Agriculture, Ecosystems and Environment 252 (2018) 132–147

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Research Paper

Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India

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ARTICLE INFO

Keywords:
Sustainable intensification
Zero-tillage
Global warming potential
Terminal heat stress
Direct-seeded rice
Sustainability

ABSTRACT

In the most productive area of the Indo-Gangetic Plains in Northwest India where high yields of rice and wheat are commonplace, a medium-term cropping system trial was conducted in Haryana State. The goal of the study was to identify integrated management options for further improving productivity and profitability while rationalizing resource use and reducing environmental externalities (i.e., "sustainable intensification", SI) by drawing on the principles of diversification, precision management, and conservation agriculture. Four scenarios were evaluated: Scenario 1 – "business-as-usual" [conventional puddled transplanted rice (PTR) followed by (*fb*) conventional-till wheat]; Scenario 2 – reduced tillage with opportunistic diversification and precision resource management [PTR *fb* zero-till (ZT) wheat *fb* ZT mungbean]; Scenario 3 – ZT for all crops with opportunistic diversification and precision resource management [ZT direct-seeded rice (ZT-DSR) *fb* ZT wheat *fb* ZT mungbean]; and Scenario 4 – ZT for all crops with strategic diversification and precision resource management [ZT maize *fb* ZT wheat *fb* ZT mungbean]. Results of this five-year study strongly suggest that, compared with business-as-usual practices, SI strategies that incorporate multi-objective yield, economic, and environmental criteria can be more productive when used in these production environments. For Scenarios 2, 3, and 4, system-level increases in productivity (10–17%) and profitability (24–50%) were observed while using less irrigation water (15–71% reduction) and energy (17–47% reduction), leading to 15–30% lower global warming potential (GWP), with the ranges reflecting the implications of specific innovations. Scenario 3, where early wheat sowing was combined with ZT along with no puddling during the rice phase, resulted in a 13% gain in wheat yield compared with Scenario 2. A similar gain in wheat yield was observed in Scenario 4 vis-à-vis Scenario 2. Compared to Scenario 1, wheat yields in Scenarios 3 and 4 were 15–17% higher, whereas, in Scenario 2, yield was either similar in normal years or higher in warmer years. During the rainy (*kharif*) season, ZT-DSR provided yields similar to or higher than those of PTR in the first three years and lower (11–30%) in Years 4 and 5, a result that provides a note of caution for interpreting technology performance through short-term trials or simply averaging results over several years. The resource use and economic and environmental advantages of DSR were more stable through time, including reductions in irrigation water (22–40%), production cost (11–17%), energy inputs (13–34%), and total GWP (14–32%). The integration of "best practices" in PTR in Scenario 2 resulted in reductions of 24% in irrigation water and 21% in GWP, with a positive impact on yield (0.9 t/ha) and profitability compared to conventional PTR, demonstrating the power of simple management changes to generate improved SI outcomes. When ZT maize was used as a diversification option instead of rice in Scenario 4, reductions in resource use jumped to 82–89% for irrigation water and 49–66% for energy inputs, with 13–40% lower GWP, similar or higher rice equivalent yield, and higher profitability (27–73%) in comparison to the rice-based scenarios. Despite these advantages, maize value chains are not robust in this part of India and public

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http://dx.doi.org/10.1016/j.agee.2017.10.006
Received 23 May 2017; Received in revised form 10 September 2017; Accepted 12 October 2017

procurement is absent. Results do demonstrate that transformative opportunities exist to break the cycle of stagnating yields and inefficient resource use in the most productive cereal-based cropping systems of South Asia. However, these SI entry points need to be placed in the context of the major drivers of change in the region, including market conditions, risks, and declining labor availability, and matching with the needs and interests of different types of farmers.

1. Introduction

The rice–wheat cropping system occupies 13.5 Mha in the Indo-Gangetic Plains (IGP) of South Asia, 10.3 Mha of which are in the Indian IGP. This cropping system provides staple food for more than a billion people and is crucial in ensuring food security and livelihood in the region (Chauhan et al., 2012). Sustaining and increasing the production of cereal systems in the Indian states of Punjab, Haryana, and western Uttar Pradesh in the northwest (NW) IGP, together known as the “breadbasket” of the country, are essential to meet the food requirement of India’s burgeoning population, which is likely to increase from 1.3 billion in 2015 to 1.6 billion by 2050.

This cropping system in the NW IGP achieved high productivity during the early Green Revolution period. However, in recent years, the yields of rice and wheat have either stagnated or started to decline along with a decline in total factor productivity (grain output divided by quantity of total input) and profitability, and high inefficiencies in input use (Ladha et al., 2003, 2009). On the other hand, it is projected that, to feed a population of 1.6 billion, India would have to double its cereal production to meet the food demand by 2050 (Swaminathan and Bhavani, 2013). The challenge is to meet this target using fewer resources (land, water, labor, and chemicals) and with a lower environmental footprint while buffering the risks of climate variability (e.g., erratic rainfall, terminal heat) to ensure long-term sustainability.

The current agricultural production practices in the rice–wheat systems in the NW IGP are neither sustainable nor environmentally sound under the ongoing economic and environmental drivers of agricultural change occurring in the region (Bhatt et al., 2016; Ladha et al., 2009). Current practices require large amounts of resources (labor, water, energy, and biocide) with low input-use efficiencies. At the same time, these resources are becoming scarce and expensive, making conventional practices less profitable and sustainable. For example, rice is predominantly established by the conventional method of puddling and transplanting (PTR) in which rice seedlings are transplanted from the nursery into puddled (wet-tilled) soil in the main field, which is kept flooded for the majority of the growing period (Kumar and Ladha, 2011). This method provides multiple benefits, including good weed control and crop establishment, reduced percolation losses of water, and increased nutrient availability (Johnson and Mortimer, 2005; Sharma et al., 2003), and it is the preferred rice establishment method if labor and water resources are abundant and cheaply available. However, PTR is highly labor-, water-, and energy-intensive as large amounts of labor (for seedling uprooting and transplanting), irrigation water (for puddling and continuous flooding), and energy (for intensive tillage and in irrigation) are needed. Moreover, this production system emits a significant amount of methane (CH_4) – an important greenhouse gas (GHG) responsible for global warming (Reiner and Milkha, 2000). Furthermore, puddling operations done during rice land preparation can have a negative impact on the yields of succeeding non-rice upland crops (e.g., wheat yield reduction by 8–10%) in the rotation through their negative impact on soil physical properties (Kumar and Ladha, 2011; Kumar et al., 2008). Similarly, conventional practices for wheat consist of intensive land preparation involving multiple passes of discs/tine harrows and planking to create a friable seedbed. This intensive tillage operation leads to a long turnaround period; most often, it resuled. This intensive tillage operation leads to a long turnaround period; most often, it results in a delay in wheat planting, with a yield loss of 27 kg ha^{-1} day^{-1} with every day delay in wheat planting beyond November 15 (Tripathi et al., 2005). Prior to the establishment of rice and wheat, all crop residues (rice and wheat) from the previous crop are either removed for fodder or are burned. However, residue burning results in environmental pollution, nutrient loss (100% C, 90% N, 60% S, and 25% each of P and K) (Dobermann and Fairhurst, 2002), and GHG emissions, with estimates of 110, 2306, 2, and 84 Gg of CH_4, carbon monoxide (CO), nitrous oxide (N_2O), and nitrogen oxides (NOx), respectively, in India (Gupta et al., 2004).

To address these problems confronting the rice–wheat system, several improved management practices have been developed under the frameworks of conservation agriculture (CA) or integrated crop and resource management (ICRM) practices (Gathala et al., 2011a, 2011b, 2013; Gupta and Seth, 2007; Ladha et al., 2009, 2016; Laik et al., 2014). These technologies have been developed with the aim of improving the productivity, profitability, and sustainability of rice–wheat systems while reversing resource degradation, improving environmental quality, addressing labor bottlenecks, improving input-use efficiency, and increasing resilience to climate variability. The technologies include reduced or zero-tillage (ZT), laser land leveling, dry direct seeding of rice (DSR), crop residue retention as mulch, site-specific nutrient management, precise irrigation scheduling, and crop diversification (Balwinder-Singh et al., 2011a, 2011b; Gathala et al., 2011a, 2011b; Kumar et al., 2013; Ladha et al., 2009, 2016; Sudhir-Yadav et al., 2011a, 2011b).

ZT in wheat has been widely adopted in NW India, with an area of 0.26 Mha in Haryana State alone (CSISA, 2010), and it is now gaining momentum in the eastern IGP (CSISA, 2015; Keil et al., 2015) mainly because of its clear and positive impacts on productivity, profitability, resource-use efficiency, and resilience to heat stress (Erenstein and Laxmi, 2008; Keil et al., 2015). There is increased interest among government agencies to promote DSR and to diversify rice with maize in an attempt to arrest the declining groundwater table as well as the problem of labor scarcity. DSR combined with ZT was found to reduce labor and irrigation water requirements and to provide more net profit than PTR without any yield penalty (Gathala et al., 2013; Kumar and Ladha, 2011; Laik et al., 2014; Sudhir-Yadav et al., 2011a, 2011b). Similarly, maize in the monsoon season appears to be a suitable and profitable alternative to rice in the NW IGP as it can overcome problems of rising scarcity of resources (Gathala et al., 2013). Also, the availability of the “Happy Seeder”– a ZT machine that can plant rice and wheat in high-residue (anchored and loose) conditions – has made it possible to retain the residues on the soil surface, thereby providing an alternative to residue burning (Gathala et al., 2011c; Sidhu et al., 2007, 2008, 2015). To harness the full benefits of CA, ZT in combination with residue retention on the soil surface as mulch has to be integrated with precision management and a more diversified crop rotation. Despite multiple examples of the benefits associated with CA-based practices in South Asia, some recent studies have questioned the role of CA in climate change mitigation as well as the challenges in achieving economic and ecosystem benefits in smallholder farming (Brouder and Gomez-Macpherson, 2014; Palm et al., 2014; Powlson et al., 2014; Pittelkow et al., 2014).

A holistic systems approach and more medium- to long-term studies are needed to evaluate the benefits and trade-offs associated with the adoption of these CA-based best management practices (BMPs). Many of these technologies, either as stand-alone or in combination in a single crop season and in cropping systems, have been evaluated in the region. The short-term impacts of these technologies on productivity and