Conservation Agriculture based Management Practices for Sustainable Maize Systems: Learnings from South Asia

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Introduction

Food insecurity and poverty for the large hungry- and poor- population of the world, is exacerbated by soaring food and energy prices, global economic downturn, volatile markets and climate change–induced vulnerability. These are the major concerns of research for development (R4D) in the South Asia. Since the late 1960's, the Green Revolution (GR) contributed to food security and demonstrated that agricultural development is an effective means to accelerate economic growth and poverty reduction in the region. The notable achievements of the GR were largely due to both a vertical and horizontal increase in food production from the use of external inputs such as high-yielding varieties, chemical fertilizer and irrigation as well as area expansion. However, recently (at the dawn of 21st century), food security was further challenged by natural resource degradation resulting from the indiscriminate use of resources, sharp-rise in the cost of production inputs, diversion of human capital from agriculture and shrinking farm size. In South Asia, the ever-increasing population growth is interlinked with these challenges and the natural resources are three to five times more-stressed due to population and economic pressures compared to the rest of the world. Inefficient use and inappropriate management of production resources, especially of land, water, energy and agro-chemicals, has vastly impacted the quality of the natural resource base and also contributed to global warning led-climatic variability (Jat et al, 2013).

During the past half century, deterioration in soil health status has been linked to the shift in agriculture from 'traditional animal-based-subsistence' to 'intensive chemical- and tractor based-' agriculture that multiplied problems associated with sustainability of natural resources. The soil organic carbon (SOC) concentration in most cultivated soils of India is less than 5 g/kg compared with 15 g/kg to20 g/kg in un-cultivated virgin soils, attributed to intensive tillage, removal/burning of crop residues and mining of soil fertility. Large acreage of cultivated lands shows fertility fatigue and multiple nutrient deficiencies in many intensively cropped areas which will have major implications on sustainability the food production. Studies (Sivakumar and Stefanski, 2011) also predict that there would be at least a 10 percent increase in irrigation water demand in the arid- and semi-arid region of Asia with a 1°C rise in temperature. Thus, climate change could result in the increased demand for irrigation water, further aggravating resource scarcity. This will also increase the price of water for irrigation, making small-holder agriculture a more risky venture.

These multiple challenges offer multiple opportunities for maize to emerge as a potential crop in different cereal-based cropping systems globally, as well as in Asia, wherein the share of maize in total cereal production increased from 26.2 percent in 1991 to 34.2 percent in 2011 and from 15.4 percent to 21.0 percent in Asia, during the same period. South-Asia has shown similar trends wherein the maize production has more than doubled during past two decades. However, over 60 percent of this production increase came from area expansion (Chand and Saxena, 2014) which led to the emergence of new, highly-productive cropping systems such as the rice-maize and rice-potato-maize cropping system in addition to the traditional maize-wheat rotation. However, there still exists large (36 to 77 percent) *'management yield gaps'* in maize and these yield gaps are higher than in wheat and rice (Jat et al, 2011). This warrants a paradigm shift in agronomic management optimization not only to produce more, but more with higher efficiency of production inputs while sustaining natural resource base and reducing the environmental foot print of both traditional and non-traditional maize systems and ecologies.

Efforts are therefore, needed to shuffle the unsustainable elements of conventional agriculture such as: tilling the soil; removing all organic material; and replacing monoculture systems with sustainable ones. The process of shuffling these non-sustainable components of conventional agriculture culminates into Conservation Agriculture (CA). This approach is a resource-saving agricultural production system that aims to achieve production intensification and highyields while improving the natural resource base, along with other good-production practices of plant nutrition, water and pest management. With local adaptations and situation-specific refinements, the CA systems have shown tremendous potential across the ecologies, production systems, soil types and farm typologies around the world and led to the adoption of CA systems in over nine percent of the global area. In this paper we describe some examples of learnings on CA-based maize systems in terms of yields trends, economic returns, pest dynamics, water & nutrient productivity, CA machinery, environmental footprints etc. across a range of ecologies in South Asia.

Yield trends and economic profitability

Maize-wheat (MW) is the fifth-most dominant cropping system occupying ~3.0 million ha in South Asia and it contributes significantly to food security in the region. However, there exist large-management yield gaps in the MW system across the region. CA based management optimization have shown tremendous potential to increase crop and input productivity and system resilience under several studies across the region (Jat et al, 2013; Gathala et al, 2013). Six-year yield trends of maize, wheat and the MW system with CA and CT based management, in a sandy loam soil revealed that there was no significant difference in wheat yields for CA and CT for the initial two years but thereafter, the yields were significantly higher under CA and incremental. However, the trends in maize yield were different: the yields were similar and static for the initial five years, but increased significantly under CA in the 6th year compared to CT. The MW system yields were significantly higher under CA, with incremental trends (Figure 1). This suggests that CA results should be evaluated through a systems-lens and with a long-term perspective for proper interpretation and communication of a clear message.

The medium-term effect of tillage, crop establishment and residue management in a rice-maize (RM) cropping systems in eastern India, showed significant-yield-advantage for both rice and maize, and the RM system under zero-till, direct-seeded-rice –zero-till-maize (ZTDSR-ZTM) and permanent beds with residue (PB+R) compared to CT-based management (Figure 2). However, BP without residue retention (-R) were inferior to CT. The analysis of the individual and combined effects of tillage and residues on RM system- yield- trends (Figure 3) revealed that for initial three-years, the tillage effect was much higher than the residue effect, but from the fourth-year onwards, the residue effect was dominant. During the last two-years, the yield gains are primarily due to residue effect and the tillage effect is small. To explain these results more scientifically, the soil physical and chemical properties were monitored.

Participatory long-term (four-year) trials on CA based management in smallholder rice-maize systems of Bangladesh, showed that there were no significant differences in mean-grain-yield and net-returns in rice due to tillage treatments, but significant differences were observed in the maize and RM system. The permanent beds (PB) produced the highest maize grain yield (9.07 t ha^{-1}) as compared to CT (7.71 tha^{-1}) but this was at par with rest of tillage treatments i.e. fresh beds (FB), minimum tillage (MT) and strip-tillage (ST). Similar yield trends were also observed in maize as well as the RM system. The CA-based tillage treatments (PB, ST and FB) gave higher-net returns 45, 29 and 21 percent, respectively, over CT except MT. The maximum net returns were achieved under PB (1,428 US$) followed by MT. Similar trends were observed under system-net-returns PB (1,965 US$)> MT (1,842 US$)> FB (1,811US$)>ST (1,762US$) > CT (1,542 US$).The CT gave lower-net-returns than CA based tillage treatments, except MT. This study also showed that CT $_{l}$ and traditional planting required more labor as compared to mechanized CA-based treatments. In the rice crop cycle, CT required 84 man-days per hectare (ha^{-1}) followed by FB (76 man-days ha^{-1}) and the lowest number of man-days were needed in PB (54 man-days ha^{-1}). Maize production with CT involved the highest amount of labor (75 man-days ha^{-1}) which was significantly higher than CA-based tillage treatments (ST, PB, FB and MT). Overall, traditional crop production practices were more labor-intensive (158 man-day’s ha^{-1} yr^{-1}) than CA-based tillage treatments.

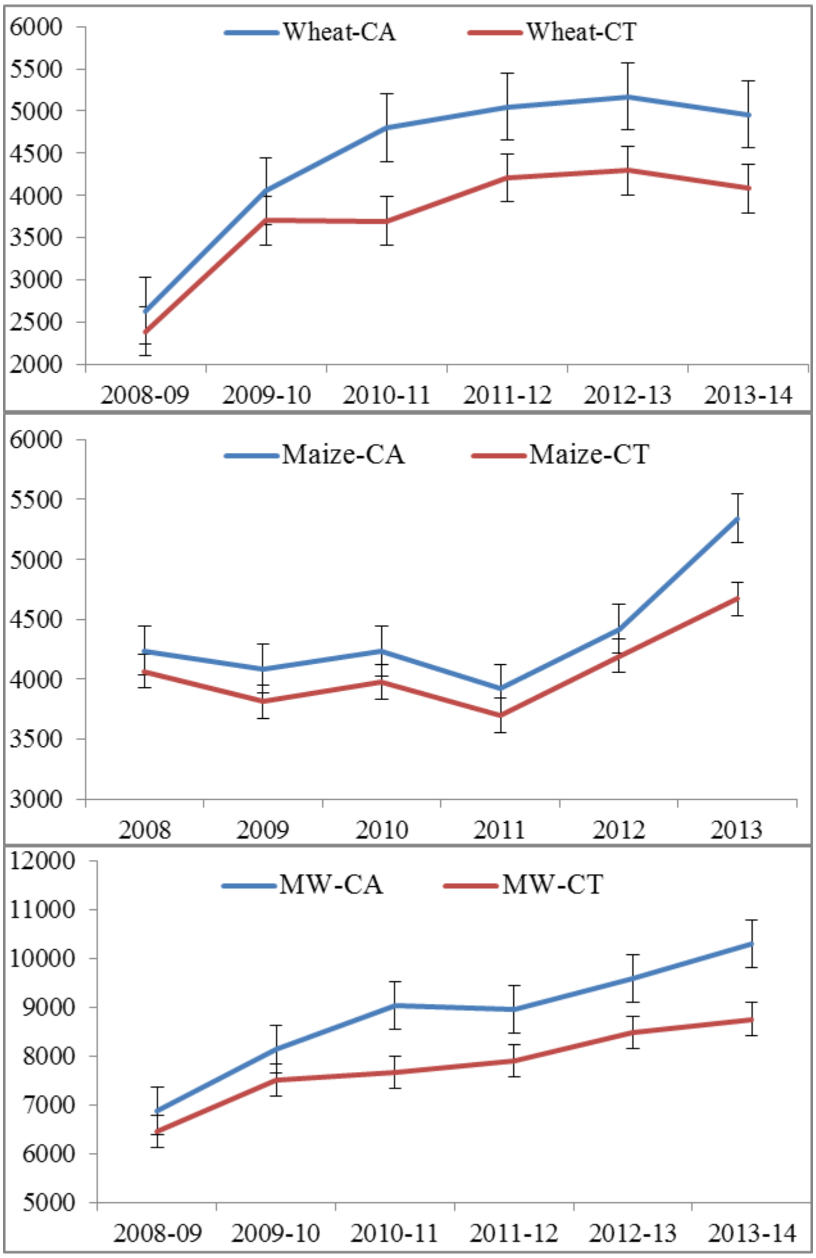

Figure 1. Medium-term yield trends of maize, wheat and maize-wheat (MW) system under CA and CT based management in a sandy loam soil (DMR, New Delhi, India)

Genotype x management interactions

For realizing the full-potential of CA-based management practices, it is necessary to optimize the cropping system by capturing genotype x management interactions (genetic adaptation) and defining their recommendation domains. The results of an experiment (average of three-years) in rainfed ecologies of eastern India (Figure 4), wherein five maize hybrids were grown with three contrasting tillage- and crop- establishment practices, revealed significant yield-interactions. HQPM-1 was the best-yielding maize hybrid under PB but it showed very-poor performance under CT, whereas DMH-117 performed better under CT compared to HQPM-1. Under ZT, all hybrids performed equally well. In terms of yield attributing characters, the tillage and crop establishment practices had significant effect only on the number of cobs/ha that in turn, led to significant variation in yield. This study demonstrated that the best-suited genotypes should be targeted for contrasting-management systems in different ecologies.

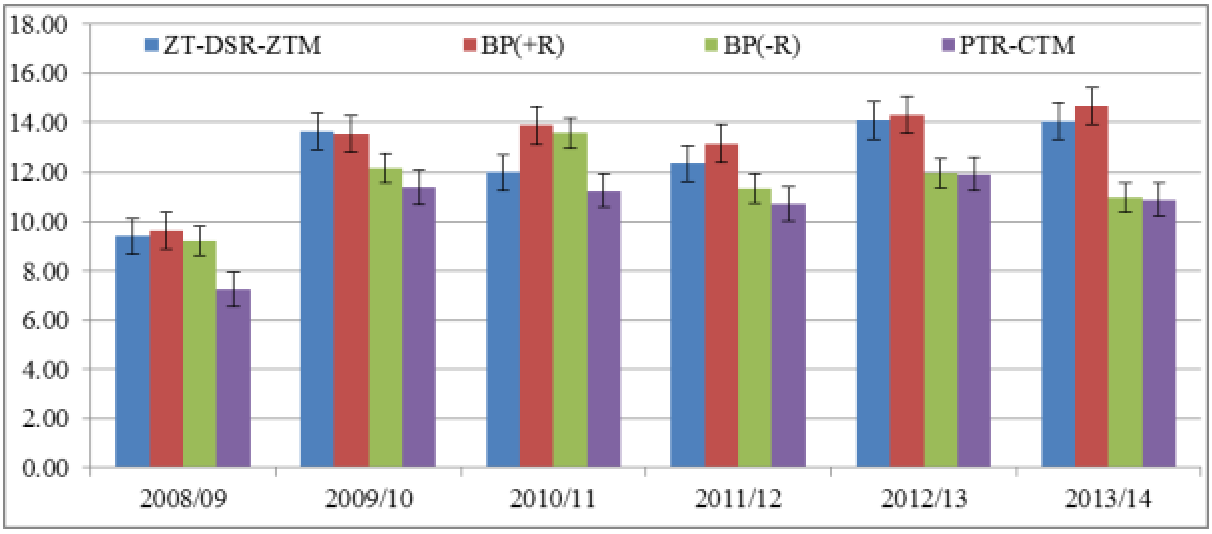

Figure 2. Rice-maize system productivity (t ha^{-1}) under different tillage practices over 6 years

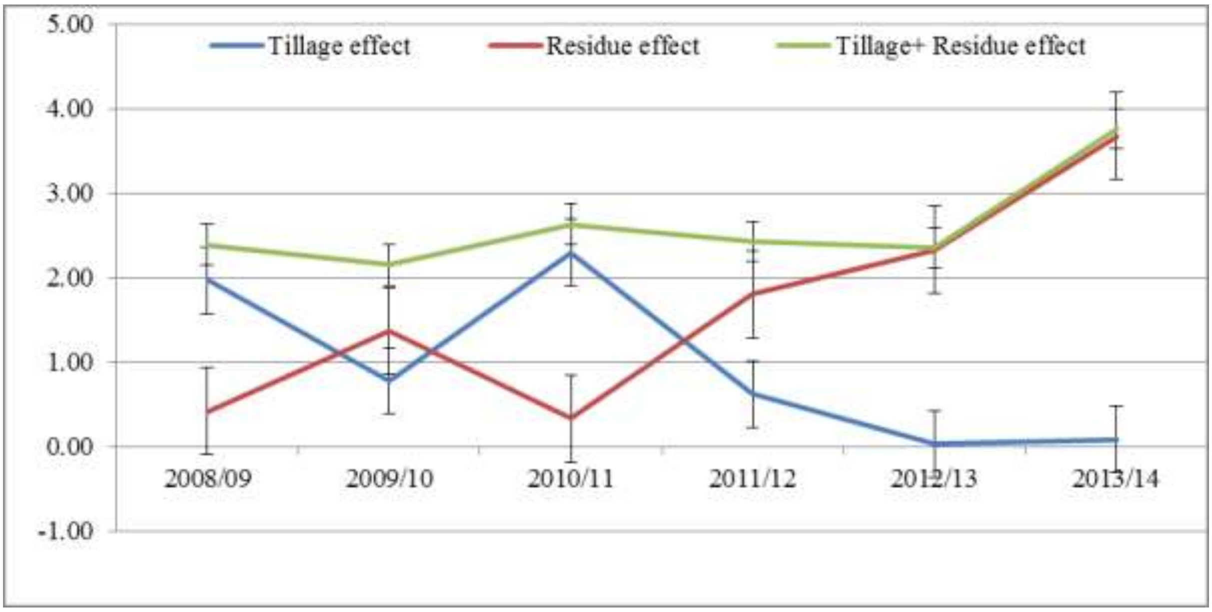

Figure 3. Trends in individual and combined effects of tillage and residues on rice-maize system grain yields

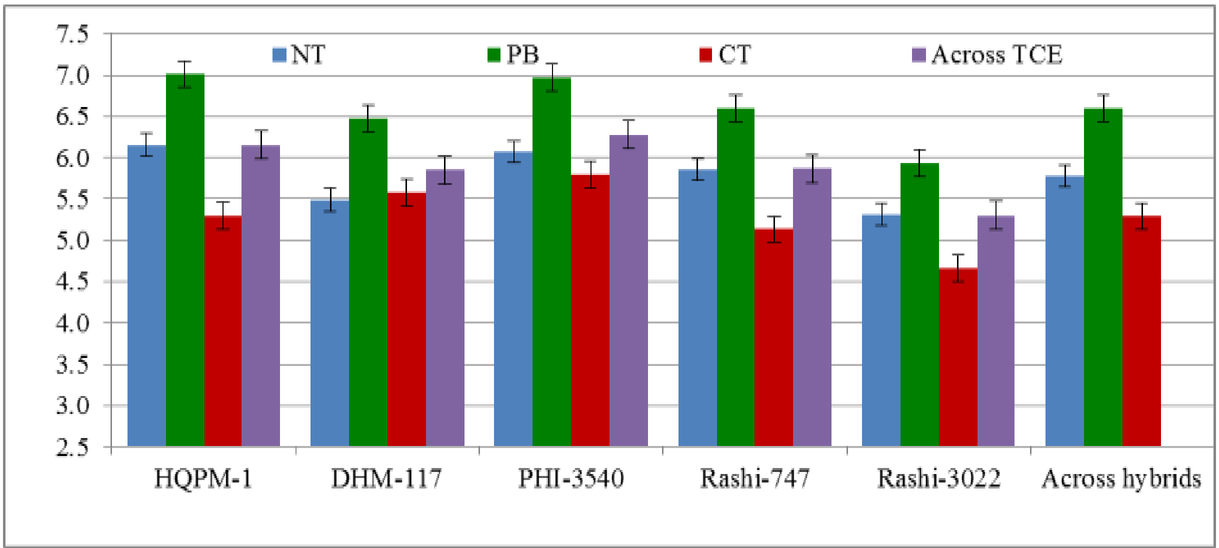

Figure 4. Maize (yield t ha^{-1}) genotype interactions with contrasting tillage management practices in rainfed ecologies, Jharkhand, India

Water management and water productivity

Water is a crucial resource for crop production and hence, improvements in water productivity (WP), the amount of food produced per unit of water consumed, have the potential to improve both food security and water sustainability. Therefore, there is an urgent need to increase the WP through water-smart technologies, strategies and enabling policies. Though there are a range of interventions available for improving irrigation WP in agriculture, their applications, accessibility, affordability and investment priorities are situation-specific. The advancement in agronomic management optimization will have to play a critical role in improving WP and sustainable food production systems. CA-based management practices have shown to produce more with less water, but defining more precise water management strategies within CA systems may add further value in terms of yield and WP. In a two-year field study conducted during the spring 2013 and 2014 seasons at the Borlaug Institute for South Asia (BISA)-CIMMYT, Ludhiana, India under the aegis of Cereal Systems Initiative for South Asia (CSISA) project funded by the United States Agency for International Development (USAID) and the Bill & Melinda Gates Foundation (BMGF), the grain yield and amount of irrigation water-use were significantly affected by crop-residue-mulch and water-management practices. Mulching caused significant increase in yield over no mulch treatments, irrespective of irrigation treatments. On average, drip-irrigation saved up to 66 percent water compared to the farmers' practice. Soil moisture tension (SMT) guided water application using a drip-system, along with residue mulch produced maize-yield similar to flood irrigation resulted in a saving of 4,232 m^3 ha^{-1} of water and thereby increased irrigation WP by 175 percent. SMT-guided irrigation application in alternate furrows with residue mulch, though using relatively more water compared to drip irrigation, produced more yield and hence, provides much better option for irrigation for the resource poor farmers (Figure 5). Efforts have further been made to develop more precise- and automated- irrigation systems for CA-based management practices in maize. The initial results at BISA-CIMMYT, Ludhiana, are very promising and show significant increases in yield, WUE, NUE with a simultaneous reduction in the environmental footprint.

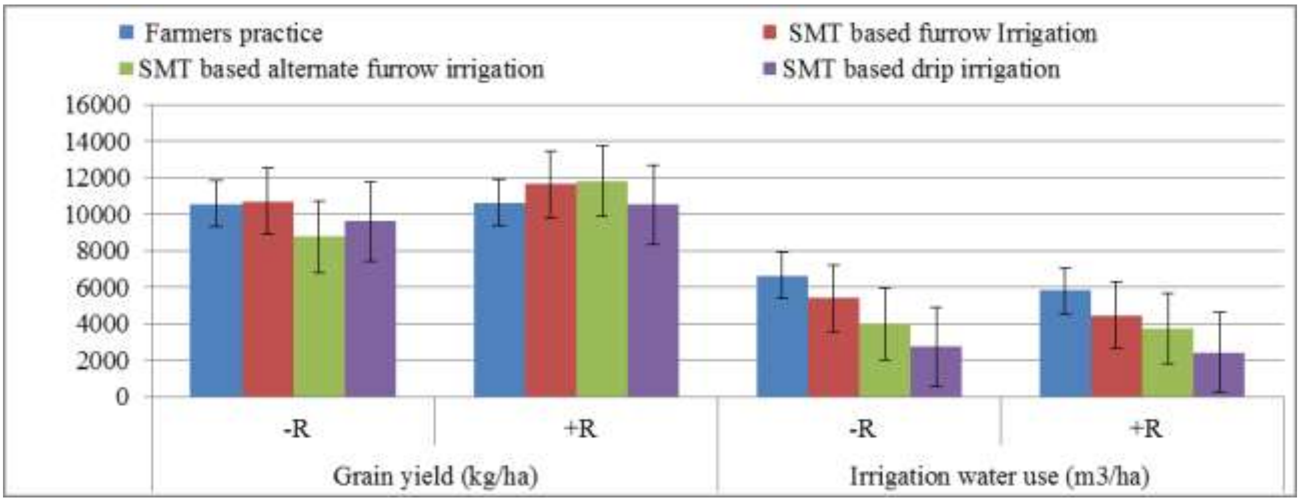

Figure 5. Spring maize yield and water use under residue mulch and irrigation management options in north-west India

Nutrient interactions

Nutrient management plays an important role in improving crop productivity and profitability of farmers when practiced in a scientific manner. Maize is rapidly emerging as a favorable option for farmers in South Asi,a as a non-traditional component crop of rice and wheat-based systems. Drivers of this change are higher productivity and profitability, reduced water requirement, and better resilience of maize to biotic and abiotic stresses than rice or wheat. However, high-yielding maize extracts greater amounts of mineral nutrients from the soil than either rice or wheat. Balanced nutrient management, in maize, should aim to (a) supply fertilizer nutrients according to the demand of the crop; (b) apply nutrients in ways that minimize their loss and maximize their efficiency of use; and (c) apply nutrients with consideration to the soil-supplying-capacity under contrasting management systems (for example CA versus CT). Therefore, the information on soil-supplying-capacity and nutrient-response under contrasting management systems is important to optimize nutrient management practices for the maize crop. The Nutrient Expert® (NE) decision-support tool developed and validated by IPNI and CIMMYT in collaboration with NARES, have shown tremendous potential to capture spatial and temporal variability and to provide precise-nutrient prescriptions for smallholder systems. Results of an experiment in black soils of peninsular India revealed that there is significant interaction of nutrient management and tillage systems. The maize grain-yield under ZT, was significantly superior to CT (8,547 kg ha $^{-1}$), but it was improved significantly with NE based SSNM (Figure 6). The NE is quite handy in prescribing customized recommendations to farmers who are interested in different target yields; NE recommendations were realized for both the targeted yields of maize. Another study on the interaction of tillage, residues, legumes and nutrient prescriptions (Table 1) in MW systems in northwest India, revealed significant interactions and additive-effects of all the parameters on crop yield and economic returns.

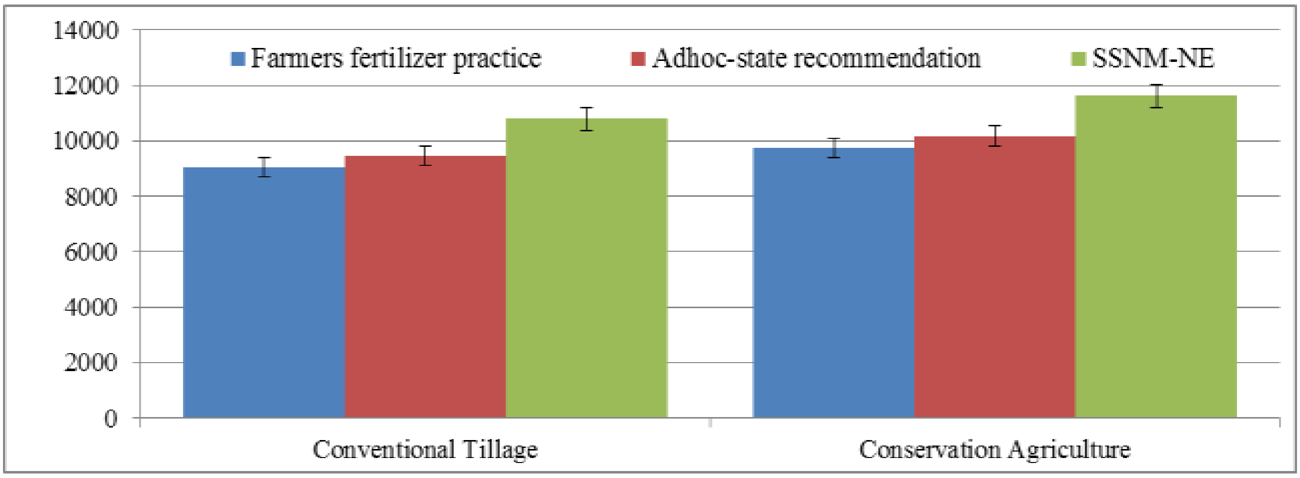

Figure 6. Maize yield responses to nutrients under contrasting tillage management systems in heavy soils of peninsular India

Table 1. Interactive effects of tillage, residue, legume and nutrient management in maize-wheat rotation in north-west India

TCE	Residue & legume	Nutrient Management	MW System yield (kg/ha/yr)	MW System net return (USD/ha/yr)	TCE-Yield effects	TCE-income effects	Residue, legume yield effects	Residue, legume income effects	Nutrient yield effects	Nutrient income effects
CT	No	FFP	11622	1666	12886	1903	12723	1889	11944	1779
CT	No	SR	12921	1911					13022 (+1078)	1991 (+212)
CT	No	SSNM-NE	13627	2091					13834 (+1890)	2243 (+464)
CT	Yes	FFP	12236	1716			13038 (+315)	2062 (+173)		
CT	Yes	SR	13039	1905						
CT	Yes	SSNM-NE	13874	2129						
PB	Yes	FFP	11975	1955	13027 (+141)	2207 (+304)				
PB	Yes	SR	13107	2156						
PB	Yes	SSNM-NE	14001	2510						

TCE: Tillage, crop establishment, CT- conventional tillage, PB-Permanent beds, FFP- farmers fertilizer practice, SR- state recommendations, SSNM-NE- site-specific nutrient management with Nutrient Expert decision support tool, MW system- maize-wheat system

Weed interactions

Heavy weed infestation in maize is one of the major production-system constraints which leads to large-yield losses (~60 percent), particularly in rainfed ecologies. Lack of effective post-emergence herbicide molecules and repeated soil inversion as a weed management strategy, leads to exposure of deeper soil-weed-seed-bank near the soil surface which provides favorable conditions of light, aeration, and less-depth for the germination and emergence of weeds (Brenchley and Warington, 1933). Tillage practices also change soil residue cover which affects sunlight reaching to the soil and temperature, which all are the important factors that determine weed germination (Mulugeta and Stoltenberg, 1997). Therefore, CT as a weed management strategy further aggravates the weed problem in maize in complex production ecologies. Integrated strategies including herbicide molecules and CA-based management practices that have demonstrated potential benefits in terms of both yield gains and reduction of weed pressure over time. Results of a study in MW rotation in the eastern Indo-Gangetic Plains (IGP) revealed significant reduction in the density of grassy weeds and sedges as well as total weed-biomass over time, under CA based management, compared to conventional tillage practices (Table 2). This also showed positive yield-response in maize as well as wheat over time.

Table 2. Weed dynamics in maize under conservation agricultural in eastern IGP

Tillage, Crop establish-ment	2009				2010				2011			
	Grasses	Broad leaf weeds	Sedges	Total dry weight (g/m^2)	Grasses	Broad leaf weeds	Sedges	Dry weight (g/m^2)	Grasses	Broad leaf weeds	Sedges	Dry weight (g/m^2)
No-till	14.1	15.8	18.5	28.7	9.4	24.0	4.2	18.0	2.0	1.0	5.0	2.3
Permanent beds	22.6	16.0	22.4	31.3	15.5	30.0	5.2	22.0	2.0	3.0	4.0	2.4
Conventional till	22.8	12.3	233.6	56.4	18.4	12.0	202.4	63.0	19.4	18.3	285.3	74.0
CD (P=0.05)	3.2	1.6	17.5	4.5	2.3	4.2	15.6	4.5	1.8	1.7	15.3	4.2

Soil quality

Several studies showed positive results of CA-based management practices on soil health compared to conventional tillage-based production systems. The most important factor in determining soil health is soil organic matter. Tillage tends to engender accelerated oxidative breakdown of organic matter with accelerated release of CO_2 to the atmosphere that exceed normal, soil-respiration processes. This results in reduced SOC contents and explains why it is very difficult to build-up organic matter with CT. Combining the retention of crop residues (rather than removal or burning) with direct-seeding of crops without 'normal' tillage leads to an increase of SOC, because crop residues are precursors of the SOC pool. The sub-soil compaction was much higher with CT than with the CA-based production system. This limits root growth and hence, the uptake of water and nutrients from deeper soil layers. Similarly, the infiltration rate was much higher under CA over CT, which reduces the run-off loss and also reduces soil movements and or erosion with higher intake of water in the crop-root zone. Significant improvement in soil aggregates was recorded under irrigated- as well as rainfed-maize systems which is a key indicator of soil quality and governs several soil processes (Govaerts et al, 2009; Jat et al, 2014).

Environmental footprints

CA-based management systems in general, tend to reduce the environmental footprint not only in absolute quantity but also per-unit of food grain production. Evidence from a CCAFS-supported collaborative research (DMR-CIMMYT) in India, revealed that irrespective of maize-cropping systems, cumulative CO_2 emissions in maize during monsoon season, were significantly higher in CT (2.75 Mg -CO_2-C ha^{-1}) than in CA (2.41 Mg CO_2-C ha^{-1}). Similarly, cumulative N_2O emission during the same season was also higher under CT (0.84 kg N_2O-N ha^{-1}) compared to CA (0.55 kg N_2O-N ha^{-1}). However, the cumulative CO_2 and N_2O emission was not significantly different among the tillage systems and between cropping systems during winter and spring crop seasons. These results showed that the N_2O emission during the crop cycle ranges from 0.5 percent to 1.2 percent of applied nitrogen fertilizer. The system-level global warming potential based on soil flux (without considering photosynthetic uptake) in this study, ranged from 40.17 (CA) to 56.06 Mg CO_2-eq ha^{-1} (CT) in the maize-wheat-mungbean cropping system, showing reductions in the environmental footprint, using CA-based management.

CA machinery

CA based crop management technologies have demonstrated potential to address many emerging challenges across the world. However, to accelerate the pace of adoption of CA in the smallholder-dominated region (South Asia), development and adaptation of smart-CA-based machinery for the smallholder farmers are critical. To advance this, significant efforts led to the development and validation of a wide-range of CA mechanization options (multi-crop no-till planter, multi-crop raised bed planter for 4 wheel tractor m[4WT], 2WT, animal-drawn, manual-drawn, inter-culture implements, harvesting and threshing solutions etc.) for maize systems.

Targeting CA to diversity of farm typologies

Characterizing the diversity of farming systems is essential to delimit the recommendation domains of CA-based management portfolios relevant to diverse farm typologies. In smallholder-dominated intensive cereal based systems, successful development of alternative, efficient and resilient cropping systems, CA-based practices portfolios will have to be coherent with the specific resource-endowment of the production area, and the full range of activities carried out by farming households. Grouping farming systems in terms of resources and livelihood activities, as well as current cropping practices, could provide guidelines for the development of adapted innovations and better- targeted dissemination. In reality, recommendations on agronomic management practices in South Asia, do not consider farm resources. Consequently, these non-flexible recommendations are generally not accepted by farmers. The problem of yield-gap along with a lack of site-specific agronomic management necessitates the identification of yield-limiting factors in different socio-economic settings and characterization of farm typologies for targeting site-specific management interventions. Farm typology recognizes that farmers: i) are not a monolithic group; and ii) face differential constraints in their farming decisions based on the available resources and their lifestyle. Developing farm-typology is an essential step in any realistic evaluation of the constraints and opportunities that exists within farm households for appropriate policy interventions.

Conclusion

During the past two decades, researchers and extension agents, in close association with farmers, have invested significant efforts in solutions to address the issues of yield-plateau, increasing cost of labor, water and energy, declining farm-profitability, and deteriorating soil-health by developing and adapting CA- based crop management practices for the major cereal-based systems across South Asia. This has paid dividends for addressing these challenges not only in South Asia, but across the globe. However, interaction of tillage and crop establishment techniques with other management practices of water nutrient, weed, genotypes etc. are critical for realizing the full potential of CA-based management systems. Therefore, the future direction of CA research for development (CAR4D) should have a strong layering-component, with diverse technologies to promote adoption of the key principles of CA.

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