention. The same as below. Vertical bars shows the standard error of the mean (*n*=120). Adapted from Aryal *et al.* (2015).

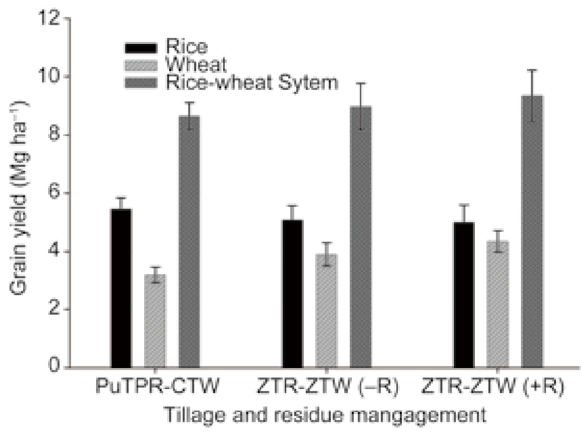

Fig. 2 Rice, wheat and rice-wheat grain yield under different tillage and crop establishment methods in eastern Indo-Gangetic Plain (IGP). PuTPR-CTW, puddled transplanted rice followed by conventional tilled wheat; ZTR-ZTW (–R), zero-tilled rice followed by zero-tilled wheat without residue retention; ZTR-ZTW (+R), zero-tilled rice followed by zero-tilled wheat with residue retention. The same as below. Vertical bars shows the standard error of the mean (*n*=18). Adapted from Jat *et al.* (2014).

of suitable herbicides for effective weed control and lack of refined technology for ZT based rice production which was improved over time to make CA-based system cost effective, productive and sustainable (Jat *et al*. 2014). Further, puddling is reported to have beneficial effect on rice through better weed control, reduction in percolation loss of water and nutrients, quick establishment of seedlings and improved nutrient availability (Sharma *et al*. 2003; Gathala *et al*. 2011). Lower rice yield under direct drill-seeded rice as compared to puddled transplanted rice has also been reported by other researchers (Jat *et al*. 2009a; Kumar and Ladha 2011) from the region. Improvement in weed control and proper management of crop under ZT system make CA-system more cost effective, productive and sustainable than CT in a long run. At system level, however, CA had always been more productive than conventional production systems (Fig. 2).

2.2. Adaptation to heat stress

The effect of climate change on agriculture has been mostly examined by linking the impact of temperatures changes on crop growth and yields. Changes in temperatures can impact on the biophysical activities of crops and the system in which they are dependent. High temperature increases the photosynthesis rate of crops, speed-up crop's phenology and heat stresses during critical growth periods. Grain yields are affected both by changes in grain number and grain size. Grain number is determined from 30 d before anthesis until shortly after anthesis whereas grain size is determined during grain filling stage (Lobell *et al*. 2012). In the IGP, higher temperature towards the maturity stage of winter crops shorten the duration of grain filling (Tashiro and Wardlaw 1989) and slows photosynthesis and grain-filling rates (Lobell *et al*. 2012), all leading to smaller grain size and lower yield, commonly known as "terminal heat effect". Adoption of ZT in cereal cropping system in the IGP has been reported to advance the planting time (Erenstein *et al*. 2012) thereby increasing the thermal window for wheat thus escaping from terminal heat effect.

Similarly, crop residue placed at soil-atmosphere interface offers profound water conserving effect by reducing run-off and evaporative losses. Through a long-term trial in rice-wheat system in IGP, Jat *et al*. (2009b) found that retention of rice residue lowered the canopy temperature in wheat by 1–4°C than atmospheric temperature between 138–153 days after showing (DAS). In the system without previous rice crop residue, they observed only slightly lower canopy temperature between 138–143 DAS and no difference in canopy and atmospheric temperature between 148–153 DAS. These differences were probably due to soil moisture conservation with residue mulching which provided cooling effect on canopy as a result of enhanced evapotranspiration.

2.3. Increase water use efficiency

Since the early 1970s, there has been a steady increase in the depth to the groundwater in North-West IGP which has accelerated alarmingly in recent years (Humphreys *et al*. 2010). Increase in the depth of groundwater has the consequences such as increased energy requirement and cost of groundwater pumping, increased tube well infrastructure costs and deterioration of groundwater quality due to saline water intrusion into fresh groundwater. Driven by these challenges, various water saving technologies have been designed, developed and tested over the past couple of decades (Gupta and Seth 2007). Total water requirement of rice-wheat system, a major cropping system of IGP, ranges from 1 382 to 1 838 mm, 80% of which is consumed by rice (Gupta *et al*. 2002). This finding suggests that savings must be made during rice-growing season in order to save water in rice-based cropping systems. Puddling operation in rice requires large amount of water. Further, in some parts of IGP, there is a long pre-puddling soil soaking period which results in huge amount of water loss through evaporation. One of the strategies could be to forego tillage and puddling in rice followed by growing another crop in the system also without any tillage operation. In the rice-wheat production system of North-West India, we found 55% more water saving in direct seeded rice with retention of previous wheat residue (DSR+R) than in puddled transplanted rice (PuTPR) without retention of previous wheat crop residue. Although nature of these savings has not been well established and rate of percolation would apparently be higher under direct seeded rice, lower water requirement in DSR was mainly through better water management by adopting alternate wetting and drying.

ZT with crop residue mulch in DSR+R may have reduced evaporative loss of water thereby requiring less water in this system than in puddled transplanted system where continuous ponding without residue cover might have increased evaporation. In this region, if rice crop is seeded by utilizing pre-monsoon rainfall and well established by the onset of monsoon, wherein precipitation exceeds potential evapotranspiration, the rice crop can benefit from the monsoon rain thereby increasing rainwater-use efficiency and requiring less irrigation (Gupta *et al*. 2002). The results from farmers' participatory trials have shown that adopting zero-tillage increases water productivity also in wheat crop which further increases with retention of previous crop residues (Fig. 3). Increased water productivity in ZT-based production systems in these trials was mainly due to requirement of less water to produce same or even more than CT-based production systems. This savings in water arise because with zero-tillage, wheat can be sown just after rice harvest utilizing residual moisture for wheat germination saving a pre-sowing irrigation. Further, in case of wheat, irrigation water advances faster in untilled soil thereby requiring less water per irrigation than in tilled system. Gupta *et al*. (2002) also reported 20–25% savings in irrigation water from the zero-tillage practice for wheat in rice-wheat system of IGP. Adoption of zero-tillage in rice-wheat system in this region

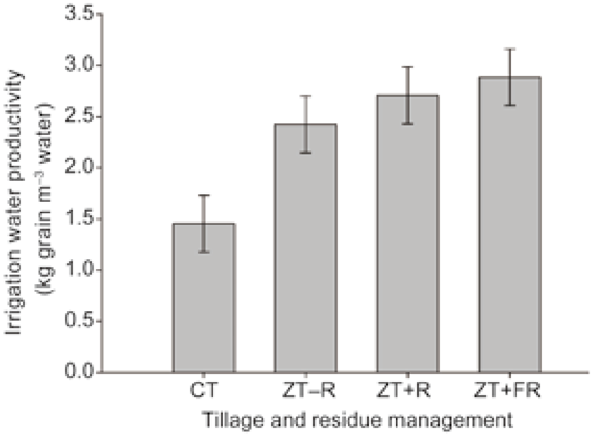

Fig. 3 Irrigation water productivity of wheat under different tillage and residue management strategies. Vertical bars show the standard errors of the mean (*n*=20). Data source: Authors' compilation.

advances planting time of both rice and wheat thus increasing rainwater-use efficiency, conserving soil moisture and escaping terminal heat effect in wheat, all contributing to climatic risk management and increase system productivity.

2.4. Energy use and GHGs emission reduction

Appropriate agricultural practice can contribute to climate change mitigation through sequestration of carbon in soil and plant biomass as well as reducing fossil fuel combustion and soil related emissions. Since soil disturbance tends to stimulate soil carbon losses through enhanced decomposition and erosion of soil organic matter, zero-tillage in CA often results in soil carbon gain. However, the issue is still debatable. But, reduced power and energy requirements due to non-requirement of tillage in CA translates into less fuel consumption, lower working time and slower depreciation rates of equipment, all leading to emission reduction from farm operations as well as from the machinery manufacturing processes. While enhanced C sequestration, if any, will continue for a finite time, emission reduction from less fossil-fuel, energy and machinery use can continue indefinitely, as long as such practices are continued (West and Post 2002). On an average, by adopting of ZT for land preparation and crop establishment in rice-wheat system of the IGP, farmers could save 36 L diesel ha^{-1} (Erenstein and Laxmi 2008), equivalent to a reduction in 93 kg CO_2 emission ha^{-1} yr^{-1}. Further, retention of crop residues in the system adds carbon fixed in the crop biomass by means of photosynthesis to soil thereby improving soil health and fertility. This measure may reduce fertilizer use and associated GHG emission over time (Corsi *et al*. 2012). CA can also reduce emissions by saving irrigation water. In North-West IGP, irrigation water is mainly pumped by using electricity whereas in eastern IGP diesel pumps are used, both the ways contributing to CO_2 emission.

In the context of agro-ecosystem, CO_2 emission occurs mainly due to the decomposition of plan residues which is enhanced by soil disturbance. Methane (CH_4) flux from soil is a result of methanogenesis (CH_4 production in anoxic microenvironment) and consumption as well as oxidation of CH_4 by methanotrophs in aerobic micro-environment. Nitrous oxide (N_2O) is mainly produced through nitrification under aerobic soil environment and through denitrification under anaerobic soil condition. Besides emission reduction through less energy and power use, CA also affects the soil flux of CO_2, CH_4 and N_2O. Puddling and continuous flooding of rice field promote methanogenesis thereby increasing CH_4 emission whereas safe alternate wetting and drying has been reported to reduce CH_4 emission effectively (Yan *et al*. 2003). Foregoing puddling and tillage in rice-based production systems of IGP coupled with improved water management can reduce CH_4 emission. However, some researchers (e.g., Smith *et al*. 2008) claim that this benefit may partly be offset by higher N_2O emission.

Through our continuous monitoring of GHGs by using static chamber method in a rice-wheat production system of Northwest India, we found much higher emission of CH_4 from rice production in puddle transplanted field with continuous flooding compared to direct seeded production system (50–250 mg CH_4 m^{-2} d^{-1} in puddle transplanted *vs*. <50 mg CH_4 m^{-2} d^{-1} in direct seeded rice). In this experiment, total cumulative GHGs emissions (soil flux of CO_2, N_2O and CH_4) in terms of CO_2-equivalent was about 27% higher in the conventional tillage-based rice-wheat system (PuTPR-CTW) than in CA-based systems (ZTDSR-ZTW+R) (Fig. 4). This difference mainly came through higher soil CO_2 flux from CT-based rice-wheat than from ZT based rice-wheat and higher CH_4 emission from CT-based rice than ZT-based rice. Higher CO_2 emission in CT based productions was probably due to enhanced decomposition because of tillage-induced disturbances. No detectable level of CH_4 emission was observed under ZT-based rice both with and without residue retention probably because of higher redox potential of soil thereby arresting methanogenesis process. Through life-cycle analysis of wheat production in Northwest India by using CoolFarmTool, we found that global warming potential per unit of wheat yield was 10 times higher in CT-based production (~400 kg CO_2-eq Mg^{-1} wheat yield) than in ZT-based production (~35 kg CO_2-eq Mg^{-1} wheat yield) (Sapkota *et al*. 2014).

2.5. Barriers of slow adoption of CA

Despite economic, agronomic and environmental benefits

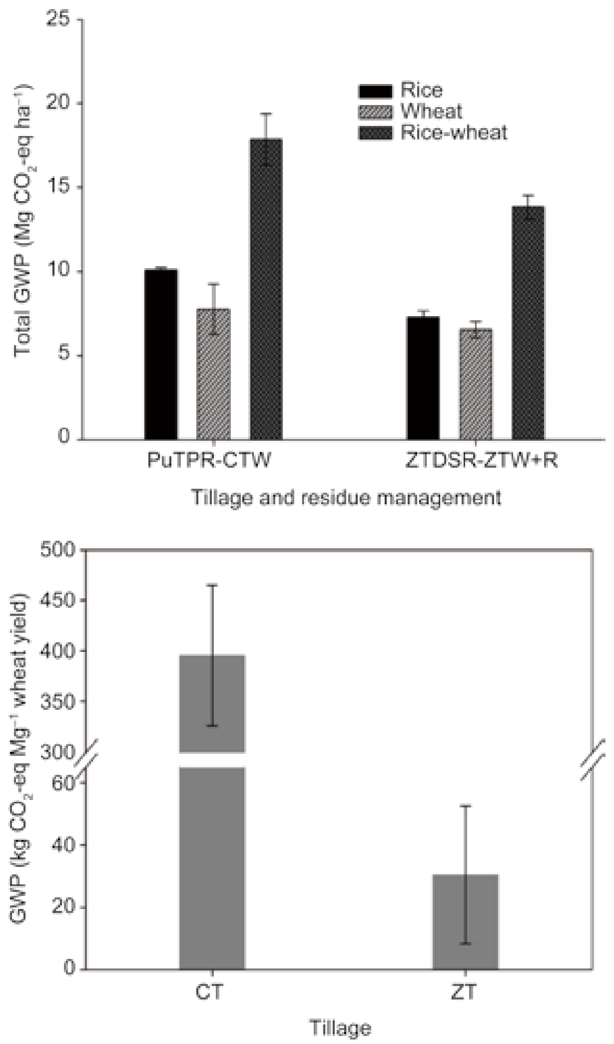

Fig. 4 A, tillage and residue management effect on total greenhouse gas (GHGs) emission from rice-wheat production system in Northwest IGP, 2011-12 (*n*=12). B, estimated global warming potential of CT- and ZT-based wheat production in North-West India (*n*=200). Vertical bars indicate the standard errors of the means. Data sources: A, unpublished data; B, Sapkota *et al.* (2014).

of CA, its adoption is still slower in South Asia. Various technological and socio-economic factors are responsible for slow adoption of CA in South Asia. First of all CA is highly knowledge intensive. Although the CA principles are common and have widespread applicability, actual practices towards these desirable objectives can vary across agro-ecosystems and socio-economic conditions (Erenstein *et al*. 2012). For example, the specific components of CA-based management such as crop establishment methods, selection of farm implement, selection of crops in the rotation, management of plant nutrients, crop residue, water and the selection of genotypes can be different across environments (Harrington and Erenstein 2005). Hence not only farmers, but also researchers, extension agents and other institutions involved in agricultural development need to have proper knowledge to successfully adapt and adopt CA options suited to their specific farm typologies.

Readily availability of scale-appropriate CA machinery and other inputs is another major reason for the lower uptake of CA particularly in eastern IGP. For example, simple ZT machine cannot seed over the previous crop residues as it drags loose residues retained on the surface. To avoid this, farmers generally burn the previous crop residue before planting new crop. However, with the development of Happy Turbo Seeder that can drill seed and fertilizer over the loose straw left in the field, this technological constraint has overcome recently (Sidhu *et al*. 2007). Its uptake, however, needs its own time. Weed management has been one of the constraints to adopt CA by smallholder farmers. This is, however, no more an issue with the recent advancements in weed management technologies including new herbicides molecules (Jat *et al*. 2014). As crop residue management is an important component of CA for continuous soil cover, competing uses of crop residue as livestock feed, fuel, mulch, and compost, can impose a substantial challenge for the expansion of CA (Erenstein and Thorpe 2010; Tittonell *et al*. 2015). Therefore, local adaptive researches are needed to strategically adjust residue management for different completing objectives that helps sustainability of CA.

Nutrient management is an important aspect of CA for crop productivity and for the adoption of CA by farmers (Vanlauwe *et al*. 2014). Nutrient management following blanket recommendations which are largely calibrated for intensive tillage-based systems can be counterproductive under CA. For example, retention of cereal residues having high carbon to nitrogen ratio (C:N ratio) coupled with low N content in the soil of IGP necessitates slightly higher N rate under CA in the first year of conversion to compensate microbial immobilization (microbial uptake of added N making it unavailable to plants). In the subsequent years, N requirement of CA may be even lower than conventional system due to mineralization of previously immobilized N. If these dynamics are not considered while designing nutrient management strategies under CA, farmers may reveal lower yield in first year of CA adoption. As farmers usually compare the yield benefits in the first year of adoption, this can create a perception that CA does not yield as much as the conventional practice.

Farmer uptake of CA is not only related to technology, but also with various socio-economic factors. Due to the conventional mind-set of clean cultivation, it is not easy to dissociate tillage and farming from the farmers' mind and establish the new concept that farming is possible without tillage (Hobbs and Govaerts 2010). Although exposure of farmers to ZT has created a belief among the farmers in the IGP about the viability ZT wheat (Erenstein *et al*. 2012), farmers still prefer to practice tillage in rice crop for weed control and reduction in percolation loss of water/nutrient. To realize the full potentials of CA in RW system, rice should also be grown under ZT and continuous research is needed to refine and optimize system performance under different environments based on local pedo-climatic and socio-economic condition. This paradigm shift in crop management requires a "transition of mindset changes" of not only farmers but also other actors of whole value chain such as researchers, extension agents, market players and other institutions. Such transition always takes its own time.

Enhancing the adoption of CA among smallholders requires integrated approach that ensures farmer participation, practical orientation, community involvement, flexibility, local manufacturing and private sector involvement, and a long-term perspective (Erenstein 2003). For instance, purchasing ZT drill machine or other CA machineries requires large investment and is beyond their capacity. Therefore, private market of ZT rental service is required to improve smallholder's access to such services. A study by Erenstein and Laxmi (2010) in the Indian IGP showed that almost 60–74% of ZT adopters use the service from private service providers on rent, indicating that emergence of rental market contributes to the adoption of CA.

3. Conclusion

Conservation agriculture (CA) is being promoted as a means to enhancing sustainability of agricultural production mainly through resource conservation. In this paper, we analyzed and examined various components of CA for their potential to adaptation and mitigation of climate change based on literature and evidences from the field experiments. Results clearly indicate that CA practices and technologies implemented in the cereal systems of the IGP have positive impacts on crop yields, returns from crop cultivation, input use efficiency (water, nutrient and energy), adaptation to heat stress and reduction of GHGs emissions. While increasing productivity and resilience of production system is need and priority in the IGP, CA is instrumental in developing low emission cropping system without compromising yield, profit and resilience to climatic threat. This study widens the scope of CA to address the challenges of present agriculture in the face of progressive climate change and variability in the IGP and beyond. Wide-scale promotion of CA-based production system could be an important government strategy in IGP region to address triple challenges of present agriculture: food security, climate change adaptation and GHG mitigation. Current climate change adaptation policies, for example, National Agriculture Development Strategy can incorporate many CA practices and technologies in their implementation programs.

This paper indicates that the investment in CA practices and technologies can lead to improved crop productivity and income and minimized some climatic risks in agriculture. However, despite the economic and environmental benefits, CA practices are yet to be widely adopted by the farmers in the IGP region. This is mainly because of lack of scale-appropriate and locally adapted machineries, incomplete understanding of rational use of crop residues by farmers and traditional mindset on crop establishment and management practices. Even at government extension, present understanding of the rational use of crop residues for livestock and soil amendment is incomplete, partial and primarily based on anecdotal evidence with limited systematic assessments. Further, farmers' investment decisions are mainly influenced by their socio-economic characteristics, for instance, investment capacity, knowledge on CA practices and technologies, and access to markets. Systematic assessments of these attributes are needed for wide-scale promotion of CA practices in the IGP.

4. Materials and methods

The Indo-Gangetic Plains (IGP) of South Asia comprise the Indus and the Gangetic plains covering parts of Pakistan, India, Nepal, and Bangladesh (Fig. 5) and are home to nearly one billion people. Average annual precipitation ranges from 400 to 650 mm yr^{-1} in the Northwest IGP and increases towards the eastern IGP reaching annual average as high as 1 800 mm yr^{-1}, nearly 85% of which is received between June to September (Gupta and Seth 2007).

During last decades, several component technologies of CA such as zero-tillage (ZT) and residue retention have been evaluated under diversified cropping systems across IGP as steps towards sustainable agriculture. These efforts were initiated mainly with a realization that conventional mode of agriculture is highly resource intensive and thus, cannot be sustainable. Over the past few decades, international institutions such as Food and Agricultural Organization (FAO) and the Consultative Group of International Agricultural Research (CGIAR) have focused more on the development and promotion of such technologies. Initially, Rice-Wheat Consortium promoted resource conserving technologies such as zero-tillage wheat and initiated a base for spreading CA in the IGP. This trend is continued with several other projects carried out by CGIAR centers such as Cereal System Initiatives for South Asia (CSISA) and CGIAR Research Program on Climate Change Agriculture and Food Security (CCAFS). As a result, CA practice expanded and now there are more evidences to compare the

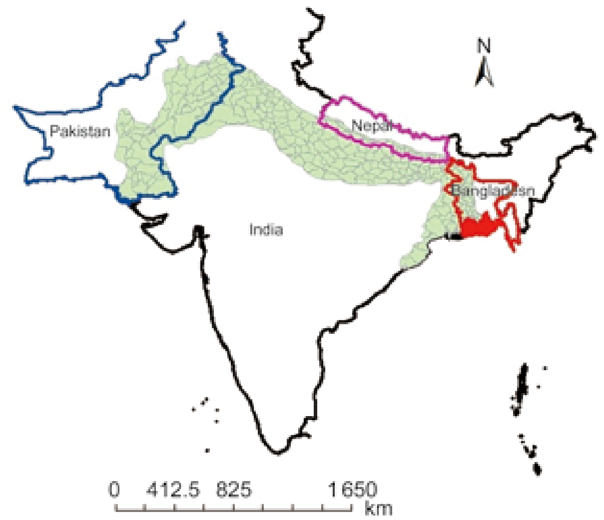

Fig. 5 Location of the Indo-Gangetic Plains (IGP) in South Asia. The light green colored area is the stretch of IGP.

productivity and resource use efficiency between CA and traditional practices in the IGP.

This paper is based on the review of published literatures supported by the field evidences generated during design, pilot and upscaling of various CA practices by the International Maize and Wheat Improvement Center (CIMMYT) research team in the IGP of India. The data presented here come from various CA trials conducted for variety of research activities in IGP region. Details of these on-station and -farm trials can be found elsewhere in CIMMYT's publication (Jat *et al*. 2014; Sapkota *et al*. 2014; Aryal *et al*. 2015). Briefly, agronomic productivity of the system was determined following standard agronomic measurements by harvesting the randomly chosen sampling area. Cost of production was determined over variable inputs by multiplying with respective market price. Plant canopy temperature was recorded with plant canopy thermometer. Irrigation water productivity was determined by dividing the crop yield with total volume of water applied during entire crop duration. Greenhouse gas emission presented here come from both measurement (by using static chamber method) and model simulation by using CoolFarmTool (Hillier *et al*. 2011).

Acknowledgements

Financial supports for these works come from Bayer CropScience, Indian Council of Agricultural Research (ICAR) and CGIAR's research program (CRP) on Climate Change Agriculture and Food Security (CCAFS). Authors would like to thank field staffs of various experiments generating data included in this paper. Finally, we would like to thank two anonymous reviewers and editor of the journal for their excellent comments to improve the manuscript.

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(Managing editor WANG Ning)