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Foreword

In North-western India, rice–wheat (RW) cropping system is playing pivotal role in the food security of the country. Despite the fact, the practice of rice–wheat cultivation has brought forth several edaphic, environmental, ecological and social implications over the years. Continuous cultivation of rice–wheat system in North-Western Indo-Gangetic plains (NW-IGP) of India has led to emergence of several second-generation problems over the last five decades, threatening the sustainability of the system. Over-exploitation of ground water reserves leading to depletion of ground water level, low carbon content, emergence of multiple nutrient deficiencies, increased cultivation cost, labour shortage and climate change, all pose threats to the sustainability of this system in NW India. Evidences showed that the RW system is now showing signs of fatigue and yields of rice and wheat in this region have reached a plateau or are declining, the soils have deteriorated, the groundwater table is receding at an alarming rate, total factor productivity or input-use efficiency is decreasing, cultivation costs are increasing, profit margins are decreasing, and the simple agronomic practices that revolutionized RW cultivation in the IGP are fast losing relevance, output growth, employment generation and natural resources sustainability.

To overcome formidable problems of soil health deterioration, irrigation water shortage and climate change in RW system of North-West India, sustainable intensification based on the principles of conservation agriculture (CA) coupled with micro irrigation technologies has emerged an important alternative to attain the objectives of improved and sustained productivity, increased profits and food security while preserving and enhancing the natural resources and the environmental quality. The CA based agro-technological package, intensified cropping system and holistic farming approach not only saves natural resources but may help in producing more at low costs, improves soil health, promotes timely planting and ensures crop diversification, reduces environment pollution and adverse effects of climate change on agriculture. Implementation of micro irrigation based agricultural diversified system intensification in NW India may be a productive way to build resilience into agricultural systems for national food security while fulfilling the goal of 'more crop per drop'. Sustainable intensification and micro irrigation are the important components of the overall strategies needed to enable future generations to practice agriculture in NW India.

I am very happy to see that a group of scientists from ICAR and CGIAR has developed CA based intensified futuristic cereal systems to address the second-generation problems of RW system in North-West India. I am sure the National Agricultural Research and Extension System (NARES), in partnership with all stakeholders (CGIAR, NGOs, private sector organizations and farmer's societies) will take full advantage of recommendations emerging from the outcomes of the project. It is also expected that this publication will be immensely helpful to policy planners, administrators, researchers, extension workers, farmers, stakeholders and other users for sustainable crop production while preserving the natural resources base and environmental quality for betterment of livelihood in North-West India. I congratulate authors as well as ICAR and CIMMYT for bringing out this valuable publication.

(RK Yadav)
Director, ICAR-CSSRI

C O N T E N T

1. Introduction

Rice based systems constitute the main economic activity in rural areas and provide staple food for >400 millions of people throughout South Asia. The slowdown in the growth rate of cereal production has emerged as formidable challenge for the future food and nutritional security in South Asia. Furthermore, natural resource degradation, declining labor availability, environmental quality and climate change induced weather variability pose steep challenges in the region. Continuous cultivation of rice-wheat (RW) system in North West (NW) Indian IGP (Indo-Gangetic plains) has led to an over-exploitation of fresh ground water reserves, poor soil health, low input response, environmental pollution through residue burning and low farmer's profitability. Furthermore, increased cultivation cost, labour shortages and climate change pose additional threats to the sustainability of this system.

The sustainability of RW system in NW India is crucial to meet out the National Food Security Act, 2013. Sustaining and increasing the production of cereal systems in the Indian states of Punjab, Haryana, and western Uttar Pradesh in the NW IGP, popularly known as the "breadbasket" of the country, is essential to meet the food requirement of India's burgeoning population, which is likely to increase from 1.4 billion in 2024 to 1.6 billion by 2050. The sustainability of this system is at high risk because of resource degradation, declining factor productivity and shrinking farm profitability under current farming practices.

In NW India, urbanization, labor migration, preference for non-agricultural work, gender inequalities etc. are the emerging issues hampering the growth of the agricultural sector. Intensive cereal cropping systems are the main economic activity in the region which greatly influence their livelihoods. As there is little scope for expanding the area under cultivation, an urgent strategy is needed to further sustainably intensify land use to increase the productivity and quality of cereal systems to meet the growing demand. Rising costs of chemical fertilizers and change in the subsidy policies of the Government are forcing the use of chemical fertilizers in favor of N at the cost of P, K and other micro-nutrients resulting in depletion of soil fertility, nutrient imbalances in soil, decreasing factor productivity and increasing cost of nutrient management. Conventional management practices of RW system in NW India involve intensive tillage and favors open-field burning of crop residues resulting in loss of lives, soil nutrient depletion, respiratory diseases in human beings and environmental pollution through greenhouse gas (GHG) emissions. More than 30 million tonnes of cereal crop residue is burnt in NW India annually. Climate change is another concern affecting agriculture. It has been projected that India could lose 4-5 million tonnes of wheat with every 1°C rise in temperature. Unusual terminal heat and untimely rainfall are causing yield declines in wheat, especially in NW India. Labor scarcity and escalating fuel costs are multiplying the overall cost of cultivation, making conventional cereal-based agriculture a less profitable enterprise. Resource availability and socio-economic conditions of farmers play a major role in technology targeting, decision making and adoption of agricultural technologies and practices.

To overcome formidable and complex problems of RW system in North-West India, conservation agriculture (CA) based sustainable intensification with systemic and holistic research approach has the potential to arrest ground water table depletion, curb residue burning, improve soil health, and enhance crop productivity and farm profitability while minimizing the risks of expected climate change impacts. CA stands out as a highly effective alternative to conventional crop production practices (Jat et al., 2021), defined as the collection of practices for managing soil, crops, nutrients, water, and landscape systems, which could accomplish all the objectives mentioned above while protecting other limited natural resources like energy (Kassam et al., 2019; Jat et al., 2014). CA offers numerous benefits, including efficient utilization of crop residue, water and nutrients, soil moisture conservation, weed reduction and improvement in soil quality (physical, chemical and biological) (Jat et al., 2009; Jat et al., 2015). In CA-based management system, ZT along with crop residues retention can play an important role in buffering soil moisture, temperature, replenishing soil nutrients stocks (adaptation to climate risks) and organic matter in addition to reducing the environmental footprints (mitigation of GHGs) by eliminating in-field burning, thus leading to CA-based sustainable intensification in RW production ecologies.

Conventional till-based RWCS often results in inefficient water and energy use, as well as soil health degradation. Conservation agriculture practices, such as zero tillage (ZT) and direct-seeded rice (DSR), help conserve water by reducing evaporation and runoff. Additionally, micro-irrigation systems like sub-surface drip irrigation (SDI) further enhance water-use efficiency by delivering water directly to the root zone. Unlike surface drip systems, SDI requires less maintenance, making it more compatible with conservation agriculture systems (Sidhu et al., 2019). With laterals permanently laid at specific soil depths, SDI eliminates the need for frequent anchoring and has a longer lifespan compared to surface drip systems, making it better suited for conservation agriculture. SDI systems can reduce water use, electricity consumption for irrigation, and fertilizer usage, aligning with conservation agriculture practices to optimize water, energy, and fertilizer savings.

Despite its benefits, the adoption of CA in the Indo-Gangetic Plains (IGP) remains limited due to several challenges, such as the lack of a national policy on CA, nearly free electricity, inadequate enabling policies, limited access to resources, and deeply rooted traditional farming practices. Furthermore, knowledge gaps regarding the long-term advantages of CA-such as energy savings, greenhouse gas (GHG) mitigation, water conservation, sustainable yields, and improved soil health—prevent widespread adoption among farmers. Overcoming these obstacles through targeted research and extension services is crucial to promoting CA practices and achieving sustainable intensification in cereal-based systems throughout South Asia.

2.Conceptual framework and research platform design

Development and deployment of cost-effective and farmer friendly option for the management of natural resources (soil, water and crop residues) in cereal-based systems is a major challenge as well as opportunity for the sustainability of the intensive RW systems in the "food bowl" of India. It mainly focused on process-oriented research to design a next generation of cereal systems that are highly productive, resource efficient, sustainable, and adapted to the expected changes in environmental and socioeconomic drivers (Fig. 2.1). At ICAR-CSSRI, near-production scale long-term Research Platform (RP) was designed and established to assess the performance of different agricultural systems, using a wide range of indicators (crop rotation, tillage, crop establishment, crop, water and residue management) (Fig. 2.2).

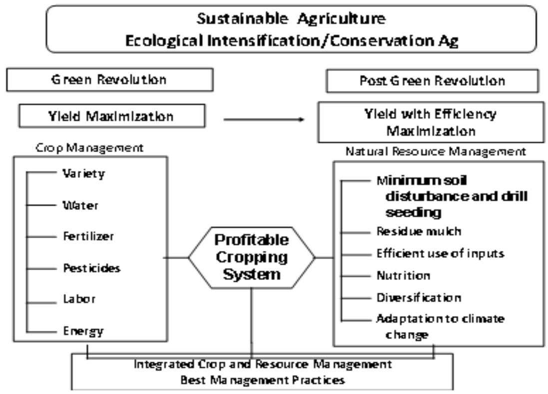

Fig. 2.1: Framework of the integrated crop and resource management

In order to give a boost to cereal production during early nineties in IGP, efforts were made to develop and deployed the resource conserving technologies (RCTs) through a NARS (ICAR) led and CGIAR (CIMMYT) managed, Rice-Wheat Consortium (RWC). However, the approach of technology development was primarily commodity centric revolving around tillage and crop establishment methods. Over time, it was realized that the required increase in cereal yield could not be achieved with piecemeal efforts, rather a holistic, integrated systems approach with multi-disciplinary, multi-institute and multi-stakeholder perspective is desired for ensuring increase in cereal yields. Considering these facts and challenges, opportunities and potential impacts at sub-national, national and regional levels, the Cereal Systems Initiative for South Asia (CSISA) was conceptualized as a regional project. The CSISA was started in 2009 at ICAR-CSSRI Karnal with funding from International Maize and Wheat Improvement Center (CIMMYT), and International Rice Research Institute (IRRI). All the project activities continued with funding from CIMMYT-Climate Change Agriculture and Food Security (CCAFS) up to December 31, 2021 and Transforimg Agri-food Systems in South Asia (TAFSSA) up to November 2024. The project aimed to provide an overall strategy and umbrella so that new developments in science and technology to contribute in short- and long-term cereal production growth on a sustainable basis in South Asia's most important grain baskets.

To tackle water, labour, and energy-related challenges in the Indo-Gangetic Plain (IGP), a prolonged field experiment was started in 2009-10. This experiment encompassed four distinct cereal-based scenarios (Sc), each varying in terms of cropping systems, residue handling, tillage techniques, crop establishment methods, irrigation water, and other aspects of crop management practices (Kumar et al., 2018). The broad four scenarios are as follows: Sc I (farmers' practice): - Puddled transplanted rice–conventional till wheat (CTRW); Sc II (partial CA): Puddled transplanted rice–zero till wheat–zero till mung bean (TPR-ZTWMb); Sc III (full CA): Zero till direct seeded rice–zero tillage wheat–zero till mung bean (ZTDSR-ZTWMb); Sc IV (CA): Zero till maize–zero till wheat–zero till mung bean (ZTM-ZTWMb). These scenarios were evaluated and ideally matched with farmers' field units on an area of 2000 m^2 (100 m × 20 m plot) with three replications in a complete randomized block design (CRBD). In May 2016, 2 additional scenarios with subsurface drip irrigation (CA+SDI), were introduced by dividing the primary plots of Sc III and Sc IV as Sc V and Sc VI making the total number of scenarios to six. Table 1 contains details on all the scenarios, factors driving agricultural changes and practices related to crop management. For rice, maize, and wheat crops, irrigation was administered based on tensiometers (IRROMETER, Riverside, California) readings that measured soil moisture potential (SMP). The tensiometers were positioned at a depth of 15 cm between the crop rows and lateral lines. Table 1 provides a detailed breakdown of the specific SMP values used for all crops under varying management scenarios. In the case of rice grown with CT, the fields were continuously flooded in the first three weeks post-transplantation to promote optimal growth of the seedlings. However, for DSR, irrigation was carried out frequently from sowing until the emergence of 3-4 leaves to ensure successful germination and establishment of the crop. Thereafter, subsequent irrigations were scheduled based on predetermined threshold values of SMP to maintain ideal soil moisture levels.

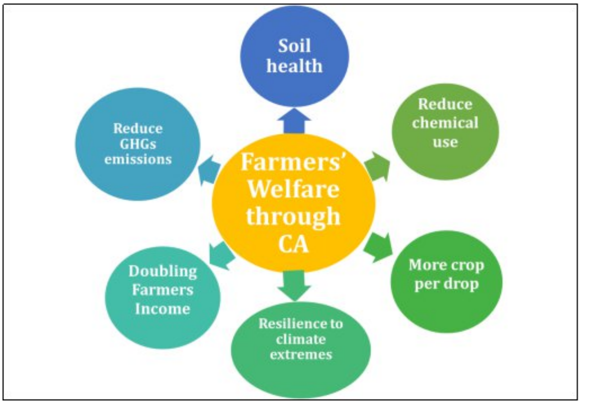

Fig. 2.2: Expected changes in environmental and socioeconomic drivers though CA

Evaluation of different scenarios

Grain yield and system productivity

All the crops were sampled at maturity by manual harvesting. Random samplings were carried out from two locations, each covering of 25 m2 area for rice, wheat and mungbean crops. For maize crops, samples were harvested from two random locations of 30 m2 each, making a total area of 60 m^2 per plot. The grain yield of rice and maize crops was adjusted at a moisture content of 14%, while wheat grain yields were adjusted to 12% moisture level for uniformity across the samples and scenarios. For comparing the kharif crops (rice and maize), the grain

Table 2.1: Drivers of change, crop rotation, tillage, crop establishment methods, and residue and water management of different scenarios

Scenario (Sc)	Drivers of Change	Crop sequences	Tillage	Crop Establishment Method	Residue Management	Nutrient Management (NPK, kg/ha)	Water Management
I	Business as usual (Farmer's Practice)	Rice-Wheat-Fallow	CT-CT	Rice: Transplanting Wheat: Broadcast	All residue removed	Rice: 175+58+0 Wheat: 150+58+0	Rice: Continuous flooding of 5-cm depth for 1 month, followed by irrigation applied at hair-line Wheat: Need-based irrigation or at critical crop growth stages
II	Increase food production, income & nutrition through intensification and best management practices	Rice-Wheat-Mung bean	CT-ZT-ZT	Rice: Transplanting Wheat: Drill seeding Mung bean: Drill/relay	Full (100%) rice and anchored wheat residue retained on the soil surface; full mung bean residue incorporated	Rice: 150+58+60 Wheat: 150+64+32 Mung bean: 0+0+0	Rice: Continuous flooding of 5-cm depth for first 15-20 days after transplanting followed by irrigation at -40 to -50 kPa matric potential at 15-cm depth till 1 week before flowering followed by irrigation at -15 to -20 kPa Wheat: Flood irrigation at -40 to -50 kPa matric potential
III	Deal with rising scarcity of labour, water, energy, malnutrition, degrading soil health and emerging climatic variability	Rice-Wheat-Mung bean	ZT-ZT-ZT	Rice: Drill seeding Wheat: Drill seeding Mung bean: Drill/relay	Full (100%) rice and mung bean; anchored wheat residue retained on the soil surface	Rice: 160+64+62 Wheat: 150+64+32 Mung bean: 0+0+0	Rice: Kept soil wet for first 20 days followed by irrigation at -20 to -30 kPa matric potential Wheat: Flood irrigation at -40 to-50 kPa matric potential

Scenario (Sc)	Drivers of Change	Crop sequences	Tillage	Crop Establishment Method	Residue Management	Nutrient Management (NPK, kg/ha)	Water Management
IV	Sustainable intensification (SI) with a futuristic cropping system to deal with the same issues as in scenario III	Maize-Wheat - Mung bean	ZT-ZT-ZT	Maize: Drill seeding Wheat: Drill seeding Mung bean: Drill/relay	Maize (65%) and full mung bean; anchored wheat residue retained on the soil surface	Maize: 175+64+62 Wheat: 150+64+32 Mung bean: 0+0+0	Flood Irrigation at -50 kPa in maize and -40 to-50 kPa matric potential
V	SI of RW system with CA+SSDI to deal with same issues as in Sc III	Rice-Wheat -Mung bean	ZT-ZT-ZT	Same as in scenario III	Same as in scenario III	Rice: 130+64+62 Wheat: 120+64+32 Mung bean: 0+0+0 N in rice- 8 splits & wheat- 4 splits through SSDI Fertigation	Subsurface drip irrigation (SDI) at -20 to -30 kPa in rice and -40 to -50 kPa matric potential in wheat
VI	SI of MW systems through CA+ SSDI to deal same issues as in Sc III	Maize-Wheat - Mung bean	ZT-ZT-ZT	Same as in scenario IV	Same as in scenario IV	Maize: 140+64+62 Wheat: 120+64+32 Mung bean: 0+0+0 N in maize- 3 splits & wheat- 4 splits through SDI Fertigation	Subsurface drip irrigation (SDI) at -50 kPa in maize and -40 to-50 kPa matric potential in wheat

yield of maize (Sc 4 and Sc 6) was converted into rice equivalent yield (REY). While, for comparing the overall system productivity, the grain yields of maize, wheat, and mungbean were converted to rice-equivalent system yield (REYS) by using Eq. (1)

Eq. 1:

$$Rice\ equivalent\ yield\ (Mg\ ha^{-1}) = \frac{Wheat\ or\ Maize\ or\ Mungbean\ yield\ (Mg\ ha^{-1}) \times MSP\ of\ respective\ crop\ (INR\ Mg^{-1})}{MSP\ of\ rice\ (INR\ Mg^{-1})}$$

Where MSP- the minimum support price of Govt. of India; INR-the Indian rupee.

Economic analysis

The economic analysis/profitability was worked out for all crops and cropping systems under the respective treatments. The total cost of cultivation (COC) includes all the input and related costs (field, labour, and electricity) that are involved in crop production from sowing to marketing. The net returns were calculated as the difference between the gross returns (GR) and the COC. The net returns (NR) were calculated by using equation (2).

Eq. 2: $Net\ Returns = Gross\ returns\ - Total\ cost\ of\ Cultivation$

The system NRs were calculated by adding NRs of crops harvested within an individual calendar year.

Water productivity and water footprint

The amount of irrigation water that was applied was quantified (in mm ha-1) by using Eqs. (3) and (4). The irrigation water productivity (WPI) was then calculated by using Eq. (5), as depicted below:

Eq. 3: $$Volume\ of\ irrigation\ water\ (kl\ ha^{-1}) = \frac{(Final\ water\ meter\ reading - Initial\ water\ meter\ reading)}{Plot\ area\ in\ m^2} \times 10000$$

Eq. 4: $$Irrigation\ water\ (ha - mm) = \frac{Volume\ of\ irrigation\ water\ (kl\ ha^{-1})}{10}$$

Eq. 5: $$WP_I\ (kg\ grain\ m^{-3}) = \frac{Grain\ yield\ (kg\ ha^{-1})}{Irrigation\ water}$$

Where, 1 ha–mm irrigation depth = 10 kl = 10 m^3; 1m^3 = 1000 L.

Eq. 6: $$\text{Water footprint (L } kg^{-1}) = \frac{Irrigation\ water\ (m^3\ ha^{-1}) \times 1000}{System\ productivity\ (Mg\ ha^{-1}) \times 1000}$$

Partial factor productivity of nitrogen (PFPN)

The partial factor productivity assesses the resource utilization efficiency of the production system, serves as an approach for evaluating the total economic gain relative to utilization of any resource applied to the system, including nutrients. Fertilizer nitrogen partial factor productivity was estimated using the formula provided in the equation 7.

Eq. 7: $Partial\ factor\ productivity\ of\ N\ (PFP_N) = \frac{Grain\ yield\ (kg\ ha^{-1})}{Fertilizer\ N\ applied\ in\ kg\ ha^{-1}}$

Energy calculations

All the inputs used in crop production under different scenarios, as well as the outputs (grain and straw/stover), were considered to calculate the energy use indices. The direct (operational or renewable) and indirect (non-operational or non-renewable) energy input sources were used in energy inputs (Devasenapathy et al. 2009). Direct energy involved human labour, fuel, and machineries, while indirect energy sources included crop biomass (grains and residues), and chemicals viz., fertilizers and pesticides. We also assessed the utilization patterns of different energy inputs and operations across various CSAPSs. The energy equivalents of various input and outputs were used for the computation of energy inputs and outputs expressed in MJ ha-1 (Table S2) for every item and crop production technologies by considering their primary data as recommended by Mittal and Dhawan (1988), and Singh et al. (1997). Then energy use indices were computed following the procedures described by Devasenapathy et al. (2009) and Mittal and Dhawan (1988) as per equations (8)-(11).

Eq. 8: $Net\ energy\ (MJ\ ha^{-1}) = Energy\ output\ (MJ\ ha^{-1}) - Energy\ input\ (MJ\ ha^{-1})$

Eq. 9: $Energy\ use\ efficiency = \frac{Energy\ output\ (MJ\ ha^{-1})}{Energy\ input\ (MJ\ ha^{-1})}$

Eq. 10: $Energy\ productivity\ (Kg\ MJ^{-1}) = \frac{Biomass\ yield\ (kg\ ha^{-1})}{Energy\ input\ (MJ\ ha^{-1})}$

Eq. 11: $Specific\ Energy\ (MJ\ Mg^{-1}) = \frac{Energy\ Input\ (MJ\ ha^{-1}) \times 1000}{System\ productivity\ (kg\ ha^{-1})}$

3.Productivity, profitability and resource use efficiency

In IGP of North-West India where high yields of rice and wheat are common, a medium-term (11 yrs) cropping system trials were conducted in Karnal, Haryana with the aim of identifying integrated management options on the principles of CA, diversification and precision input management. Research results provide strong science-based evidences of enhancing productivity and profitability of cereal-based systems.

Productivity and profitability

- CA-based rice–wheat–mungbean (RWMb)systems improved the system productivity by 8% and profitability by 22% compared to conventional rice–wheat (RW) system/farmers practice (12.3 Mg ha^{-1} and INR 85,662 ha^{-1}, respectively) (Table 3.1).
- CA-based maize–wheat–mungbean (MWMb) systems have potential to increase the productivity by 16% and profitability by 56% compared to conventional rice–wheat system/farmers practice and hence provide scalable technology package for much needed diversification in RW system of NW India (Table 3.1).
- CA layered with SDI (subsurface drip irrigation) increased the RWMb system productivity and farm profitability by ~21 and 31% and for MWMb system 37 and 73%, respectively compared to farmers' practice/conventional flood irrigated RW system.
- Climate smart agriculture practices (layering of carbon, water, nutrient, energy, weather and knowledge smart techniques) increased 8% in system productivity and 23% in profitability over conventional RW system (3 yrs' mean).
- Zero-till direct seeded rice (ZT-DSR) also shown to be an economically viable alternative to puddled transplanted rice (PTR) as it helped in reductions of production cost by11-17% (5 yrs' mean) with 25-30% less irrigation water at similar yield levels.

Table 3.1: System productivity and profitability under CA-based management systems (11 years mean)

Scenario	Productivity (Mg ha^{-1})	Irrigation water (mm ha^{-1})	Irrigation water productivity	Energy productivity (kg system yield M^{-3}	Energy requirement (MJ ha^{-1}) (kg system yield MJ^{-1})	Net returns (INR ha^{-1})
I- Rice-wheat (CT/TPR)	12.45	2387	0.52	75077	0.17	85662
II- Rice-wheat-mungbean (TPR-ZT-ZT)	14.89 (20)	2154 (-10)	0.69 (32)	65172 (-13)	0.23 (38)	115322 (35)
III- Rice-wheat-mungbean (ZT-ZT-ZT)	13.41 (8)	1938 (-19)	0.69 (33)	61102 (-19)	0.22 (32)	104310 (22)
IV- Maize-wheat-mungbean (ZT-ZT-ZT)	14.42 (16)	720 (-70)	2.00 (284)	38175 (-49)	0.38 (128)	134029 (56)
V- Rice-wheat-mungbean (ZT-ZT-ZT)+SDI	15.00 (21)	1101(-54)	1.36 (161)	37383 (-50)	0.40 (142)	111854(31)
VI- Maize-wheat-mungbean (ZT-ZT-ZT)+SDI	17.08 (37)	298 (-88)	5.73 (999)	22151(-70)	0.77 (365)	147941 (73)

- On an average, inclusion of mungbean in cereal systems (RW/MW) contributed an 18% (3 yrs' mean) increase in system productivity and a 15% increase in net returns. CA-based sustainable intensification helped in mitigating the negative effects of terminal heat stress on wheat and increased the wheat yields by 0.7–0.8 t ha^{-1} (5 yrs' mean) than conventional till wheat (5.0 Mg ha^{-1})

Resource use efficiency

- Adoption of CA-based management practices have shown tremendous potential to tackle the problems of falling ground water, nutrient and energy use efficiencies as well as other associated input management issues in RW system. Results showed that CA-based sustainable intensification saved irrigation water and energy, and improved water productivity and weed control efficiency.
- Zero-tillage direct-seeded rice (ZT-DSR) also found an economically viable alternative to PTR as it saved 22–40% of irrigation water and 13–34% energy inputs.
- Maize with CA-based management appeared as a suitable diversification alternative to transplanted rice because it reduces the demand of irrigation water by 89% and energy use by 66% compared with conventional PTR (2650 mm ha-1 and 79.2 GJ ha^{-1}, respectively).
- CA-based rice–wheat–mungbean (RWMb) systems increased the irrigation water productivity by 33% (0.69 kg system yield m-3) while using less irrigation water (19%) and energy input (19%) (61.1 GJ ha^{-1}) (11 yrs' mean) over conventional RW system (Table 3.1).
- CA-based maize–wheat–mungbean (MWMb) systems on improved the irrigation water productivity by 284% (2.00 kg system yield m-3) by using less irrigation water (70%) and energy input (49%) (38.2 GJ ha^{-1}) (11 yrs' mean) over conventional RW system.

- In CA systems, crop residues contributed the maximum (~76%) in total energy input (167,995 MJ ha-1); however, fertilizer application (nonrenewable energy source) contributed the maximum (43%) in total energy input (47,760 MJ ha-1) in CT-based systems. CA-based cereal (rice/maize) systems recorded higher net energy and energy intensiveness (EI) levels of 251% and 300%, respectively, compared with those of the CT-based rice–wheat system.
- On system mean basis, SDI saved 54 (128.6 cm yr-1) and 88% (208.9 cm yr-1) irrigation water under rice-wheat (RW) and maize-wheat (MW) system integrated with mungbean, respectively compared to flood irrigation system under same management level.
- Application of nitrogen through SDI reduced the fertilizer N requirement by 20% (30 kg N ha^{-1}) under each crop of rice, wheat and maize crops. On system basis, RW and MW systems recorded 45 and 50% higher PFP_N with SDI compared to CT flood.
- Overall, Nutrient Expert-based recommendations reduced N input by 15–35%, increased grain yield by 4–8% and reduced global warming potential by 2–20%.
- GreenSeeker increased the RW system productivity and profitability to the tune of 5-8%.
- CA-based RWMb/ MWMb system saved 21-man days yr^{-1} compared to conventional rice-wheat system.
- CA-based reduces the menace of P. minor, A. arvensis, M. indicus and C. album by 50-80% in terms of total weeds density and biomass and shifted weed flora towards broadleaf weed species i.e., S. nigrum and R. dentatus (Fig. 3.2).
- Herbicide consumption in wheat is negligible after 3 years of continuous cultivation with CA-based management system in RWMb system.
- A residue load of 6 t ha^{-1} with early sowing (last week of October) was optimized to reduce the Phalaris population by 75% (Fig. 3.1). After 3 cropping cycles, no herbicide was required in wheat crop.

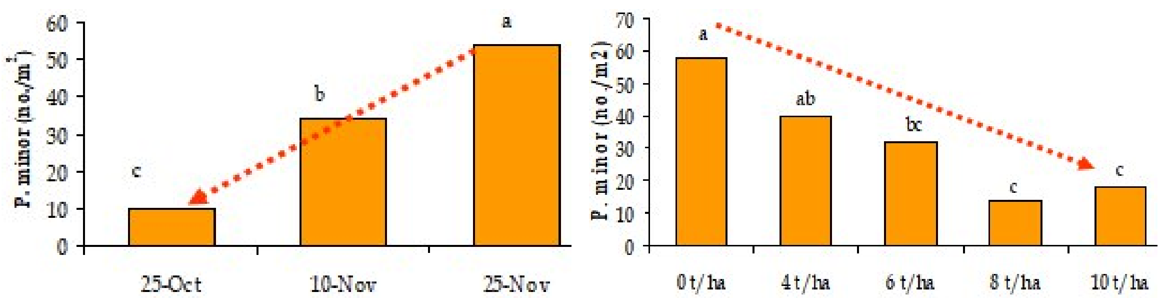

Fig. 3.1: Effect sowing dates and residue load on Phalaris population

- To assess the stability of individual crop yields and overall system productivity, we utilized Wricke's Ecovalance (wi2) and Sustainability Yield Index (SYI) across various scenarios over 10 years. CA-based scenarios exhibited higher stability in wheat yields, REY (indicated by lower wi2 and higher SYI values) compared to conventional tillage-based scenarios (ScI). Particularly, scenarios with SSDI (Sc V and VI) showed greater stability during both kharif and winter seasons, and across the entire system. However, during the kharif season, transplanted rice (Sc II) showed more stability compared to zero-tilled DSR with full CA (Sc III).

Table 3.2: Yield stability indexes under different scenarios

Scenarios	Wheat		Rice/Maize		System	
	Wi^2	SYI	Wi^2	SYI	Wi^2	SYI
Sc I	1.15±0.57[a]	0.63±0.04[d]	2.85±1.12[abc]	0.70±0.05[bc]	7.40±3.49[ab]	0.65±0.05[b]
Sc II	1.31±0.97[a]	0.69±0.03[d]	1.95±0.67[abc]	0.77±0.04[ab]	4.86±1.60[b]	0.76±0.03[a]
Sc III	1.29±0.41[a]	0.76±0.02[bc]	4.43±1.89[a]	0.65±0.03[c]	6.68±1.92[ab]	0.68±0.04[b]
Sc IV	1.08±0.28[a]	0.75±0.03[c]	3.93±0.49[ab]	0.75±0.03[ab]	6.60±0.54[a]	0.73±0.01[a]
Sc V	0.82±0.15[a]	0.81±0.04[ab]	0.89±0.53[c]	0.70±0.02[bc]	3.73±1.03[b]	0.73±0.03[a]
Sc VI	0.85±0.20[a]	0.82±0.04[a]	1.23±0.45[bc]	0.81±0.04[a]	5.91±1.75[b]	0.83±0.06[a]

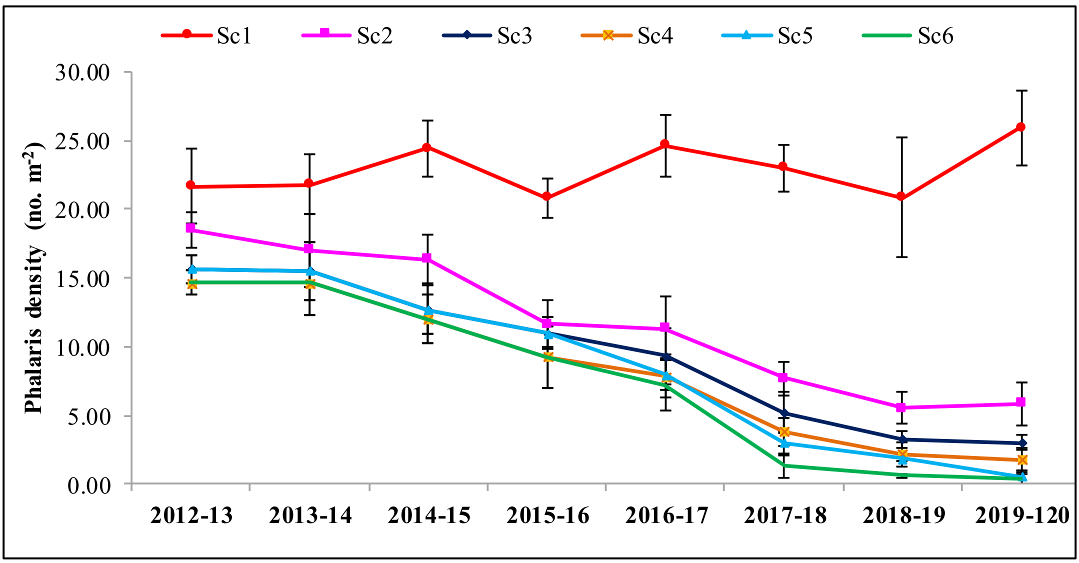

Fig. 3.2 Change in Phalaris minor density under different scenarios over the years

4.Soil health

Deteriorating soil health coupled with multi-nutrient deficiencies is a major problem in NW-IGP. Layering of improved management practices helped in improving the soil organic carbon and soil fertility in the region. Results showed that CA-based management improved soil properties and availability of nutrients (N, P, K, Zn, Fe and Mn) to crop plants which helped in cut down the nutrient doses (N and K). Salient findings were:-

- In CA-based rice-wheat-mungbean (RWMb) and maize-wheat-mungbean (MWMb) systems, organic carbon increased by 67 and 71%, respectively compared to conventional RW system (0.45%) after 4 years of cultivation (Fig. 4.1). After 6 and 10 years it was increased by 75 and 100%, respectively.
- In CA-based RWMb systems, available N, P and K was increased by 33, 38 and 18%, respectively,
- however in CA-based MWMb systems it was increased by 68, 25 and 73%, respectively compared to conventional RW system (117:15.7:183.4 Kg NPK ha^{-1}) after 4 years.
- Appreciable amount of N and K fertilizers (to the tune of 30% and 50%, respectively) can be saved under CA-based management system after 4 years of continuous cultivation. ·

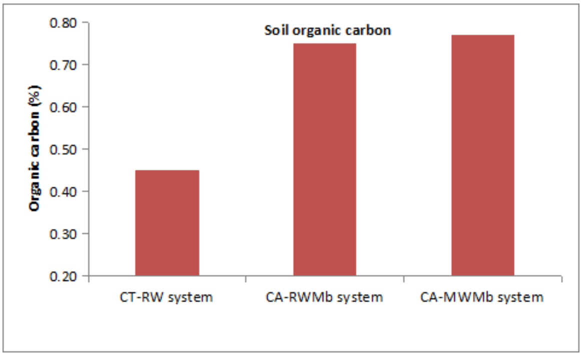

Fig. 4.1 Effect of different scenarios on soil organic carbon

- Efficient lignocellulosic crop residue degrading fungi belonging to genera Aspergillus and Alternaria were able to degrade crop residue by 26-31%.
- CA-based MW system registered 208, 263, 210 and 48% improvement in soil microbial biomass C (MBC) and N (MBN), dehydrogenase activity (DHA) and alkaline phosphatase activity (APA), whereas CA-based RW system registered 83, 81, 44 and 13%, respectively compared with farmers practice of RW system (MBC- 646 $\mu g g^{-1}$ dry soil; MBN-201 $\mu g g^{-1}$ dry soil; DHA-180 μg TPF g^{-1} soil 24 h^{-1}); APA-144 μg p-NP g^{-1} h^{-1})) after 3 years.

- Fungal diversity: At phylum level, relative abundance of Ascomycota was ranged from 55 to 74%, with the highest dominance found in ZT-MWMb (74%) followed by ZT-RWMb (71%) and lowest with conventional RW (55%), however at class level Sordariomycetes had the highest abundance followed by Dothideomycetes and Eurotiomycetes.

- Bacterial diversity: At phylum level, Proteobacteria, Acidobacteria, Actinobacteria, and Bacteroidetes accounted for more than 70% of the identified phyla. Rice based systems were dominated by phylum Proteobacteria; however, maize based system was dominated by Acidobacteria. At class level, Proteobacteria was dominated by Alphaproteobacteria, and it was closely followed by Deltaproteobacteria, Betaproteobacteria, and Gammaproteobacteria.
- Microbial population was increased by 28%, 68% and 98% respectively of bacteria, fungi, and actinomycetes under CA-based MW management system than RW system.
- CA-based MW system recorded the highest SQI of 1.45, whereas 0.58 with CA-based RW system and the lowest score (0.29) being in conventional RW system after 3 years of continuous cultivation. Mungbean integration in CA based MW system showed higher SQI (0.76) than other RW systems.
- Among the size classes of aggregates, highest aggregate associated C (8.94 g kg^{-1}) was retained in the 0.5-1 mm size class under CA-based scenarios.

- The CA-based scenarios (Sc III, IV, V, VI) exhibited lower soil bulk densities compared to CT-based scenarios (Sc I, II), typically associated with increased accumulation of organic residues and enhanced soil faunal activity. Even though Sc V and Sc VI exhibited higher BD values, these treatments demonstrated faster infiltration rates compared to other treatments (Fig. 4.2 and 4.3).

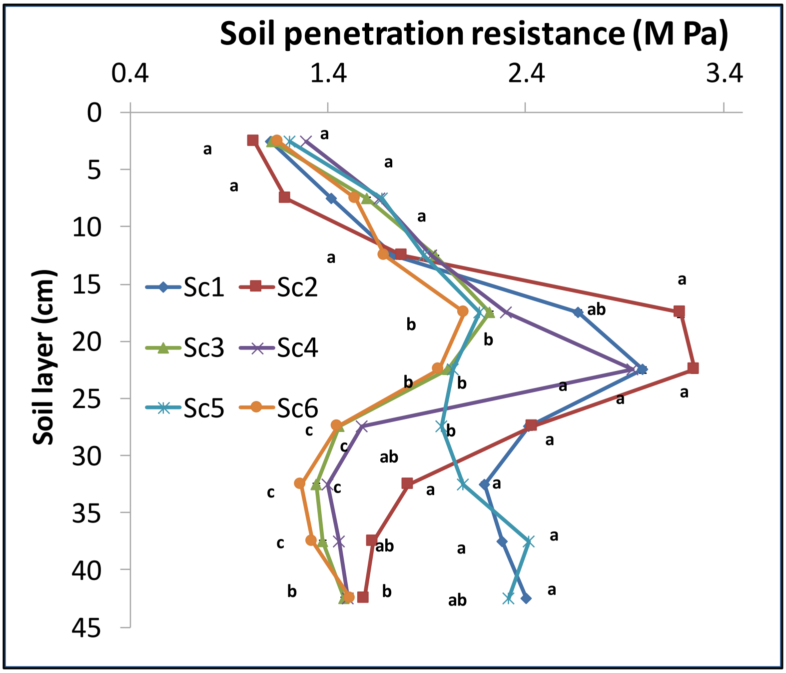

Fig. 4.2 Effect of different scenarios on soil penetration resistance

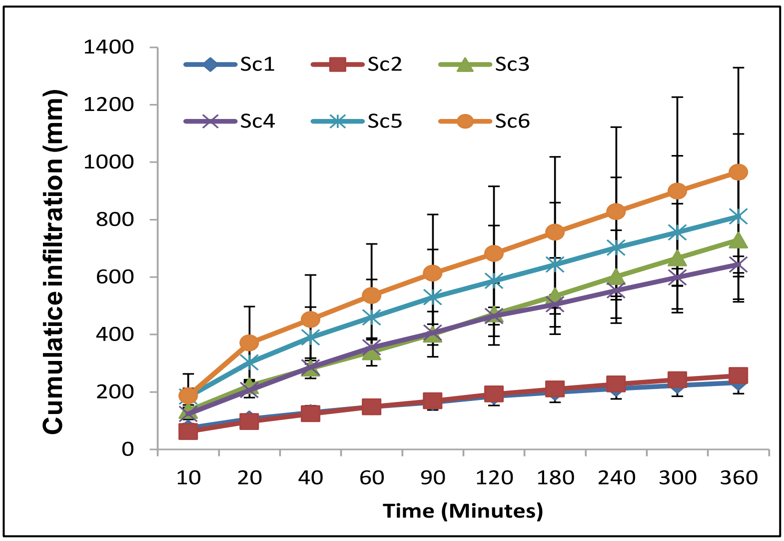

Fig. 4.3 Effect of different scenarios on water infiltration rate

5.Greenhouse gases (GHGs) emission and mitigation potential

Business as usual in RW system not only requires intensive use of resource (labor, water and energy), but also emits significant amounts of GHGs (CH_4, N_2O, and CO_2) depending on the conditions (anaerobic /aerobic) of the soil. CA- based systems have potential to increase the productivity and profitability with less environmental footprint by using less irrigation water, energy and reducing total global warming potential (GWP).

- Shifting from conventional practice of tillage and crop establishment in rice to conservation practice of tillage and crop establishment (CT-PTR to ZT-DSR) reduced CH_4 emissions by ~56% (2 yrs' mean).
- Zero-till DSR reduced the global warming potential (GWP) by 32% (5 yrs' mean) compared to conventional PTR (4713 kg CO_2 eq ha^{-1}). Diversification of rice with CA-based maize cultivation reduced the global warming potential (GWP) by 40% (5 yrs' mean) compared to conventional PTR (4713 kg CO_2 eq ha^{-1}).
- CA-based rice–wheat–mungbean (4861 kg CO_2 eq yr^{-1}) and maize–wheat–mungbean (4455 kg CO_2 eq ha^{-1}) systems have potential to reduce GWP by 23 and 30%, respectively (5 yrs' mean) compared with conventional RW system (6321 kg CO_2 eq ha^{-1}) (Fig. 4.2).
- Crop residue retention reduces the GHG emissions by ~80% compared to those of farmers' common practice of burn+disc (4757 CO_2 eq kg ha^{-1} $year^{-1}$).
- CA-based RW and MW systems have potential to reduce GWP by 16-26% (1.3-2.0 Tg CO_2 eq

yr^{-1}) (2 yrs' mean) and 15-30% (5 yrs' mean) compared with business as usual/ farmers' practice.Fig. 4.2: Total global warming potential (GWP) under CA-based management systems

- Climate smart agriculture lowered global warming potential and greenhouse gas intensity by 40 and 44% (3 yrs' mean) respectively, compared to farmers' practice (7653 kg CO_2 eq ha^{-1} yr^{-1} and 0.64 kg kg^{-1} CO_2 eq ha^{-1} yr^{-1}).

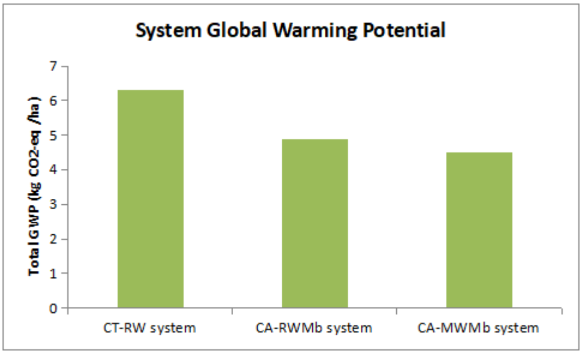

Fig. 4.2 Total global warming potential (GWP) under CA-based management systems

6. Out-scaling of CA-based technologies

A number of technologies (Laser land leveling, Zero-tillage with anchored residue condition, Happy Seeder sown wheat under full residue condition, Direct seeded rice, Crop diversification with maize, SSNM using GreenSeeker, Nutrient Expert systems, precision water management, Bed planting etc.) standardized under project were tested to record their impact at the field scale.

- **Laser land leveling:** Irrigation time in laser leveled fields was reduced by 47–69 h ha^{-1} $season^{-1}$ in rice and by 10–12 h ha^{-1} $season^{-1}$ in wheat and the productivity of wheat and rice were increased by 7–9% and 7%, respectively compared to traditionally leveled ones in Haryana (96 farmers) and Punjab (96 farmers). By the year 2020, >35000 units are working in the Punjab and Haryana State.

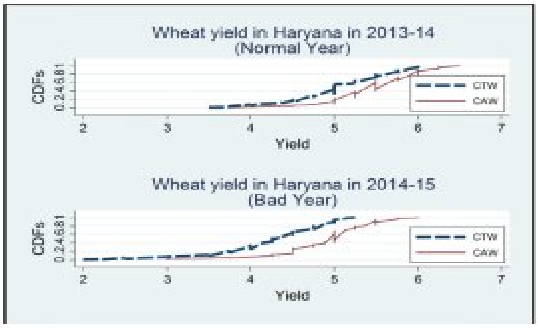

Figure 6.1: Stochastic analysis of the wheat yield difference between CTW and CAW

- **Happy Seeder with super SMS:** Happy Seeder sown wheat under full residue condition was found good under normal year and very good under bad year as shown by results recorded from 208 trials at farmers field in Haryana during normal year (2013-14) and bad year (2014–15, a period with untimely excess rainfall). Happy Seeder sown wheat produced two-fold increase in productivity during the bad year against the normal year (16% vs. 8%) compared to conventional sown wheat (5.05 and 4.23 Mg ha^{-1}). Wheat productivity was increased from 0.2-0.8 M ha^{-1} with Happy Seeder seeding done after rice harvesting with combine harvesting with super SMS.
- **ZT technology:** Results based on farmers participatory field trials at 500 sites during 10 consecutive years (2009-19) showed that shifting of wheat from CT to ZT production system reduced farmers total input cost per hectare by 20% (INR 3950 ha^{-1}), increases net revenue per hectare by 28% (INR 4875 ha^{-1}) and reduce CO_2 emission by 1.5 Mg per hectare per wheat season. Farmers trials showed that farmers started cut short the N dose by 10-

15% in the plots where CA was practiced continuously for past three years in wheat crop seeded with Happy seeder under full residue condition (455 farmers).

- **DSR technology:** In North-west India, the area from 426 hectares in 2009 and presently DSR is out scaled in larger landscape of ~6 lakh hectare in Haryana and Punjab. The cost of sowing with DSR machine does not exceed Rs 2,000 to 2,500 per acre which includes DSR machine rent, seed, and herbicides spray and preparation of the field compared to Rs 5,000-6,000 per acre with PTR. By these calculations with DSR sowing farmers managed to save around Rs 4000 to 5000 per acre, which adds up to roughly a saving between Rs 500 to 600 crores. Also, there is around 30 per cent water saving in DSR paddy area.
- **Layering CA with precision nutrient management:** Happy/Turbo Seeder seeded ZT wheat layered with site specific nutrient management (Green Seeker, Nutrient Expert; NE) and found that NE reduced N application in rice and wheat by 5-25% and increased rice and wheat yield by 2-2.5%, in Western IGP as compared to farmers' practice (no. 1000 farmers). Besides, it lowered global warming potential (GWP) by about 2.5% in rice and between 12-20% in wheat. Green Seeker based N application saved 15-20 kg N ha^{-1} at similar yield levels in rice-wheat system compared to farmers fertilizer N application (based on > 250 farmer field trials). Nutrient Expert system increased the productivity by 0.3-0.5 t ha^{-1} in rice and wheat and net return by INR 3500 to 5500 ha^{-1} (based on >100 farmer field trials).
- **Bed planting of maize in IGP:** Bed planting of maize-wheat system may provide the opportunities for rice replacement from rice-wheat system. Bed planting improved the maize yield by 10-15% and saved irrigation water 25-30%. The wheat is also improved on succeeding wheat crop by 5-10% (no. 200 farmers).

7. Capacity development of multi-stakeholders

In this project large number of stakeholders were trained and guided on sustainable intensification based on CA principles across the Asia. These training programmes were aimed at building the capacity of researchers, scientists, professors, agricultural/subject matter specialists from the Indian National Agricultural Research and Extension System (NARES) and the CGIAR system. Master of Science (M.Sc) and Ph.D students also conducted research trials under this project. The students were imparted training on different aspects of natural resource management (NRM). Details of capacity building activities under taken:

Activities	**Numbers**	**Duration**
1. Training Programs		
(i)International training programs	12	One to two weeks
(ii)National Training Program	5	1-3 days
2. Students guided		
(i)Ph.D	7	2-3 years
(ii)M.Sc	3	1 year
(iii)B.Tech	1	3-6 months
3. Students (Interns) trained	26	1-3 months
4. Farmers fair/travelling seminar/field days	40	1 day

8. Summary and Recommendations

Conservation Agriculture (CA) based Sustainable Intensification (SI) practices portfolio can potentially address the current and future sustainability challenges of rice-wheat system in the "food bowl" of NW India.

- Fully validated science-based evidence on conservation agriculture have demonstrated that system based targeted CA-based management practices portfolio has potential to produce more (10-15%) food from less water (20-75%) and energy (20-45%) use while increasing farmers income (25-50%) in an environmentally responsible manner through lowering carbon foot prints by 25-30%.
- For much needed diversification of rice in NW India, system (maize-wheat-mungbean) based solutions through bundling conservation agriculture and precision water and nitrogen management can provide economically and environmentally sustainable opportunities.
- Layering precision water and nitrogen (N) applications with CA through subsurface drip irrigation (SDI)/fertigation has potential not only for addressing the critical issues (water, soil health, climatic risks) but also for increasing farmer profits in environmental efficient manner and significantly reducing the subsidy burden on public money as adoption of these practices on mere 1 M ha area can reduce the consumption of 20 lakh bags of urea costing Rs 533 crore for the farmers and Rs 1170 crore for the Government.
- Conservation agriculture based sustainable intensification has a potential to provide safety nets to farmers through reducing the risks of climate change with improving adaptive capacity against climatic risks and hence can potentially save public investments on insurance.
- The science-based evidence on greenhouse gas (GHG) mitigation in rice-wheat (5-8 tons CO_2-eq ha^{-1} $year^{-1}$) can not only contributes to reducing agriculture's environmental footprints but also provide opportunities for carbon farming through incentives for carbon credits by global carbon markets thereby creating a pull factor for adoption of sustainable and resilient farming practices in addition to reducing air pollution and providing public health benefits.
- Continuous adoption of conservation agriculture in intensive cereal systems has significant potential to improve soil health through improving soil physical, chemical and biological properties and overall soil quality index by 50-100%. After 5 years of CA, 30 and 50% of N and K fertilizers can be curtailed and in-turn saving significant foreign exchange on fertilizer imports and contributing to Atma Nirbhar Bharat.

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