CHAPTER SIX


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Contents

1. Introduction 316
2. Problems 319
   2.1. Diverse Agronomy of Rice and Wheat 320
   2.2. Declining Water Availability and Groundwater Pollution 321
   2.3. Deteriorating Soil Health 322
   2.4. Disposal of Crop Residues 324
   2.5. Weed Flora Shifts and Herbicide Resistance 326
   2.6. Climate Change 328
3. Opportunities and Strategies 330
   3.1. Conservation Agriculture 330
   3.2. Crop Residue Management 338
   3.3. Precision Land Leveling 340
   3.4. Crop Diversification 341
   3.5. Soil Nutrient Management 343
   3.6. Reducing Water Requirements 344
   3.7. Weed Management 346
   3.8. Climate Change 352
4. Conclusions 354
Acknowledgments 355
References 355

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Abstract
Rice and wheat are the staple foods for almost the entire Asian population and therefore they occupy a premium position among all food commodities. The era of the Green Revolution started during the early 1970s with wheat and rice and since then the rice—wheat cropping system of the Indo-Gangetic Plains has played a significant role in the food security of the region. However, recent years have witnessed a significant slowdown in the yield growth rate of this system and the sustainability of this important cropping system is at risk due to second-generation technology problems and mounting pressure on natural resources. Traditional cultivars and conventional agronomic practices are no longer able to even maintain the gains in productivity achieved during the past few decades. Demand for food is increasing with the increasing population and purchasing power of consumers. The rice—wheat cropping system is labor-, water-, and energy-intensive and it becomes less profitable as these resources become increasingly scarce and the problem is aggravated with deterioration of soil health, the emergence of new weeds, and emerging challenges of climate change. Therefore, a paradigm shift is required for enhancing the system’s productivity and sustainability. Resource-conserving technologies involving zero- or minimum-tillage in wheat, dry direct seeding in rice, improved water- and nutrient-use efficiency, innovations in residue management to avoid straw burning, and crop diversification should assist in achieving sustainable productivity and allow farmers to reduce inputs, maximize yields, increase profitability, conserve the natural resource base, and reduce risk due to both environmental and economic factors. A number of technological innovation and diversification options have been suggested to overcome the system’s sustainability problems but some of them have not been fully embraced by the farmers as these are expensive, knowledge-intensive, or do not fit into the system and have resulted in some other unforeseen problems. Different concerns and possible strategies needed to sustain the rice—wheat cropping system are discussed in this review on the basis of existing evidence and future challenges.

1. Introduction
Rice and wheat crops have been grown in South Asia (India, Pakistan, Nepal, Bangladesh, and Bhutan) and China for more than 1000 years. The rice—wheat (RW) cropping system, that is, growing these crops in a sequence in an annual rotation, has been developed through the introduction of rice in the traditional wheat-growing areas and vice versa (Paroda et al., 1994; Tran and Marathee, 1994). This cropping system is one of the world’s largest agricultural production systems, covering an area of 26 million hectares (Mha) spread over the Indo-Gangetic Plains (IGP) in South Asia and China. It accounts for about one-third of the area of both rice and wheat in South Asia and produces staple food for more
than 20% of the world population. The RW system now comprises about 13 Mha in area in the IGP, of which the Indian part of the IGP comprises about 10 Mha (Table 1; Timsina and Connor, 2001). More than 85% of the RW system practiced in South Asia is located in the IGP. About one-third and one-half of the total cereals of India and Pakistan, respectively, are produced in this region. In India, the IGP cover about 20% of the total geographical area (329 Mha) and about 27% of the net cultivated area, and produce about 50% of the total food consumed in the country (Dhillon et al., 2010).

The IGP, spread from the Indus basin in Pakistan Punjab in the west, passing through India and Nepal to the Brahmaputra floodplains in Bangladesh in the east, are the most important agricultural regions of the Indian subcontinent. The IGP comprise (i) the Trans IGP (Punjab in Pakistan, and Punjab and Haryana in India), (ii) Upper and Middle IGP (western, central, and eastern Uttar Pradesh and Bihar), (iii) Terai (an extension of the IGP) in Uttrakhand in India and parts of Nepal, and (iv) Lower IGP (West Bengal in India and parts of Bangladesh). In Pakistan, the RW cropping system occupies about 10% of the total cultivated area (2.1 Mha), mainly in two zones, the Punjab RW zone, comprising about 1.2 Mha, and the Sindh RW zone, occupying the remaining area (Aslam, 1998a).

The Indian portion of the IGP comprises Punjab, Haryana, Uttrakhand, western and eastern Uttar Pradesh, Bihar, and West Bengal. These plains are believed to be formed by alluvium soil brought from the Himalayas by the Indus and Ganges river systems about 7000 years ago (Pal et al., 2009). Except for a strip of the Shivalik hills, alongside its eastern border, the entire area is flat alluvial plain at 180–290 m above mean sea level. The soils of the plains region are generally deep alluvium, sandy loam to loam in texture, having moderate water-holding capacity, alkaline in reaction, and poor in organic matter content. In the plains of the Indus and Ganges between west and east, there is a gradual transition in physiography,

<table>
<thead>
<tr>
<th>Country</th>
<th>Area (Mha)</th>
<th>Rice</th>
<th>Wheat</th>
<th>Total cereal production</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>13.0</td>
<td>31</td>
<td>35</td>
<td>72</td>
</tr>
<tr>
<td>India</td>
<td>10.3</td>
<td>23</td>
<td>40</td>
<td>85</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2.3</td>
<td>72</td>
<td>19</td>
<td>92</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>0.5</td>
<td>5</td>
<td>85</td>
<td>100</td>
</tr>
<tr>
<td>Nepal</td>
<td>0.6</td>
<td>35</td>
<td>84</td>
<td>71</td>
</tr>
</tbody>
</table>

(Timsina and Connor, 2001)
climate, natural vegetation, and cropping patterns. Alluvial soils deposited by the river systems are highly fertile and underlain by extensive aquifers resulting in the development of an extensive groundwater network for irrigation. The rice and wheat crops have become so important for this region that rapid expansion of a tubewell network in the northwest (NW) part of the IGP has led to the exploitation of even poor-quality groundwater aquifers for irrigation.

Until the mid-1960s, rice cultivation in some pockets of the IGP was restricted to basmati rice (tall-statured aromatic rice with good cooking quality) having low productivity of about 1 t ha$^{-1}$ (Kumar and Nagarajan, 2004). The introduction of dwarf wheat cultivars (Sonora 64 and Lerma Rojo) from Mexico, which required lower temperature for germination and tillering, led to a shift in the sowing time of wheat from mid-October to late October/early November, allowing the cultivation of kharif (rainy season) crops of longer duration. This provided an opportunity for the cultivation of input-responsive, high-yielding dwarf cultivars of rice in the non-traditional areas of the IGP. In the subsequent years, rice and wheat in these areas replaced the less remunerative coarse cereals and more risk-prone oilseed and pulse crops. The Green Revolution technologies led to the emergence of RW as the major cropping system in the IGP, which now ranks first among the 30 major cropping systems identified in India (Das, 2006). In the Trans and Western parts of the Upper Gangetic Plains, rice (indica-type monsoon rice)-wheat (spring) is the main cropping system, whereas rice-wheat-mungbean/cowpea/jute in the eastern part of the Upper Gangetic Plains and in the Middle and Lower Gangetic Plains and the rice-wheat cropping system in the Nepal Terai region are predominantly followed.

After the mid-1960s, a substantial increase in area under rice and wheat took place in NW India, particularly in Punjab and Haryana states, despite semi-arid climatic conditions. These two states constitute a highly productive RW zone in the IGP contributing about 69% of the total food output in the country (about 84% wheat and 54% rice) and this region is called the “food bowl of India.” This region has played a vital role in sustaining the food security of India by contributing about 40% of wheat and 30% of rice to the central stock of India every year during the last four decades (Hira and Khera, 2000). Average combined yields of rice and wheat in the RW system in the IGP area are 5–7 t ha$^{-1}$ while yields of 8–10 t ha$^{-1}$ are attained with greater fertilizer application and the adoption of better agronomic practices (Timsina and Connor, 2001).

The soils of the IGP region have developed from alluvium brought from the Himalayas by the Indus River system. Soil moisture regimes are udic, ustic, and aridic, whereas the soil temperature regime is mainly hyperthermic. Soils under the RW system in the IGP, especially in the NW,
are porous, coarse, and highly permeable and are being used for raising upland crops as well as wetland rice (Aulakh and Bijay-Singh, 1997).

Groundwater and rainfall are the major water resources. Mean annual rainfall in Punjab, Haryana, and Uttar Pradesh plus Uttrakhand is 61, 56, and 84 cm, respectively, with a coefficient of variation often exceeding 20% (Parthasarthy et al., 1987). NW India and Bangladesh are perhaps the only regions in the world where groundwater is used for rice (mainly transplanted) cultivation. Of the net cultivated area, 97% of the area in Punjab, 83% in Haryana, and 68% in Uttar Pradesh is irrigated.

2. Problems

The spread of the RW system has brought forth several edaphic, environmental, and social implications. A number of problems have cropped up in the region with the cultivation of rice and wheat in a system mode for the last four decades, threatening the sustainability of the system. The NW IGP region has paid a heavy price to earn the status of food bowl. Evidence is accumulating 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 (Hobbs and Morris, 1996). In India, rice production and productivity that increased at an annual compound growth rate of 3.62% and 3.19%, respectively, in the 1980s, declined to 1.61% and 1.34%, respectively, in the 1990s. During the same period, wheat productivity declined from 3.10% to 2.32%. This declining rate of production has posed serious challenges before the nation to produce enough food for the increasing population and has raised some doubts about sustaining the productivity gains of rice and wheat in the region (Paroda et al., 1994).

The major factors that have stalled the productivity of the RW system are (i) overexploitation of groundwater resources leading to a decline in the groundwater table (Hira, 2009; Hira et al., 2004; Humphreys et al., 2010), increased energy cost of pumping water, and deterioration of groundwater quality; (ii) declining soil organic matter and increasing multiple deficiencies of major nutrients (N, P, K, and S) and micronutrients (Zn, Fe, and Mn) due to their overmining from soils (Ladha et al., 2000; Tiwari, 2002); (iii) increasing salinity (Tiwari et al., 2009); (iv) the development of herbicide resistance and a shift in weed flora and pest populations (Hobbs et al., 1997); and (v) poor management of crop residues, leading to their burning.
The situation in the Pakistan Punjab is similar to that of the Indian Punjab, where waterlogging, soil salinity and sodicity, inadequate and unreliable water supplies, poor-quality underground water for irrigation, and inadequate drainage are the major constraints (Aslam, 1998b). These problems are expected to be further aggravated unless interventions are made soon. Judicious use of fertilizers and water will determine the sustainability of RW and future food security of the IGP. About a decade ago, some challenges confronting the productivity and management of the RW system were described (Timsina and Connor, 2001). Since then, several new developments have occurred. In this article, the problems confronting the productivity of rice and wheat in the RW system are updated and discussed and efforts are made to suggest technological innovations to overcome these problems to sustain the productivity of these crops in the region.

2.1. Diverse Agronomy of Rice and Wheat

Rice and wheat crops have diverse edaphic requirements. Rice is generally transplanted in puddled soils and prefers continued submergence. Puddling is achieved by repeated intensive tillage under ponded-water conditions, which serves to break down soil aggregates, reduce macro-porosity, reduce soil strength in the puddled layer, disperse fine clay particles, and form a dense zone of compaction (i.e., plow pan) in subsoil. In contrast, wheat is grown in well-drained soils having good tilth, obtained with repeated (5–6 operations) tillage in dry soil. Therefore, the dominating feature of the RW cropping system is the annual conversion of soil from aerobic to anaerobic conditions for rice and then back to aerobic conditions for wheat. This causes several physical, chemical, and biochemical changes in the soil, which regulate transformation and availability of nutrients, root penetration, moisture availability, and crop–root interactions (Ponnamperuma, 1985), and this may have important implications for management practices, including crop establishment and nutrient, water, and weed management in the RW system. Long-term cultivation of puddled rice results in the formation of a hard pan with a consequent increase in bulk density and lowering of hydraulic conductivity below the plow layer (Singh et al., 2009). The hard pan impedes root growth of subsequent upland crops, including wheat. The nutrient transformations due to flooding of rice fields increase the availability of P, K, Si, Mo, Cu, and Co, and decrease those of N, S, and Zn (Timsina and Connor, 2001).

The conventional method of land preparation for transplanting or sowing in the RW system not only disturbs the soil environment but also leads to atmospheric pollution. It is estimated that 2.6 kg of carbon dioxide (CO₂) is released to the atmosphere for each liter of diesel fuel consumed (Erenstein and Laxmi-Vijay, 2008). About 150 l of diesel are
consumed per hectare per annum to run a tractor for field preparation and
to pump water for irrigation in a conventional system, which amounts to
emissions of about 400 kg CO₂ per hectare per annum. Thus, the
farming practices used for RW cultivation over the years have changed
the soil structure and nutrient availability, and increased dependence on
synthetic fertilizers and machinery. This has increased the cost of
cultivation and affected the immediate environment.

2.2. Declining Water Availability and Groundwater Pollution

A large amount of water is used to maintain flooding in rice fields. Rice
grown by traditional practices requires approximately 1500 mm of water
during a season. In addition, around 50 mm of water is required to grow
seedlings to the transplanting stage. The actual amount of water applied
by farmers, however, is much higher than the requirement, especially
where rice is grown on light-textured soils in India and Pakistan
(Timsina and Connor, 2001).

Availability of sufficient irrigation water has made the RW system in the
NW IGP a typical example of a highly productive system in non-ideal rice
soils (porous, coarse, and highly permeable). Four decades of RW cropping
have depleted the water resources in this region to a great extent. In the
Indian Punjab alone, there is an annual shortage of about 1.2 M ha meters
of water (Hira, 2009). The excess demand for water is being met through
overexploitation of groundwater, leading to a decline in the water table.
Though the name Punjab signifies land of five rivers (Panj means five
and Aab means water), only 23% of the area in the Indian Punjab is
irrigated by canals. Tubewells have become a more reliable source of
irrigation for about 77% of the area in the state as their control is with
the farmers and water supplies from these tubewells can be regulated.

Rice and wheat crops have become so important for this region that
rapid expansion of the tubewell network in the NW IGP has led to the
exploitation of even low-quality groundwater aquifers for irrigation of
these crops. The problem in the central districts of the Indian Punjab,
where about two-thirds of the total number of tubewells in the state (about
1.28 million) have been installed, is alarming. The groundwater table in this
region during 1993–2003 went down at about 0.55 m yr⁻¹. In some areas
of NW IGP, the water table is now being depleted at nearly 1 m yr⁻¹.

The areas having a water table below 9 m increased from 3% in 1973 to
about 90% in 2004 and almost 100% in 2010 (Kumar et al., 2010). The
water table in more than 70% of the area has now gone down to 21 m
or more. In other words, 101 out of 143 blocks in the Indian Punjab
have been declared dark zones. This has resulted in an increasing number
of submersibles as the centrifuge pumps are no longer effective in
pumping water. The cost of installing tubewells as well as the electricity
consumption to pump water have increased several-fold. About 30% of the total electricity in the state is being used for pumping water for irrigation. A recent study by NASA (National Aeronautics and Space Administration, Washington, D.C., USA) suggests that 13–17 km$^3$ of groundwater is lost permanently every year from the aquifers in the northwestern plains of Punjab, Haryana, and western Uttar Pradesh (Rodell et al., 2009).

The problem of groundwater pollution by nitrates does not normally arise in areas where wetland rice is grown on fine-textured ideal rice soils because nitrate is not normally formed under flooded conditions. Nitrate is formed when soil is allowed to dry, particularly in typical or ideal rice fields that possess very low percolation rates; once these soils are puddled, nitrate may be promptly converted to nitrous oxide (N$_2$O) via denitrification (Aulakh et al., 2009). Increasing irrigation rate (amount or depth) and decreasing irrigation frequency cause more leaching of nitrate to the deeper soil layer, whereas light and frequent irrigations cause much less leaching of nitrate (Singh and Sekhon, 1976). Depending upon the rooting habit of the plants, vegetation retards nitrate leaching from the root zone by absorbing nitrate and water. The study of a 600-ha farm at the Punjab Agricultural University, Ludhiana, revealed that NO$_3$–N content varied from 1.3 to 11 mg l$^{-1}$ in deep irrigation tubewells, from 0.4 to 11 mg l$^{-1}$ in shallow irrigation tubewells, and from 0.6 to 28 mg l$^{-1}$ in hand pumps (Thind and Kansal, 2002).

To feed India’s projected population of 1.35 billion in 2025, agricultural production, especially that of rice and wheat (staple foods of India), would have to increase by approximately 25%. Agricultural production in Punjab, Haryana, and western Uttar Pradesh might not be sustainable unless major steps are taken to improve management of groundwater (Hira, 2009). Thus, groundwater management holds the key to the future sustainability of RW in the region. The development of water-efficient cultivars and alternative methods of irrigation as well as crop establishment methods that require less water will be the deciding factors for future rice cultivation. The time has come to seriously think about rainwater harvesting.

### 2.3. Deteriorating Soil Health

Crop production removes varying amounts of mineral nutrients from the soil, depending on production and nutrient-supplying capacity of the soil, which in turn is influenced by soil type, soil organic matter content, amount of nutrients applied, and removal or recycling of crop residues in the soil. Rice and wheat are heavy feeders of nutrients. The RW system has not only resulted in mining of major nutrients (N, P, K, and S) from the soil but also has created a nutrient imbalance, leading to deterioration in soil quality. Deficiencies of N, P, and K are most extensive. One ton of wheat grains is estimated to remove 24.5, 3.8, and 27.3 kg N, P, and
K, respectively, whereas similar production of rice grains removes 20.1 kg N, 4.9 kg P, and 25.0 kg K (Tandon and Sekhon, 1988). Soils in the IGP contain low organic matter content and are being consistently depleted of their finite reserve of nutrients by crops (Bijay–Singh and Yadvinder–Singh, 2004). Excessive nutrient mining of soils is one of the major causes of fatigue experienced by soils under the RW system. The quantities of nutrients removed by rice and wheat are greater than the amount added through fertilizers and recycled. Sulfur deficiency has been observed in about one-quarter of the samples tested in the NW region of India, particularly in soils that are coarse-textured, low in pH, and poor in organic matter (Sharma and Nayyar, 2004). The micronutrient requirement of rice is more than that of wheat. Zn deficiency has become widespread in the IGP (Nayyar, 2003) and it has become the third most limiting nutrient after N and P, particularly in soils with high pH and those irrigated with poor-quality water. Forty-nine percent of more than 90,000 soil samples tested in India and 55%, 47%, and 36% of the soil samples in the trans–northern, central, and eastern parts of the country, respectively, have been found deficient in Zn (Shukla and Behera, 2011). Deficiency of Zn is more in rice and that of Mn is more in wheat. Deficiencies of other micronutrients such as Fe, Cu, and B are also appearing.

Removal of all the straw from crop fields leads to K mining at alarming rates because 80% to 85% of the K absorbed by the rice and wheat crops remains in the straw. Removal of K by crops far exceeds that of N and P, resulting in a negative K balance in the soil (Tandon and Sekhon, 1988). K removal by crop residues represents approximately five times as much as is supplied by fertilizers (Chander, 2011). Soils in the IGP generally contain adequate exchangeable K and K-bearing minerals (illite), which release exchangeable K for the crop. The absence of a response of crops to the application of K at present is mainly due to sufficient release of K from K-rich illitic and biotic minerals, and burning of rice straw, which is rich in K. The continuous RW cropping system is expected to deplete soil of K when residues are not returned to the soil even when optimum doses of fertilizer K have been applied (Meelu et al., 1995; Tandon and Sekhon, 1988). A negative K balance can be substantially improved by returning wheat residues to the field (Bijay–Singh and Yadvinder–Singh, 2004), which are now being removed mainly for dry fodder.

The fertilizer use pattern in the RW system in the IGP varies greatly, with the highest doses applied in the Trans–IGP, particularly in the Indian Punjab, and lower doses in the Central and Eastern IGP (Timsina and Connor, 2001). Fertilizer use is consistently increasing and so is the N:P2O5:K2O ratio due to the imbalanced use of these nutrients. Application of nutrients through fertilizers is highly skewed toward N
with a very low rate of K application. The partial factor productivity of N, P, and K for food grain production has dropped from about 81 kg grain per kg of N, P, and K in 1966–67 to 15 kg grain per kg N, P, and K in 2006–07 (Benbi and Brar, 2009). This decline is attributed to changes in physical and biochemical composition of soil organic matter and a decline in nutrient-supplying capacity of soil. Long-term application of inorganic fertilizers at optimum rates has either maintained or increased soil organic carbon (Biswa and Benbi, 1997). In the RW system also, an increase in soil organic carbon content with the application of recommended amounts of fertilizers was reported in long-term experiments after 13 years (Rekhi et al., 2000) and 25 years (Benbi and Brar, 2009). The response was due to a progressive increase in productivity (making available more biomass) and submergence of soils for 3–4 months during rice cultivation, which reduced the oxidation of soil C.

The efficiency of applied nutrients has been about 50% for N, <25% for P, and 40% for K (Witt et al., 1999). Lower efficiencies are due to significant losses of nutrients by leaching, runoff, gaseous emission, and fixation by soil. These losses can potentially contribute to degradation of soil and water quality and eventually lead to overall environmental degradation (Prasad, 2005). There is a need to tackle the emerging concerns of soil organic matter degradation and reduced nutrient-supplying capacity of the soils in the RW system. Inclusion of short-duration legumes between wheat and rice, balanced application of nutrients, returning rice crop residues to the soil after harvest, and the possibility of introducing some microbes for fast decomposition of residues to facilitate wheat sowing may help to restore soil fertility.

2.4. Disposal of Crop Residues

The RW system accounts for nearly one-fourth of the total crop residues produced in India (Sarkar et al., 1999). Wheat straw is considered important as dry fodder for dairy animals and farmers do not mind its harvesting and collection with the help of special cutting machines though this requires additional operation and investment. Traditionally, straw of rice and wheat (other than that used as dry fodder) and residues of other crops are removed from fields for use as livestock bedding, thatching material for housing, and fuel but these form only a small portion of the total quantity of crop residues produced by the system. The remaining rice and wheat stubbles are burned or incorporated after crop harvest (Bijay-Singh et al., 2008). There is an increasing trend of harvesting of rice and wheat through combines, leading to the production of an enormous quantity of crop residues. According to a survey, 91% of rice area and 82% of wheat area in the Indian Punjab is
harvested by combines (ICAR, 1999), annually producing about 37 M tons of crop residues and this practice is increasing in other regions of the country where the RW system is practiced. A combine harvester leaves a large quantity of straw residue on the field surface and farmers are not equipped to handle such a large mass of residues left in the field. With the increasing trend of combine harvesting, disposal of crop residues, especially of rice, has become a problem.

Crop residues, particularly from wheat and rice crops, have a wide C:N ratio of 70:1–100:1. About 30% to 40% of C added through crop residues becomes decomposed in about 2 months (Beri et al., 1992). As long as added C remains in the soil, it causes immobilization of applied N (Toor and Beri, 1991). Thus, the effect of crop residues on grain yield depends upon the amount, mode, type, and state of the applied residues (shredded or non-shredded), and the crop itself. A crop grown immediately after the incorporation of residues suffers from N deficiency caused by microbial immobilization of soil and fertilizer N in the short term (Mary et al., 1996). The magnitude of immobilized N is influenced by the decomposition period of rice straw prior to fertilizer application (Yadvinder-Singh et al., 2005).

The addition of wheat straw at 4 t ha$^{-1}$ before sowing wheat depressed wheat yield (Sidhu and Beri, 1989). An addition of N fertilizer along with residue could only partly offset the immobilization process, whereas allowing adequate time for the decomposition of residues before planting the next crop can be more beneficial. Recycling of rice residues poses more problems to succeeding wheat than wheat straw to the following rice crop because of the shorter window between rice residue incorporation and wheat sowing, low temperature, and the slow rate of decomposition of rice straw due to high silica content. Sidhu and Beri (2005) observed that incorporation of rice residue resulted in lower N content in wheat grain compared to a control as it increased organic C, labile C, water-soluble C, potentially mineralizable C, humic acid, and fulvic acid. Only a small amount, 6 to 9 kg ha$^{-1}$, of N is released during the growing period of the wheat crop from incorporated residue, hardly offering any significant effect on the yield of wheat. Application of rice residue to wheat generally has little effect on wheat yields during the short term of 1–3 years (Bijay-Singh et al., 2008; Gupta et al., 2007; Yadvinder–Singh et al., 2005).

Rice straw takes a longer time for decomposition due to high silica content. Since rice straw has no economic value, farmers hesitate to invest in cleaning the field by using a chopper. This practice also requires another operation and increases cost. Farmers in NW India have discovered burning as the cheapest and easiest way of removing large loads of crop residues produced by rice and wheat grown in the cropping system mode. In a study, the yields of rice and wheat crops decreased with the incorporation of
crop residues, whereas burning increased yields significantly over the residue removal treatment (Beri et al., 1995). Residue burning and residue removal resulted in greater grain yields of rice and wheat than residue incorporation when residues of both crops were managed immediately (Beri et al., 1995). In another study, the encouraging effects of residue incorporation and burning on yield became apparent after 5 years (Sidhu and Beri, 1989).

In the Indian Punjab, about 15 M tons of rice and wheat residues out of a total of 37 M tons of residues are being burned in situ annually, leading to a loss of about 5 M tons of C equivalent to a CO₂ load of about 18.3 M tons per year and a loss of 69,000 tons of N (Benbi et al., 2011). One ton of wheat residue contains 4.8 kg N, 0.7 kg P, and 9.8 kg K, whereas 1 ton of rice residues contains 6.1 kg N, 0.8 kg P, and 11.4 kg K (Singh and Singh, 2003). Burning of rice straw causes gaseous emission of 70% CO₂, 7% CO, 0.66% CH₄, and 2.09% N₂O (Sharma, 1998). Smoke from the burning of crop residues pollutes the air with a mixture of gases and fine particles, which can clog the lungs and cause breathing problems. Asthmatic people have great difficulty in breathing under these conditions. The peak in asthmatic patients in hospitals in India coincides with the annual burning of rice residue in surrounding fields (Bijay-Singh and Yadvinder-Singh, 2003). Smoke particles can remain in the atmosphere up to several weeks. Smoke can also create haze that impairs visibility. Thus, burning of crop residues not only results in a loss of organic matter and nutrients but also causes atmospheric pollution due to the emission of toxic and greenhouse gases such as CO, CO₂, and CH₄ (methane) that pose a threat to human and ecosystem health.

2.5. Weed Flora Shifts and Herbicide Resistance

The main reason for the adoption of transplanted rice is the desirable control of weeds due to continuous submergence of rice fields and efficacy as well as ease of application of herbicides such as butachlor. *Echinochloa colona* and *E. crus-galli* are the dominant weeds of rice in the RW system. Use of a single herbicide or the same group of herbicides for the control of *Echinochloa* species in rice has led to the occurrence of a number of weed species belonging to the grass, broadleaf, and sedge family in different ecological regions throughout the NW IGP. *Cynodon dactylon*, *Ischaemum rugosum*, *Leptochloa chinesis*, and *Paspalum distichum* among grass weeds, *Ammannia baccifera*, *Luduvigia hyssopifolia*, *Luduvigia octovalvis*, *Caesalia axillaris*, *Commelina benghalensis*, and *Eclipta prostrata* among broadleaf weeds, and *Cyperus difformis*, *Cyperus iria*, *Cyperus rotundus*, and *Fimbristylis milacca* among sedges have become important and dominant weeds in rice. The major problem preventing the success of direct-seeded rice (DSR), an emerging crop establishment method in Asia, is competition from weeds
such as *L. chinensis*, *Digitaria sanguinalis*, *Dactyloctenium aegyptium*, *E. colona*, and *Cyperus* spp. (Chauhan, 2012; Chauhan and Johnson, 2009b, 2010a, c, 2011b; Chauhan et al., 2011; Mahajan et al., 2009). In general, the weed flora of direct-seeded upland rice is quite different from that of transplanted lowland rice and therefore requires different approaches, including choice of herbicides for weed management. Successful cultivation of DSR requires an intensive use of herbicides for weed control. Currently, aceto-lactase synthase (ALS) inhibitor herbicides that may have more selection pressure are being widely advocated for weed management in DSR. Evolution of resistance in weeds to ALS inhibitor herbicides has been reported more frequently than for any other herbicide (Kumar et al., 2008). This is because these herbicides exert strong selection pressure as a result of high activity on susceptible biotypes as well as persistent soil residual activity (Tranel and Wright, 2002).

In wheat, *Phalaris minor*, *Coronopus didymus*, *Melilotus* spp., *Vicia sativa*, *Lathyrus aphaca*, *Chenopodium album*, *Anagallis arvensis*, and *Polygonum* spp. are the dominant weeds. The most dominant and problematic weed is *P. minor*, which was introduced in India with wheat seed imported from Mexico in the late 1960s and soon became a major weed of wheat in the RW cropping system in the fertile and irrigated conditions of the NW IGP. The morphological similarity of *P. minor* with the wheat plant and narrow row spacing inhibited its mechanical control. Its prolific seed production and earlier maturity than wheat resulted in its dominance in wheat fields over other weeds. The herbicide isoproturon (substituted-urea group) introduced for its control in the 1970s proved to be a “magic herbicide” that ruled the wheat fields for more than two decades due to its broad spectrum of weed control (almost complete control of *P. minor* and some other prominent grass and broadleaf weeds), low cost, and postemergence application. However, faulty spraying techniques, the use of lower than recommended rates, the use of less quantity of spray solution, and repeated use of the herbicide year after year eventually resulted in the evolution of biotypes of *P. minor* resistant to isoproturon.

The first sign of *P. minor* developing resistance to isoproturon in the NW IGP occurred during the mid-1990s. This seriously affected the productivity of wheat on many farms; severe cases compelled growers to harvest the wheat crop at anthesis along with weeds for stock feed, sometimes resulting in complete crop failure with a potential to make the RW cropping system unsustainable in the region. The causes and the extent of dominance of *P. minor* in this cropping system in the IGP have been highlighted in previous reports (Harrington et al., 1992; Malik et al., 1998; Malik and Singh, 1995). The isoproturon resistance mechanism is metabolic degradation, mediated by P-450 mono-oxygenase enzymes (Singh, 2007). This type of resistance could become serious and lead to the evolution of multiple resistances to herbicides of different modes of action. There are
now confirmed reports of cross-resistance of *P. minor* to other substituted herbicides such as clodinafop, fenoxaprop–*p*-ethyl, methabenztiazuron, and metoxuron (Mahajan and Brar, 2001).

Chhokar and Sharma (2008) reported that the multiple herbicide-resistant populations of *P. minor* had low sulfosulfuron resistance but high resistance to clodinafop and fenoxaprop (ACCase inhibitors). The clodinafop-resistant populations also showed higher cross-resistance to fenoxaprop (fop group) but low cross-resistance to pinoxaden (den group). Some populations of *P. minor* resistant to four groups of herbicides (phenylureas, sulfonylurea, aryloxyphenoxypropionate, and phenylpyrazolin), however, were susceptible to the triazine (metribuzin and terbutryn) and dinitroaniline (pendimethalin) herbicides. The studies suggest that RW monoculture has resulted in the dominance of some weeds in rice and others in wheat.

### 2.6. Climate Change

The global climate witnessed warming of 0.74°C between 1906 and 2005 due to an increase in concentration of greenhouse gases CO₂, CH₄, and N₂O. CO₂ concentration increased from 280 ppm in the pre-industrial era to 379 ppm in 2005 (IPCC, 2007a). The IPCC (2007b) has further projected a rise in temperature from 0.5 to 1.2°C by 2020 and from 0.88 to 3.16°C by 2050 in the South Asia region depending upon future developments. Timsina and Humphreys (2006a, b) extensively reviewed the evaluation and application of the CERES-Rice and CERES-Wheat models for estimating yields of these crops under current and future change scenarios. They concluded that the projected increase in temperatures due to global warming would decrease the growth duration and yield of both crops. Other crop models (WTGROWS and INFOCROP) have also predicted a decline in rice productivity by 0.75 t ha⁻¹ with a 2°C increase in mean air temperature (Wassmann et al., 2009). A group of scientists from the Climate Research Unit, University of East Anglia, UK, have predicted a similar reduction in wheat yields in NW India (Ortiz et al., 2008).

The frequency of extreme events such as high temperature is predicted to increase in the future (IPCC, 2001). Heat stress severely restricts plant growth and productivity and is regarded as one of the major abiotic adversities for many crops (Georgieva, 1999; Hassan, 2006), particularly when it occurs during the reproductive stage, which may lead to a substantial yield loss in wheat (Hays et al., 2007). In the RW cropping system, crop damage due to heat stress under late-planting conditions has become an important factor limiting wheat yields (Aslam et al., 1989). High temperatures during early crop development and particularly after anthesis may limit yield (Hunt et al., 1991). Temperature fluctuations
during grain filling in wheat were found to cause deviations from expected dough properties (Blumenthal et al., 1991). The rise in daily average temperature, up to about 30°C, increased dough strength, while temperatures above this threshold value (35–40 °C), even only for few days, tended to decrease dough strength (Borghi et al., 1995; Corbellini et al., 1997).

Increases in temperature reduce crop duration, increase crop respiration rates, reduce crop yield, reduce the number of grains formed, inhibit sucrose assimilation in grains, affect survival and distribution of pest populations, hasten nutrient mineralization in soils, decrease fertilizer-use efficiency, and increase evaporation. In a simulation study, an increase in temperature by 2°C led to a 10–20% decrease in grain yield of both rice and wheat but, beyond that, the yield reduction was very high in wheat (Hundal and Kaur, 2007). Pandey et al. (2007), using the CERES-Wheat model, reported that the simulated grain yield of wheat under incremental units of maximum temperature (1 to 3 °C) gradually decreased from 3546 to 2646 kg ha\(^{-1}\) (8% to 31% less than the base yield) under optimal moisture conditions. Similarly, under suboptimal conditions, yield declined from 2841 to 2398 kg ha\(^{-1}\) (9% to 23% less than the base yield). The reduction in wheat yield with an increase in maximum temperature was mainly because of a reduction in duration of anthesis and grain filling with a rise in ambient temperature and vice versa (Aggarwal and Kalra, 1994).

An increase in atmospheric CO\(_2\) concentration, though, has a favorable effect on the productivity of C\(_3\) plants (rice and wheat are C\(_3\) species) in the arid region, but any increase in temperature might offset such benefits of enhanced CO\(_2\) supply and might even increase the evapotranspirational demand of water (Timsina and Humphreys, 2006a). Rising temperatures caused heat-induced spikelet sterility or increased crop respiration losses during grain filling. Such reductions in the grain-filling capability (termed crop “sinks”) of rice also have implications for greenhouse gas emissions from rice paddies and the use efficiency of fossil fuel-based N fertilizer. Thus, any anticipated rise in temperature may jeopardize food production in the region.

Next to CO\(_2\), CH\(_4\), and N\(_2\)O are two very active trace gases in the atmosphere. In addition to other sources (coal mining, oil and natural gas flarings, domestic ruminants, sewage, etc.), rice fields and residue burning are the important anthropogenic sources of CH\(_4\). Methane is produced by methanogenesis, the process that occurs when easily degradable organic matter is devoid of oxygen and other suitable electron acceptors (Cheng et al., 2006). The C for CH\(_4\) production leading to methanogenesis in the rice ecosystem mainly comes from root exudates and debris of the rice plant growing in the field. Such release of C represents a loss of valuable assimilates that would have otherwise been incorporated into
plant tissue or grain (Cheng et al., 2006). N\textsubscript{2}O is produced as an intermediate by-product in the processes of nitrification and denitrification. Wetland rice is a major source of atmospheric CH\textsubscript{4} due to extended flooding periods resulting in anaerobic decay of organic material. About 10% of the rice cultivated area in the world is close to natural wetlands and constitutes a significant source of CH\textsubscript{4}. Irrigated rice cultivated in East Asia accounts for about 97% whereas South and Southeast Asia account for about 60% of the CH\textsubscript{4} emissions from all kind of rice ecosystems (Wassmann et al., 2000). Rainfed rice and deepwater rice contribute about 24% of the CH\textsubscript{4} emissions in South Asia and 16% in Southeast Asia. In the IGP, particularly northern India, where rice is grown in rotation with wheat on coarse-textured soils of high percolation rates requiring frequent irrigations, constant inflow of oxygen into soils restricts CH\textsubscript{4} emissions (Jain et al., 2000). Factors that contribute to an increase in rice production such as the application of organic manures, crop residues, and inorganic fertilizers also increase CH\textsubscript{4} emissions whereas fertilizer N applications regulate the production of N\textsubscript{2}O. Denitrification is a significant N-loss process in wetland rice amounting to about one-third of the applied N (Aulakh et al., 2001). About 15 kg N\textsubscript{2}O-e N ha\textsuperscript{-1} is emitted from the RW system.

Substantial production of CH\textsubscript{4} occurs even in non-flooded soils amended with rice straw (Sass et al., 1992). Anaerobic microsites can create congenial conditions for CH\textsubscript{4} production. Emission of CH\textsubscript{4} resulting from rice straw burning were in a similar range of straw incorporation into the soil (Miura and Kanno, 1997).

3. Opportunities and Strategies

3.1. Conservation Agriculture

Conservation agriculture is a concept designed for optimizing crop yields, and reaping economic and environmental benefits. “Conservation agriculture is recognized as agriculture of the future, the future of agriculture” (Pretty et al., 2011). The key elements of conservation agriculture are minimum disturbance of soil, rational organic soil cover using crop residues or cover crops, and the adoption of innovative and economically viable cropping systems and measures undertaken to reduce soil compaction through controlled traffic (Hobbs et al., 2008). These conservation agriculture principles are not “site-specific” but represent “unvarying objectives” that are practiced to extend conservation agriculture technologies efficiently across all production environments. Therefore, other than the key elements described above, conservation
agriculture systems include best management practices of component technologies (weed, water, nutrient, integrated pest management, etc.). The way crop management is practiced in different ecologies (e.g., plains and sloping lands) may vary the importance of the ‘unvarying objectives’ according to local situations, resource endowments of farmers, and farming systems. Thus, conservation agriculture is an innovation process of developing appropriate conservation agriculture implements, crop cultivars, etc., for iterative guidance and fine-tuning to modify crop production technologies. This only suggests that conservation agriculture systems should be “divisible” in nature and “flexible” in operation, allowing farmers to benefit from them under diverse situations. Conservation agriculture-based crop management technologies are an “open” approach, easier to mainstream and be able to quickly respond to critical needs that address the concerns faced by South Asian agriculture today: i.e., farm economics and climate change.

Conservation agriculture practices have been widely adopted in tropical, subtropical, and temperate regions of the world for rainfed and irrigated systems. The area of conservation agriculture is increasing steadily worldwide. Recent estimates revealed that conservation agriculture-based resource-conserving technologies that include laser-assisted precision land leveling, no-till, reduced tillage, direct drilling into residues, DSR, unpuddled mechanical transplanted rice, raised-bed planting, diversification/intensification, etc., are being practiced over nearly 3.9 M ha in South Asia (Jat et al., 2011a).

Several studies conducted across the production systems under varied ecologies of South Asia revealed potential benefits of conservation agriculture-based crop management technologies (listed above) in resource conservation, use efficiency of external inputs, yield enhancement, soil health improvement, and adaptation to changing climates (Table 2) (Gupta et al., 2010b; Gupta et al., 2003; Gupta and Sayre, 2007; Gupta and Seth, 2007; Jat et al., 2010; Malik et al., 2005b). The details of individual conservation agriculture-based crop management technologies are described below.

3.1.1. No-till system

Tillage contributes significantly to the labor and fuel cost of intensive agriculture in any crop production system, resulting in lower economic returns and soil degradation. There are indications of non-sustainability of the RW cropping system with the traditional practice of planting rice seedlings manually in random geometry after repeated dry and intensive wet tillage followed by conventionally tilled seeding of wheat. A shortage of water, labor, and energy resources, prohibitive costs of diesel, inappropriate crop management practices, adverse effects of conventional tillage on the carbon-based sustainability index, and declining profit margins are forcing
Table 2  Effect of different conservation agriculture-based crop management technologies on crop yields, water savings, and water productivity

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Location, country</th>
<th>Crop/cropping system</th>
<th>Yield gain over conventional practices (kg ha(^{-1}))</th>
<th>Water savings over conventional practices (ha-cm)</th>
<th>Increase in water productivity (kg m(^{-3}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser leveling</td>
<td>Meerut, India</td>
<td>Rice—wheat</td>
<td>750</td>
<td>26.5</td>
<td>0.06</td>
<td>Jat et al. (2009a)</td>
</tr>
<tr>
<td></td>
<td>Karnal, India</td>
<td>Rice—wheat</td>
<td>810</td>
<td>24.5</td>
<td>—</td>
<td>Jat et al. (2009b)</td>
</tr>
<tr>
<td></td>
<td>Ludhiana, India</td>
<td>Rice</td>
<td>750</td>
<td>22.0</td>
<td>—</td>
<td>Sidhu (2010)</td>
</tr>
<tr>
<td>No-till</td>
<td>Karnal, India</td>
<td>Wheat</td>
<td>150—400</td>
<td>2—4</td>
<td>0.10—0.21</td>
<td>Malik et al. (2005a); Saharawat et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Meerut, India</td>
<td>Wheat</td>
<td>610</td>
<td>2.2</td>
<td>0.28</td>
<td>Gathala et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Delhi, India</td>
<td>Corn</td>
<td>150</td>
<td>8.0</td>
<td>0.21</td>
<td>Parihar et al. (2011)</td>
</tr>
<tr>
<td>No-till with surface residue</td>
<td>Karnal, India</td>
<td>Rice—wheat</td>
<td>500</td>
<td>61</td>
<td>0.24</td>
<td>Gathala et al. (2010)</td>
</tr>
<tr>
<td>Direct-seeded rice</td>
<td>Meerut, India</td>
<td>Wheat</td>
<td>410</td>
<td>10</td>
<td>0.13</td>
<td>Jat et al. (2009c)</td>
</tr>
<tr>
<td></td>
<td>Ghaziabad, India</td>
<td>Rice</td>
<td>120</td>
<td>25</td>
<td>0.08</td>
<td>Jat et al. (2006a)</td>
</tr>
<tr>
<td></td>
<td>Ludhiana, India</td>
<td>Rice</td>
<td>510</td>
<td>13</td>
<td>0.09</td>
<td>Gill et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Karnal, India</td>
<td>Rice</td>
<td>62</td>
<td>18</td>
<td>0.10</td>
<td>Gupta and Jat (2010)</td>
</tr>
<tr>
<td>Raised-bed planting</td>
<td>Meerut, India</td>
<td>Corn</td>
<td>324</td>
<td>12</td>
<td>0.80</td>
<td>Jat et al. (2006b)</td>
</tr>
<tr>
<td></td>
<td>Meerut, India</td>
<td>Wheat</td>
<td>310</td>
<td>16</td>
<td>0.58</td>
<td>Jat et al. (2011a)</td>
</tr>
<tr>
<td></td>
<td>Kaithal, India</td>
<td>Wheat</td>
<td>270</td>
<td>5.0</td>
<td>0.50</td>
<td>Chandra et al. (2007)</td>
</tr>
</tbody>
</table>
farmers of the IGP to switch over to no-till practices. No-till in the RW system has helped to save fuel and water, reduce the cost of production, and improve system productivity and soil health (Gupta et al., 2003; Gupta and Sayre, 2007; Gupta and Seth, 2007; Jat et al., 2009a; Malik et al., 2005b; Saharawat et al., 2009; Saharawat et al., 2010).

Declining soil health has become an important constraint to productivity in the region. Traditionally, land preparation constitutes the major cost of production of wheat in the transplanted RW production system due to repeated plowings needed to obtain desirable tilth and this practice also delays wheat sowing, thus affecting its productivity. The adoption of no-till, which is based on the principle of no or minimum soil disturbance, is considered vital for maintaining the productivity of the RW system. A number of benefits of a no-till system such as lower production costs achieved through savings in fuel, labor, and irrigation water, early sowing of wheat, positive effects on soil health, better quality of environment, lower weed (P. minor in wheat) infestation, reduced lodging, etc., have been documented (Gupta et al., 2005; Khan et al., 2001; Ladha et al., 2003; Malik et al., 2005a). No-till cultivation of wheat was once practiced on over 2.0 M ha in India, with potential of a further increase in eastern India (RWC-CIMMYT, 2005). A similar trend was witnessed in Punjab Province of Pakistan (Gill, 2006; Khan et al., 2001). Gill (2006) has reported problems and constraints faced by farmers in the use of a zero-till drill for wheat sowing in Pakistan. There are contrasting reports of an increase in incidence of rice stem borer in the RW system due to the use of zero-till in Pakistan (Gill, 2006; Inayatullah et al., 1989). However, in India, an increased problem of pink stem borer and rats in wheat has been observed (Jaipal et al., 2005). Contrary to expectations, a significant reduction has occurred in area under no-till cultivation of wheat in the last few years. In fact, a zero-till seed drill works well when there is no rice residue in the field, a condition normally achieved by manual harvesting of rice. Besides saving time and facilitating sowing immediately after the rice harvest, sowing in residue-free fields leads to reduced biotic stresses in terms of weeds, insects, and diseases and generally does not result in a decline in crop yields when compared with other crop residue management options (Samra et al., 2003).

The introduction of no-till and other resource-conserving technologies into the rice phase of the RW system may further increase long-term profitability as there is considerable scope to reduce the cost of cultivation and soil health hazards in aerobic rice systems and the subsequent negative effects on the succeeding wheat crop. It is possible to significantly reduce CH$_4$ emissions from rice paddies in the RW system through the adoption of resource-conserving technologies (Samra, 2004). Transplanting of rice in the NW IGP is becoming increasingly difficult due to the non-availability of labor and uneconomical due to high wages, the high cost of fuel, and
decreasing availability of irrigation water. A no-till system omits prior land preparation and the seed is placed into the soil by a seed drill. No-till DSR and no-till transplanted rice have shown promising results and they have the potential for large-scale adoption. In spite of promising benefits from the adoption of no-till cultivation of DSR or transplanted rice, farmers may not be able to adopt the technology until the problems of no-till cultivation in wheat and DSR are solved and the technologies are fine-tuned to suit farmers' conditions.

3.1.2. The furrow-irrigated raised-bed system (FIRBS)
For the past one and a half decades or more, efforts have been in place to popularize FIRBS of planting rice and wheat in the IGP. It is a system in which the crop is sown on ridges or raised beds of 15–20-cm height. Usually, the bed is 37.5 cm wide with furrow width of 30 cm (total bed size of 67.5 cm) to accommodate two rows of wheat. Beds of bigger size (90 or 120 cm wide) could also be prepared. The system aims at saving irrigation water and increasing nutrient-use efficiency. The FIRBS is already popular in irrigated wheat-corn systems in northwest Mexico (Meisner et al., 1992; Sayre and Hobbs, 2004), where area under bed planting increased from 6% in 1981 to 75% in 1994 (Sayre and Moreno Ramos, 1997), and for the production of irrigated non-rice crops on heavy clay soils of Australia since the 1970s (Maynard, 1991). Potential agronomic advantages of beds include improved soil structure due to reduced compaction through controlled trafficking, reduced waterlogging, better surface drainage, improved fertilizer placement, feasibility of mechanical weed control, reduced irrigation time, and improved yields on fine-textured soils prone to waterlogging. There are several reports of reduced irrigation amounts or time, with similar or higher yields, for wheat on beds compared with conventional-tilled wheat. Although the potential benefits of bed planting for wheat in corn-wheat systems have been established in the IGP for some time (Bhardwaj et al., 2009; Dhillon et al., 2000; Hari Ram et al., 2012), the evaluation of beds for rice and permanent beds in the RW system commenced more recently (Connor et al., 2002).

Connor et al. (2002) listed advantages of the FIRBS: (i) reduced tillage and direct seeding on permanent beds reduce the costs of labor, diesel, and machinery in comparison with the costs of initial bed formation and maintenance; (ii) it arrests soil structural degradation and hard pan formation from intensive rice; (iii) it provides feasibility of mechanical weeding and inter-culture operations in wheat and other non-rice crops to reduce herbicide or labor costs and reduce the development of herbicide resistance and this could also extend to rice on beds; (iv) mechanical placement of fertilizers below the soil surface and near the root zone, leading to improved fertilizer-use efficiency; (v) saving up to
30–40% of irrigation water in wheat and rice; (vi) reduced cost incurred in digging, maintenance, and deepening of wells, power for pumping, and labor for irrigation; electricity for pumping is generally not available in the hot summer season prevailing during rice seasons due to peak demand from other sectors; (vii) reduced seed requirement of a range of crops compared with flat surfaces; (viii) increased opportunities for crop diversification in both the wet and dry seasons; and (ix) lower groundwater pollution and CH₄ emissions from non-puddled intermittently irrigated rice on beds compared with puddled rice on flat surfaces.

In the FIRBS, irrigation savings range from 18% to 50% (Gupta et al., 2005; Jat et al., 2005; RWC-CIMMYT, 2003). Farmer and researcher trials in the IGP suggest irrigation water savings of 12% to 60% for DSR and transplanted rice on beds, with similar or lower yields for transplanted rice on beds compared with puddled flooded transplanted rice, and usually slightly lower yields with DSR on beds (Balasubramanian et al., 2003). The RW system on permanent beds has been intensively studied in the Indian Punjab and the results showed that there was no yield advantage of growing crops on beds compared with flats but there was little advantage in water savings (Humphreys et al., 2008a; Humphreys et al., 2008b; Kukal et al., 2008; Kukal et al., 2010; Yadavinder-Singh et al., 2008b; Yadavinder-Singh et al., 2009b). Another study in the NW IGP also showed little effect of rice on beds on water productivity (typically around 0.30–0.35 g kg⁻¹) as the decline in water input was accompanied by a similar decline in yield (Sharma et al., 2002).

With few exceptions (e.g., Limon-Ortega et al., 2000; Maynard, 1991), the beds are heavily cultivated and reshaped or completely reformed each year, at considerable expense. The acceptance of this technology by RW system farmers has been low owing to the significant cost of making beds and their subsequent reshaping on a regular basis. In addition, bedplanters in the NW IGP with large farm size require tractors with high horsepower (>45) and custom hiring is still not a popular practice. Farmers have also reported difficulty of movement through these narrow furrows while spraying herbicides. Permanent raised beds prepared with no-till seeders in situations where wheat is rotated with crops other than rice, however, still look promising. There is a further need to refine the FIRBS technology to fit in the RW cropping system so that irrigation water in the IGP region can be saved.

3.1.3. Direct-seeded rice
The common method of establishing rice in South Asia is manual transplating with random geometry after repeated wet tillage, the process called puddling. The puddling process consumes 30% of the total water requirement in rice culture to form a dense clay layer, which controls
water losses through percolation. Puddled transplanted rice consumes 120 to 180 cm-ha of water in the Eastern and Western IGP. In recent years, declining water tables, increasing labor shortage, and deteriorating soil health due to edaphic requirements make the RW system uneconomic and unsustainable. The fixed support price of rice and committed procurement policy of the government of India do not encourage farmers to shift away from the rice crop. As a result, the water table in this region is declining at a fast rate and efforts are being made toward crop diversification, which is considered crucial to conserve natural resources. Preliminary research investigations conducted over a period of a decade clearly reveal the possibility of cultivating aerobic rice, which requires discernibly low irrigation water (Mahajan et al., 2011c; Sudhir-Yadav et al., 2010).

The alternative establishment techniques for rice, such as dry DSR, have shown promise in different production environments in South Asia and may alleviate many of the problems associated with puddled transplanted rice. In South Asia, DSR (wet- and dry-seeded) is already practiced in many medium-deep and deepwater rice ecologies of the Eastern Gangetic Plains of India and Bangladesh, on terraced and sloping lands in the North-east and Western Himalayan region, and the Ghats along the west coast of India. The area under DSR in India, Pakistan, and Bangladesh is 14.2 Mha of the total rice area of 55.3 Mha (Pandey and Velasco, 2005). In the past, the common factors contributing to poor yields of DSR were supra-optimal seeding rates (60–100 kg ha\(^{-1}\)), increased weed competition, insufficient fertilizer use, and a lack of improved cultivars selected for good stand establishment with direct seeding.

Recently, some of these problems have been overcome and agro-technology with respect to cultivars, sowing time, seeding rate, crop geometry, and weed, nutrient, and water management has been developed and deployed in the RW system, which resulted in similar or higher outputs (system productivity), with 25% less water and labor and timeliness in planting (Gathala et al., 2011). Sowing in the first fortnight of June, using 15–30 kg seed ha\(^{-1}\) at 2–3-cm soil depth (Mahajan et al., 2010) and 20–25-cm row spacing gives rice productivity of 6–8 t ha\(^{-1}\) (Gansham and Singh, 2008). A seeding rate of 30 kg ha\(^{-1}\) is adequate if weeds are properly controlled. In Pantnagar, India, no differences in the yields of dry DSR were observed at seeding rates ranging from 15 to 125 kg ha\(^{-1}\) when grown under weed-free conditions (Fig. 1) (Chauhan et al., 2011). Since the conditions are not conducive for perfect seedling emergence in the farmers' fields, the seeding rate should be kept higher than 15 kg ha\(^{-1}\) to compensate for damage by rats and birds, to partially overcome the adverse effects of herbicides, and to compensate for poor stand establishment if rains occur immediately after sowing (Chauhan et al., 2011).
Irrigation in dry DSR is applied after 3–5 days when the ponded water is infiltrated into the soil. Mahajan et al. (2011c) found that applied irrigation water increased by 28% in puddled transplanted rice compared with dry DSR. Bouman et al. (2005) reported that, on average, an aerobic field used 190 mm less water for land preparation and had 250–300 mm less seepage and percolation than a puddled field. Gopal et al. (2010) claimed that dry DSR saved irrigation water by eliminating the need to puddle the field. Similarly, Bhushan et al. (2007) realized irrigation water savings of 25% with no-till dry DSR compared with puddled transplanted rice when irrigation for both establishment methods was scheduled based on the appearance of hair-line cracks.

The promotion of dry DSR is the appropriate option of crop diversification for high yield realization and efficient use of resources. The impact of DSR on the long-term productivity and sustainability of the RW system, however, requires careful evaluation within the context of production systems. In dry DSR, major challenges in addition to weed management are nutrient management (including iron deficiency) and water management for successful crop establishment because most of the soils in NW India, including Punjab, are coarse-textured. Mahajan et al. (2011a) reported that application of N in four splits resulted in higher grain yield of dry DSR than its application in three splits as is recommended for transplanted rice. With the application of N in three splits in dry DSR, grain filling was limited by pre- and post-anthesis assimilate, indicating that fertilizer application schedules for transplanted rice are not suitable for dry DSR. This study revealed that application of N at sowing time in dry DSR can be skipped because the N may not be immediately used by the emerging seedlings and application at anthesis may further boost the productivity of dry DSR. Cultivars having characteristics of anaerobic...
germination, weed competitiveness, and efficiency in Fe uptake from the soil are needed for wider adoption of direct seeding in the near future.

### 3.2. Crop Residue Management

Crop residues play a significant role in building soil organic matter, nutrient recycling, and improving the soil physical environment. The long-term sustainability of a cropping system depends on its carbon inputs, outputs, and carbon-use efficiency. Crop residues are the principal source of carbon and the way they are managed has a significant effect on soil physical, chemical, and biological properties (Kumar and Goh, 2000). Incorporation of crop residues into soil is known to improve soil structure, reduce bulk density, and increase the porosity and infiltration rate of soil. This may help reduce the adverse effects of hard pan in the RW system and benefit the wheat crop (Singh et al., 2005). Crop residues still play an important role in the cycling of nutrients despite the dominant role of chemical fertilizers in crop production. Crop residue management regulates the efficiency with which fertilizer, water, and other reserves are used in a cropping system.

Soil organic carbon influences physical, chemical, and biological functions and serves as an important sink and source of main plant nutrients. Soil organic carbon content, aggregation status, total porosity, pore size distribution, bulk density, dispersion ratio, and soil strength were correspondingly improved with crop residue incorporation (Bhatnagar et al., 1983; Bijay-Singh et al., 2008). Soil organic carbon content also influences the crop response to applied nutrients. Beneficial effects of rice straw (5 t ha$^{-1}$), applied in situ 20 days before wheat sowing, in conjunction with 120 kg N ha$^{-1}$ (C:N ratio of 15:1) have been observed on wheat yield (Sidhu and Beri, 2005). Organic matter decomposition releases nutrients into the mineral nutrient pool and reactive C (CO$_2$) and N (N$_2$O, NO) compounds to the atmosphere, and surface water and groundwater (NO$_3$, NH$_4$). Therefore, practices that increase organic matter addition to the soil through increased productivity, exogenous supply, or on-farm recycling improve soil fertility and crop productivity. Each ton of organic carbon in the plow layer is equivalent to 4.75 kg fertilizer N ha$^{-1}$ (Benbi and Chand, 2007).

The addition of organic materials in sufficient amounts to soil is important for improving soil health as the organic substrates influence the microbial population in the soil, which is responsible for nutrient transformations resulting in the availability of nutrients, particularly N, P, and S. Incorporation of crop residues increased the population of aerobic bacteria and fungi while burning decreased it (Beri et al., 1992). These organic sources also reduce gaseous and leaching losses of N (Beri et al., 1995; Beri et al., 1992).
With increased production of rice and wheat, straw production has also increased. Burning crop residues due to a lack of efficient and user-friendly technologies for in situ recycling (Jat et al., 2004) has significant implications, leading to a loss of organic matter and precious nutrients, especially sulfur contained in crop residues, deterioration in the quality of air, and increased emission of greenhouse gases (Samra et al., 2003). Increasing mechanization has led to increased availability of rice residues to further aggravate the situation, which may contribute substantially to air pollution. Burning not only leads to the loss of a considerable amount of N, P, K, and S but also contributes to the global NO₂ and CO₂ budget (Grace et al., 2002) and the destruction of beneficial microflora of the soil (Jat and Pal, 2000; Timsina and Connor, 2001). The decline in soil organic matter owing to residue burning has been implicated as one of the key factors in non-sustainability of the system. The incorporation of crop residues alters the soil environment, which in turn favorably influences microbial population activity in the soil and subsequent nutrient transformation (Kumar and Goh, 2000).

Rice straw can be managed successfully in situ by allowing sufficient time between its incorporation and sowing of the wheat crop (Yadvinder-Singh et al., 2004). The magnitude of immobilized N was influenced by the decomposition period of rice straw prior to fertilizer application (Yadvinder-Singh et al., 2005). Application of rice residue to wheat typically has a small effect on wheat yields during the short term of 1–3 years (Bijay-Singh et al., 2008; Yadvinder-Singh et al., 2005) but the effect appears in the fourth year with the incorporation of straw (Gupta et al., 2007). Crop residues can lower P sorption capacity and enhance P availability. Both organic and inorganic P contents and available soil K increased with straw incorporation compared with straw removed (Beri et al., 1995; Gupta et al., 2007). The release of K from rice straw occurs at a fast rate and more than 70% of total straw-K is released within 10 days after incorporation. Soil treated with crop residues contained 5–10 times more aerobic bacteria and 1.5–11 times more fungi than soil on which residues were either burned or removed (Sidhu and Beri, 2005).

The emerging residue management options in the IGP are to mulch with rice straw (5–7 t ha⁻¹) in no-till wheat and incorporate combine-harvested or even manually harvested (as in the Middle and Lower IGP) wheat straw and stubble (1–2 t ha⁻¹) in rice (Bijay-Singh et al., 2008). Rice residue can also be used as a mulch for a wheat crop established after tillage; however, this option is more feasible for farmers with small landholdings and sufficient labor (Bijay-Singh et al., 2008), as this involves temporarily removing residue from the field and then returning it after the wheat crop has been planted. Residue management in no-till systems (surface retention) helps in improving soil health (Sharma et al.,
reduces greenhouse gas emissions equivalent to nearly 13 t ha\(^{-1}\) (Mandal et al., 2004), regulates canopy temperature at the grain-filling stage to mitigate the terminal heat effects in wheat (Gupta et al., 2010a; Jat et al., 2009c), and significantly improves the C sustainability index (Jat et al., 2011b).

It has not been possible to manage crop residues in no-till systems with tine-type openers. The use of new-generation planters (Happy seeder, rotary-disc drill, double-disc drill, and punch planter) may lead to wider adoption of conservation agriculture in the region (Sidhu et al., 2007). The Happy seeder works well for direct drilling in standing as well as loose residues, provided the residues are spread uniformly. In the Cereal Systems Initiative for South Asia (CSISA) project being implemented in the four South Asian countries, including India, a straw spreader fitted to a combine was developed and tested. These straw spreaders spread residues uniformly, facilitating the direct drilling of wheat immediately after the rice harvest. The major demerit of the Happy seeder is its inability to work in the early morning and late evening hours when the straw is wet with dew, thus limiting its practical use to only a few hours of the day during the peak period of sowing of wheat. Its high cost is another prohibitive factor.

The IGP have an acute power shortage and the available hydro- and thermo-power plants have not been able to meet the rising demand. Several power plants that run on biofuel have been started in different areas on a pilot basis and have been running satisfactorily. It is expected that surplus rice straw will find its end use for running these plants in the near future. Bailing of rice straw with the help of balers for use in the card-board and paper industry seems to be another viable option in the future provided balers are available at an affordable price or custom hiring is encouraged.

### 3.3. Precision Land Leveling

Land leveling is a precursor to good agronomic, soil, and crop management practices and the levelness of the land surface has a significant influence on all farming operations. Unevenness of the soil surface influences farming operations, energy use, aeration, crop stand, and yield mainly through nutrient-water interactions. Traditionally, farmers perform land leveling by using plankers (wooden boards) drawn by draft animals or tractors. Traditionally leveled fields have frequent dikes and ditches within the fields and, even with best efforts by conventional leveling practices, field slopes vary from 1° to 3° in transects I and II (Pakistan Punjab, Indian Punjab, Haryana, and Western Uttar Pradesh) to 3° to 5° in transects IV and V of the IGP (Jat et al., 2006a). Undulating land hampers seedbed preparation, seed placement, and germination and also requires more
power for machines, which leads to the consumption of more energy, and ultimately to more cost of production and low productivity (Jat et al., 2006a; Jat et al., 2009a). In practice, it has been observed that land-leveling methods used by farmers in the IGP often result in low input-use efficiencies (nutrient and water) and low crop yields. Poor management and uneven fields lead to 10–25% irrigation water loss during application (Kahlown et al., 2002), which results in lower crop yields, higher irrigation costs, and poor resource-use efficiency (Jat et al., 2006a).

Laser land leveling is one of the few mechanical inputs in intensively cultivated irrigated farming that meets the objectives of saving irrigation water, improved input-use efficiencies, and achieving a better crop stand. Hill et al. (1991) rated the development of laser technology for precision land leveling as second only to the breeding of high-yielding varieties. It is a process of leveling the land surface within $\pm 2$ cm of its average micro-elevation using a laser-equipped drag scraper. Laser leveling has become an important component of conservation agriculture-based crop management technologies. Laser-assisted land leveling improves crop yields and input-use efficiency, including water and nutrients (Jat et al., 2006a; Jat et al., 2010). Precision land leveling has been shown to improve water use and obtain up to 50% savings of irrigation water (Jat et al., 2006a; Jat et al., 2009b; Jat et al., 2010; Rickman, 2002). Crop yields depend on optimum seedling emergence, better crop stand, and early crop vigor. Laser land leveling is also reported to improve crop stand and crop productivity (up to 30%) and reduce the labor requirement for weeding (from 21 to 5 days ha$^{-1}$) in rice (Bell et al., 1998; Jat et al., 2006a; Jat et al., 2009b; Rickman et al., 1998). Kahlown et al. (2002) reported that precision land leveling improved the performance of RW and water productivity in non-puddled soil, with no-till surface seeding and seeding on permanent beds compared with conventional tillage. Currently, laser-assisted land leveling is being practiced over 1.5 Mha in South Asia (Jat et al., 2009a; Jat et al., 2009b; Jat et al., 2011a).

3.4. Crop Diversification

Crop diversification is of paramount importance in mitigating the biotic and abiotic problems arising on account of RW monoculture. Diversification with high-value crops will encourage the export of farm produce, bringing more profits. Inclusion of certain crops in sequential and intercropping systems has been found to reduce nutrient and water needs and the population of some obnoxious weeds to a considerable extent, thereby reducing herbicide needs to a great extent in areas where such weeds have assumed alarming proportions. Continuous cultivation of crops having
similar management practices allows certain weed species to become dominant in the cropping system and, over time, these weed species become hard to control. In addition, continuous cropping can negatively interact with conservation agriculture systems and shift the weed flora toward a troublesome composition. Rotating crops having divergent and distinct morphologies, growth habits, life cycles, differing cultural practices, and nutrient and water needs can all potentially affect the community composition and distribution of weeds.

Increased fertilizer N-use efficiency through improved management in a diversified crop can reduce the potential for nitrate contamination of groundwater. Inclusion of legumes in cropping systems has been found to be effective in reducing nitrate leaching in lower profiles. Legumes can play an important role in conserving groundwater and soil water. However, profitability of legumes has remained too low in comparison with rice and wheat (Joshi, 2003). Similarly, there is a chronic shortage of edible oils in the country and massive spending of money is made every year to import 5–6 million tons of edible oils. In spite of the huge demand for pulses and edible oils in the country, farmers are not tempted to cultivate them because of lower yields in comparison to rice and wheat and their sensitivity to biotic and abiotic stresses. Cultivation of sunflower or corn during spring holds some promise but this will replace wheat rather than rice. Moreover, the water requirement of these crops (8–9 irrigations for sunflower and spring corn) is much higher than for wheat (4–5 irrigations). Soybean cultivation during the rainy/kharif season has also failed to make any impact because of establishment problems in soil with low organic carbon, low yields, damage by white fly, and lack of taste due to beanie flavor. Consistent efforts by policymakers and scientists to convince farmers to diversify the present RW system have failed to attract farmers due to a lack of profit, price support, and marketing bottlenecks for the alternative crops. The situation is unlikely to change unless some breakthrough is achieved in terms of developing high-yielding (2.5–3.0 t ha\(^{-1}\)) cultivars or hybrids of oilseeds and pulses. The cost of cultivation of groundnut, soybean, and many other crops in the region is much higher than in central or southern India, where the same yields are achieved under rainfed conditions. Moreover, the quality of these crops as well as wheat produced in these areas is better (higher protein content). Raised-bed planting technology provides an opportunity for diversification through intensification and it saves on water (Jat et al., 2005). Crop diversification within the RW system can be achieved by replacing part of the area under rice with basmati rice and bread-wheat with durum-wheat (Gill et al., 2008). There is an urgent need for the government and policymakers to make stronger efforts to convince farmers to diversify RW monoculture with other crops.
3.5. Soil Nutrient Management

Crop requirement for nutrients varies with crop potential, field history, cropping sequence, sowing time, season, location, and growing conditions (Timsina and Connor, 2001). Results of long-term experiments have shown a linear response of rice to applied nutrients, suggesting scope for their higher application (Ladha et al., 2003). Site-specific nutrient management, which takes these factors into consideration, is needed to ensure balanced and optimum nutrient use, improvement in crop productivity, and higher nutrient-use efficiency. The use of a chlorophyll meter and leaf color chart is being advocated to apply the required amount of N (Balasubramanian et al., 1999; Balasubramanian et al., 2000; Peng et al., 1996; Turner and Jund, 1991). In the Indian Punjab, a value of 37.5 was found as the critical SPAD value for rice grown sequentially with wheat, whereas, in wheat, yield increased with a topdressing of 30 kg N ha\(^{-1}\) when the SPAD reading at maximum tillering was less than 44 (Singh et al., 2002). Wheat yield increased by 20% when 30 kg N ha\(^{-1}\) was applied at a SPAD value of 42 at maximum tillering (Singh et al., 2002). Application of 50% of the recommended N dose with pre-sowing irrigation resulted in significantly higher wheat yield than its application at sowing (Sidhu et al., 1994). Probably N applied with pre-sowing irrigation was transported to the deeper layers of the soil and thus was not prone to loss via ammonia volatilization. On coarse-textured soils, application of N in three equal splits at sowing and at first and second irrigation resulted in more efficient use of N.

For P and K management, nutrient omission technology that determines the soil supplying capacity and crop requirement for P and K in individual fields is suggested (Dobermann and Fairhurst, 2000). It is estimated that only 20–25% of the applied P is used by cereal crops and the rest is retained in the soil as residual P. In general, high water solubility of P will be required for alkaline and calcareous soils and for wheat more than for rice. P-use efficiency in the case of its placement below the soil surface and into the root zone of wheat was 1.5 times higher than when it was broadcast (Vig and Singh, 1983). Balanced fertilization is the key to increasing the use efficiency of plant nutrients as it ensures the application of fertilizers in adequate amounts and correct ratios for optimum plant growth. Efficient nutrient management holds the key in RW double- or triple-cropping systems in which there is hardly any scope for keeping fields fallow between two crops. Also, nutrient recycling through organic manures is important, as shown for highly intensive triple-cropped rice–wheat–corn or rice–wheat–mungbean systems in Bangladesh (Panaullah et al., 2006; Saleque et al., 2006; Timsina et al., 2006). Whenever feasible, inorganic fertilizers should be used in conjunction with organic manures.
Since nutrient-supplying capacity and rate of mineralization of organic sources of nutrients vary greatly, these may have a short- to long-term effect on crop yields and soil fertility. The rate of mineralization of N from poultry manure was much faster than from farmyard manure (Yadvinder-Singh et al., 2009a). Poultry manure contains high amounts of uric acid and urea substances that readily release NH$_4^+$ on a par with urea N and the efficacy of poultry manure N was similar to that of urea N in increasing yield and N uptake of rice (Bijay-Singh et al., 1997). Application of 6 t ha$^{-1}$ of poultry manure or 12 t ha$^{-1}$ of farmyard manure to rice also showed residual effects in wheat, which were equivalent to 30 kg N and 30 kg P$_2$O$_5$ ha$^{-1}$ (Yadvinder-Singh et al., 2009a). Regular application of pressmud cake at 5 t ha$^{-1}$ for 4 years increased the organic carbon content and available P content of soil, with its long-term application having the potential to completely replace the P-fertilizer need of the RW system (Yadvinder-Singh et al., 2008a).

Sufficient time is available between the wheat harvest (in April) and rice transplanting/planting to grow a green manure crop, which has the potential to substitute 50% of the N needs of rice. Sesbania aculeata and Crotolaria juncea are the most commonly grown green manure crops in the IGP, which produce 4–5 t ha$^{-1}$ dry biomass and 80–100 kg N ha$^{-1}$ in 50–60 days (Beri and Meelu, 1981; Beri et al., 1989; Yadvinder-Singh et al., 1991). S. aculeata is more tolerant of salinity, acidity, and excess moisture conditions than C. juncea, which performs better in low rainfall and limited soil moisture. Vigna radiata and Vigna unguiculata are even better options as their grain is used as a pulse for human consumption and plant biomass can be incorporated into the soil.

### 3.6. Reducing Water Requirements

The Indian Punjab now occupies about 2.8 Mha under rice and 3.5 Mha under wheat. In neighboring Haryana State, rice and wheat cover about 1.2 and 2.5 Mha, respectively. In Uttar Pradesh, wheat is grown on 9.5 Mha and rice on 6.0 Mha. Some 30–35 irrigations (1500–1800 mm water) are given to rice, whereas wheat is irrigated 5–6 times during the crop season. Some simple measures that can save a substantial amount of water in rice are the cultivation of short-duration (early-maturing) cultivars, appropriate crop establishment methods, transplanting not before 15 June (Mahajan et al., 2008), submergence of fields only for the first 2 weeks for seedling establishment and application of subsequent irrigations only 2–3 days after complete removal of water (Sandhu et al., 1980), the use of tensiometers for scheduling irrigations (Kukal et al., 2005), stopping/withdrawing irrigation about two weeks before crop harvest, etc. Humphreys et al. (2010) have also suggested several ways of saving water...
in rice in the RW system, including laser land leveling, alternate wetting and drying (AWD), delayed rice transplanting, shorter duration rice varieties, cultivation on raised beds, and replacing part of the rice area with other crops. The AWD practice can save 15% to 30% of irrigation water, without any adverse effect on rice yield (Sandhu et al., 1980). Adoption of dry DSR in the IGP can save a substantial amount of water required for rice (Mahajan et al., 2011c; Bouman et al., 2005; Gopal et al., 2010; Bhushan et al., 2007).

Similarly, the use of laser land leveling in dry DSR can save a substantial quantity of water. In other parts of the world, savings in irrigation water were reported when rice was mulched with crop residue (Bijay-Singh et al., 2008). Rice yields were comparable for mulched and non-mulched rice crops, but water-use efficiency was higher for the mulched crops. Experts in the Indian Punjab have suggested reducing the area under rice by about 1 Mha (Hira, 2009). Bt (Bacillus thuringiensis) cotton, kharif corn, soybean, and groundnut, which require 2–5 irrigations, can be a viable alternative to rice (Kaur et al., 2010). Hira (2009) stated that, in cotton, a broad bed with spacing of 135 cm and planting cotton in furrows in paired rows increased yield by 44% and saved 40% of irrigation water compared with row spacing of 67.5 cm in flat-bed systems. Planting of potatoes on both sides of a narrow bed increased tuber yield (24 t ha$^{-1}$) by 25% and saved 20% of irrigation water compared with the ridge-planting method (20 t ha$^{-1}$).

In wheat, desirable productivity can be achieved with only 4 irrigations in comparison to 5–6 irrigations with better management practices. The irrigations can be applied only at the critical stages. A modeling study using the DSSAT CERES–Wheat model showed that irrigation for wheat grown after rice in Punjab, India, should be applied based on the atmospheric demand and soil water status and not on the growth stage (Timsina et al., 2008). The use of rice mulch in no-till wheat may also help in reducing evaporation and, ultimately, water requirement. As discussed earlier, compared with conventional tillage, the FIRBS can help in saving irrigation water from 18% to 50% (Gupta et al., 2005; Jat et al., 2005; RWC-CIMMYT, 2003).

Some area under wheat can also be replaced by oilseed (rapeseed–mustard) crops, which require only 2–3 irrigations. Oilseed crops offer an excellent opportunity for maximizing productivity under limited moisture availability (Reddy and Suresh, 2008). Sunflower crop productivity can be increased by more than 60% with limited irrigation at critical stages. In the western zone of Uttar Pradesh, growing of rice–mustard–mungbean for 1 year followed by rice–wheat–mungbean in the succeeding 2 years registered an 11% savings of water, clearly favoring diversification of the RW system. In Bihar, a rice–potato–sunflower cropping system recorded higher rice equivalent yield, net returns, benefit:cost ratio, land-use
efficiency, and production efficiency than a traditional rice—wheat—green manuring (S. aculeata) cropping system. At Jalander (Punjab) also, rice—potato—sunflower registered higher rice equivalent yield, economic efficiency, land-use efficiency, irrigation water productivity, and nutrient productivity than the RW system. Punjab and Haryana have become major rice- and wheat-producing states for the last three decades with the dominant RW cropping system. To reduce fatigue of the RW system, alternate crops such as oilseeds can be grown instead of wheat without hampering the profitability of the system. A modeling study using ORYZA2000 and Hybrid Corn models showed very high yield potential of winter corn after rice in all four South Asian countries (Bangladesh, India, Nepal, and Pakistan). Potential yield of winter corn in Punjab, India, exceeded 16 t ha\(^{-1}\) and that of summer corn exceeded 12 t ha\(^{-1}\) (Timsina et al., 2011; Timsina et al., 2010). At least half a million hectares of rice in Punjab could be shifted to soybean, kharif corn, or pigeon pea in comparatively upland and less irrigated area (dry area). The area that is planted with wheat in the late season due to the late harvest of basmati rice could be shifted to sunflower or winter/spring corn. In Haryana, the basmati rice area is invariably planted to late-sown wheat. It is suggested that the basmati area be sown under sunflower or corn in place of wheat. In Uttar Pradesh, where the RW system is important, it is possible to shift the part of the rice area located in higher landscapes to corn, or soybean, or pigeon pea. However, soybean as a pulse crop is not preferred by people in the region because of the typical “bean flavor” produced by soybean due to the lipoxygenase enzyme. Moreover, soybean and pigeon pea are susceptible to standing water, a situation normally experienced during the rainy season at any stage of growth of these crops and their cultivation also leads to late sowing of wheat.

### 3.7. Weed Management

Labor and water shortages are likely to become major constraints to future rice production. DSR has the potential to reduce water and labor requirements to grow rice. The success of DSR, however, depends on successful weed management. An integrated strategy of weed management is needed for sustainable production of DSR (Chauhan, 2012; Chauhan and Johnson, 2010c). The development of rice cultivars with weed-smothering characters, optimizing seeding rate, crop geometry, use of residue, and N management are some important aspects in managing weeds in DSR (Chauhan, 2012; Chauhan and Johnson, 2010a, c, 2011a, b; Chauhan et al., 2011; Mahajan and Chauhan, 2011).

Weed pressure during the early crop growing season can be reduced by adopting the stale seedbed technique, in which the seedbed can be prepared at least 7–10 days in advance of seeding with moisture ensured either by
irrigation or rain to stimulate germination and emergence of weeds, which are then destroyed either by shallow cultivation or the use of non-selective herbicides such as paraquat or glyphosate. The use of herbicide may have the advantage of destroying weeds without disturbing the soil, thus reducing possibilities of bringing more seeds to the upper soil surface. In a study in India, the use of non-selective herbicide in a stale seedbed was more effective than mechanical weeding in DSR (Renu et al., 2000). This suggests that rice should be sown with minimum soil disturbance after destroying the emerged weeds. A reduction of 59% in the density of E. colona and 78% in fresh weed weight of Cyperus spp. were recorded after the stale seedbed technique in the Philippines (Moody, 1982). Weed species that require light to germinate and have low initial dormancy and are present in the top layers of soil are sensitive to the stale seedbed practice (Chauhan, 2012; Chauhan and Johnson, 2008a, c, d).

The use of weed-competitive crop cultivars can also help to suppress weeds in the RW system. A quick-growing and early canopy cover enables a cultivar to compete better against weeds. Research studies have shown that traditional tall cultivars, such as NERICA rice, exert an effective smothering effect on weeds (Prasad, 2011). Further, it has been observed that early-maturing cultivars and hybrids of rice also have a smothering effect on weeds due to vigor and they have a tendency of early canopy cover (Mahajan et al., 2011b). Compared with shoot traits, little research has been done on the role of root competition for nutrients and water in rice—weed interactions (Chauhan, 2012; Chauhan and Johnson, 2010b). There is a need to further explore the subject of weed-competitive cultivars taking into account both aboveground and belowground plant traits.

The impact of weed on rice can be reduced by optimizing crop-plant arrangement; however, this approach should be considered as an aid in the context of integrated weed management programs, rather than a stand-alone control strategy (Chauhan, 2012). Mahajan and Chauhan (2011) observed that a paired-row planting (15–30-15 cm row-to-row spacing) pattern in dry DSR had a great influence on weeds compared with a normal row planting system (23-cm row-to-row spacing). Paired-row planting greatly facilitates weed suppression by maintaining a dominant position over weeds through modification in canopy structure. In other dry DSR studies, reduced crop row spacing increased the crop's ability to compete with weeds for light (Chauhan, 2012; Chauhan and Johnson, 2011b). Chauhan and Johnson (2011b) reported that the critical periods (days) for weed control were fewer for a dry DSR crop in 15-cm rows than in 30-cm rows (Table 3). In another study, *E. colona* and *E. crus-galli* emerging up to 60 days after rice emergence in 20-cm rows produced less shoot biomass and seeds than when they were grown in 30-cm rows (Fig. 2; Chauhan and Johnson, 2010a).
Table 3  The effect of row spacing on the critical periods for weed control to obtain 80%, 90%, 95%, and 98% of maximum yield in a weed-free plot, during the wet season

<table>
<thead>
<tr>
<th>Row spacing</th>
<th>Critical periods (days) to obtain different percent of maximum yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>15 cm</td>
<td>30–37</td>
</tr>
<tr>
<td>30 cm</td>
<td>24–42</td>
</tr>
</tbody>
</table>

(Chauhan and Johnson, 2011b)

Figure 2  Effect of narrow row spacing (20-cm) over wide row spacing (30-cm) on the reduction (%) of shoot biomass and seed production of *Echinochloa colona* and *E. crus-galli* when weeds emerged at different times after rice emergence. (Chauhan and Johnson, 2010a)

Tillage systems influence vertical weed seed distribution in the soil profile, and this differential distribution could affect weed seedling emergence (Chauhan, 2012; Chauhan et al., 2006a, b, c; Chauhan and Johnson, 2009b). A study in dry DSR in the Philippines showed greater seedling
emergence of *Digitaria ciliaris*, *E. colona*, *E. prostrata*, *Eleusine indica*, and *Portulaca oleracea* in zero-till plots than in conventional-tillage plots (Table 4; Chauhan and Johnson, 2009b). The greater emergence in zero-till plots was due to the small seed size of these weed species and the light requirement for germination. Despite these results, zero-till systems may help in reducing the weed seed bank if weeds are controlled effectively from the surface layer in the crop because soil is not disturbed and weed seeds are not brought to the soil surface (Chauhan, 2012). The large weed seed bank on the soil surface can be buried with a deep tillage operation after growing a few crops under a zero-till system. Seedling emergence of some weeds in zero-till fields can be reduced further by using residue as mulch. In recent studies, Chauhan and Johnson (2008b, c, d, 2009a, c, d) observed that, compared with no residue, rice residue amounts at 1–6 t ha$^{-1}$ reduced seedling emergence of different weed species (Fig. 3).

Dry DSR warrants an intensive use of herbicides. Sequential application of pendimethalin (1 kg a.i. ha$^{-1}$) as pre-emergence followed by post-emergence application of bispyribac-sodium (25 g a.i. ha$^{-1}$) proved effective for weed control in Punjab, India (Mahajan and Timsina, 2010). However, the continuous use of ALS-inhibitor herbicides (e.g., bispyribac-sodium) may increase the problem of herbicide resistance against weeds in DSR in the near future. Therefore, appropriate and economical weed management technologies are required for the sustainable cultivation of DSR, which may include the stale seedbed technique, proper land preparation, preventive measures (such as using clean seeds), zero-till systems, the use of competitive cultivars, optimum seeding rate, paired-row planting, water and nutrient management, mulching, rotation of crop establishment methods, and the use of suitable chemicals at the right time.

### Table 4

Seedling emergence pattern of different weed species in conventional tillage and zero-till systems (Chauhan and Johnson, 2009b). A three-parameter sigmoid model was fitted to the seedling emergence data. $E_{\text{max}}$ is the maximum seedling emergence (%), $T_{50}$ is the time to reach 50% of maximum seedling emergence (d) and $E_{\text{rate}}$ indicates the slope around $T_{50}$.

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Conventional tillage</th>
<th>Zero-till</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{\text{max}}$</td>
<td>$E_{\text{rate}}$</td>
</tr>
<tr>
<td><em>Eclipta prostrata</em></td>
<td>1.8</td>
<td>4.8</td>
</tr>
<tr>
<td><em>Portulaca oleracea</em></td>
<td>4.6</td>
<td>6.6</td>
</tr>
<tr>
<td><em>Digitaria ciliaris</em></td>
<td>2.4</td>
<td>3.7</td>
</tr>
<tr>
<td><em>Echinochloa colona</em></td>
<td>3.6</td>
<td>5.7</td>
</tr>
<tr>
<td><em>Eleusine indica</em></td>
<td>2.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>
The development of herbicide-resistant rice would enable early-season weed control, could help in promoting DSR systems (with or without tillage), and would reduce flooding of fields to control weeds (Olofsdotter et al., 2000). To date, most research has been conducted with imidazolinone-resistant rice (non-transgenic). Rice cultivars resistant to this chemical have been released for the first time in Asia (in Malaysia). The post-emergence application of herbicides in herbicide-resistant rice will allow growers to adjust doses according to the amount of weed infestation. The availability of herbicide-resistant rice will also facilitate wider adoption of conservation agriculture in the RW system as has been observed for soybean and cotton in the U.S. (Fawcett and Towery, 2003).

In the IGP, one of the reasons for the slowdown in the growth of wheat productivity during the 1990s was the widespread development of herbicide resistance in *P. minor*. The introduction of herbicides with different chemistry (clodinafop, fenoxaprop, and sulfosulfuron) in place of substituted-urea herbicides in 1997—98 together with no–till cultivation of wheat regained the lost confidence of wheat growers and wheat yields showed a sign of increase in 1999—2000 (Malik et al., 2002). The planting date of wheat determines the degree of competition with weeds, depending on their emergence periodicity. Weed emergence is governed by soil temperature and available moisture. *P. minor* germination is retarded by ambient maximum temperature of $\geq 30^\circ$C (Singh and Dhawan, 1976). *P. minor* emergence is greater at lower temperature (15—20 $^\circ$C), most prevalent in the winter months of November and December in northern India. Late-sown wheat in December suffers from severe competition from *P. minor* compared with
early planting (October to November); however, the sowing date depends on
the availability of fields after the harvest of the previous crop (rice and cotton).
The study of Mahajan and Brar (2001) revealed that a crop sown on 25 October
caused a 27% reduction in dry matter accumulation by *P. minor* and 22% higher
grain yield than a crop sown on 10 November. Therefore, early planting of
wheat in late October or early November offers a competitive advantage to
wheat against *P. minor*, giving it a substantial head start (2–4 weeks). The
combination of the adoption of early sowing and new herbicides has been
the key ingredient in the effective management of herbicide-resistant *P.
minor* in the IGP.

Wheat varieties with early canopy cover and greater dry matter accumula-
tion can shade grass weeds. In general, taller varieties compete more vigorously
with grass weeds. Varieties WH-147 and HD-2285 were found to be more
competitive with *Avena fatua* than HD-2009, WH-291, and S-308; the latter
varieties had more tillers, but that advantage did not translate into higher grain
yield (Balyan et al., 1991). Greater competition by PBW-343 than by PDW-233 was due to more tillers and thus a greater suppression effect on weeds
(Mahajan et al., 2004). Under timely-sown wheat, PBW-343 and WH-542
were equally competitive with *P. minor* (Chahal et al., 2003; Kaur et al.,
2003; Mahajan et al., 2002); PBW-343 also maintained its competitiveness
over *P. minor* in delayed plantings compared with other varieties (Kaur et al.,
2003). Growth of *P. minor* can also be curtailed by increasing the seeding
rate of wheat. Within limits, yield tends to increase at higher seeding rates,
which may be due to less dry matter production of weeds in a densely
planted crop (Walia and Brar, 2007). To improve the competitive ability of
wheat for applied fertilizers, particularly N, placement should be close to the
seed or crop plant so that a maximum quantity of applied fertilizers can be at
the disposal of the crop plant and be a minimum for weeds. Walia and Kuar
(2004) revealed that grain yield improved significantly in the crop receiving
a half dose of N with the side placement method and the remaining half
with broadcasting, which may be due to a significant reduction in dry matter
production by weeds because of more availability of nutrients to crop plants
than to weeds.

Straw management is a major factor in weed management in wheat grown
after rice. Many farmers burn straw to reduce thatch and also to burn weed
seeds, notably those of *P. minor* dispersed on the soil surface after the puddling
process followed in rice. However, because of environmental pollution, straw
burning is being banned in many states. Straw of the previous crop has a signif-
icant effect on weeds emerging in wheat. The density of *P. minor* was 1.2 and
1.4 times greater in plots where 6 and 12 t ha$^{-1}$ rice straw, respectively, was
burned compared with its removal (Singh, 1996). In the isoproturon-treated
plots, weed density was 1.9 and 2.8 times greater with a 6 and 12 t ha$^{-1}$
straw burning treatment over straw removal treatment, respectively. This
was due to the adsorption of isoproturon to ash contents.
Efforts to use rice straw in generating energy and for composting are being investigated. The turbo seeder (drill) has been found effective because it places straw in front of the tines and places it in between rows. Straw mulch placed between two wheat rows suppresses the emergence of weeds and also adds organic matter to the soil. Weeds already emerged at planting time in zero-till fields need to be controlled by non-selective herbicides (paraquat or glyphosate). The early-emerged weeds might affect the efficacy of herbicides due to their advanced stage at spraying. Another drill, a rotovator, can also be useful where straw is less and weeds have emerged because it can uproot the emerged weeds, incorporate surface straw/stubble, and do seeding in a single pass, thus reducing the cost of non-selective herbicides before wheat planting. However, rotovators are not suitable on heavy soils, or where there is low soil moisture or high amounts of crop residues. Rotovators also create a hard pan below the plow layer, leading to water stagnation, resulting in yellowing of wheat after irrigation. In the RW cropping system in the IGP, there is a need to develop ecologically based weed management strategies, and the use of these strategies will help reduce reliance on herbicides.

As mentioned earlier, crop rotation may prevent one particular weed species from becoming unmanageable because of different management requirements. Diversification of the area under a rice—wheat cropping system not only brings changes in the weed spectrum, but also makes soil conditions unfavorable for $P. minor$ emergence and growth. In the IGP region, fewer resistance cases in $P. minor$ were found where growers included sugarcane, sunflower, and vegetables in rotation than in a rice—wheat cropping system (Malik and Singh, 1995). When replacing wheat with other crops such as berseem clover, potato, sunflower, Indian mustard, and oilseed rape for 2–3 years in a rice—wheat cropping system, the population of $P. minor$ decreased significantly (Brar, 2002). Some crops such as Indian mustard, barley, and fodders can suppress weed growth significantly through their ability to grow faster. However, the adoption of a crop rotation will depend on the market price of the crop.

The use of herbicides is both efficient and economical and therefore the first choice of farmers. Metsulfuron has been found quite effective against Rumex spp. and it also provides good control of all broadleaf weeds, which cannot be controlled by 2,4-D. Herbicides with new chemistry such as pinoxaden, metsulfuron, and sulfosulfuron + metsulfuron have been recommended for the control of $P. minor$.

### 3.8. Climate Change

Water management in rice holds the key for potential trade-off between rice production and CH$_4$ mitigation options. Irrigated rice is the largest source of CH$_4$ but it also offers the most options for mitigating these
emissions. Optimizing irrigation scheduling in the field by introducing practices such as additional midseason drainage accounted for 7–80% of CH$_4$ emissions (Wassmann et al., 2000). Continuous flooding emitted more CH$_4$ than alternate flooding and drying (Mishra et al., 1997). A single midseason drainage reduced seasonal CH$_4$ emissions from rice fields but increased emissions of N$_2$O (Bronson et al., 1997).

High-yielding plants use assimilates more efficiently and spare less carbon for microbial CH$_4$ production. The development of rice cultivars that can maintain spikelet number and continue grain filling under higher temperatures with comparatively less wasteful maintenance respiration losses would not only sustain rice production but also reduce greenhouse gas emissions from rice fields. The development of cultivars with higher net assimilation rates and increased sink size (leading to increased net removal of atmospheric CO$_2$), improved N-use efficiency (reduced fossil fuel use to produce inorganic fertilizers) would lead to more stable yields under rising atmospheric CO$_2$ levels (Krishnan et al., 2007). To achieve this, research needs to identify the genetic controls and physiological processes involved in rice adaptation to higher temperature. Thrust is needed to develop early-maturing upland rice cultivars not requiring standing water conditions without a major sacrifice in yield and grain quality. Research on the development of high-temperature- and drought-tolerant high-yielding cultivars of both rice and wheat needs to begin in the target environments. The genetic resources, especially land races, from areas where past climates mimicked the projected future climates for agriculturally prime areas should be used in a breeding program to develop desired cultivars. A combination of conventional and non-conventional biotechnology tools will be required to achieve these goals.

On several occasions in the last decade, South Asia witnessed adverse effects of climatic variations in terms of terminal heat stress on wheat productivity. For example, despite favorable weather conditions during the winter of 2009–10, an abrupt rise in night temperature during the grain-filling stage in wheat adversely affected wheat productivity in the IGP and other northern states of India (Gupta et al., 2010a). Surveys indicated that terminal heat stress in the granary of Punjab in 2009–10 led to an average yield penalty of 5.8% compared with the previous year. However, yield losses were as high as 20% in a few districts of Punjab and other transects of IGP. The magnitude of losses varied depending on planting time, varieties, and other management practices.

In spite of better understanding and scientific knowledge of climate change and its implications, there is a lack of functional partnership between scientists, the private sector, policy planners, and farmers in order to move beyond rhetoric to real actions. To adapt to effects of climate change, immediate solutions could be altered management practices involving a conservation agriculture approach for buffering soil and canopy
temperatures. Farmers’ participatory field trials conducted across the IGP for developing, defining, and validating innovative solutions for overcoming terminal heat stress in wheat production (Jat et al., 2009c) included (i) advancing planting time using no-till, (ii) cultivar choices that adapt to/escape terminal heat, (iii) no-till with mulching using crop residues, (iv) irrigation management, and (v) balanced plant nutrition (using site-specific nutrient management). Results of farmers’ participatory field trials across the IGP revealed that no-till systems help in timely planting and terminal heat effects are less in no-till compared with conventional till even under late planting (from 21 Nov. till 20 Dec.). No-till drilling in residues keeps canopy temperature lower by 1–1.5 °C during the grain-filling stage (cooling due to transpiration) owing to sustained soil moisture availability to plants (Jat et al., 2009c). In the Eastern IGP, late harvest of rice and 7–10 days of additional window required for planting after conventional tillage leading to delayed planting of wheat, relatively shorter growing period, and terminal heat effects cause lower productivity than in the NW IGP. Significant tillage x genotype x cropping system interactions were also observed, suggesting a need to redefine recommendations for cultivar choices. Further, rescheduling of irrigation and plant nutrient applications had further positive effects in adapting wheat to terminal heat effects. Therefore, implementing these innovative management practices can be an immediate solution for adapting to the effects of climate change (Gupta et al., 2010a).

4. Conclusions

As one of the world’s largest agricultural production systems spread over 26 Mha in the IGP of South Asia and China, the RW cropping system meets the staple food requirements of more than one billion people. In the three decades between 1970 and the end of the twentieth century, the annual increase in rice production in the IGP was 4.1%, much greater than that achieved over the entire Indian rice belt (2.1%) over the same period. The annual rate of increase in wheat production during the same period was 4.4% in the IGP compared with 3.4% for the entire country. This increase in wheat and rice production in the IGP resulted from the introduction of input-responsive high-yielding crop varieties along with matching production and protection technologies, infrastructure development, and a protective minimum support price policy (assured purchase by the government). As long as the government supports a guaranteed purchase of wheat and rice at guaranteed prices, the economic well-being of Indian farmers in the IGP will remain dependent on the RW cropping system. To ensure food security to meet any eventuality of low production,
the Indian government maintains a buffer stock of 54 M tons of food grain. With recent legislation in the form of the National Food Security Bill, the government of India aimed to provide access to food for all at an affordable price and a buffer stock of 62 M tons will have to be maintained in the country.

With increasing pressure on natural resources, particularly land and water, decreasing labor availability, changing economic and social obligations, impact on environment of the current farming practices, increasing mechanization, etc., the RW system is under pressure to fulfill the increasing food needs of the rising population of more than nine billion people forecast by 2050. There is little scope for further expansion of area under RW, an increase in cropping intensity, and reclamation of degraded soils. The productivity gains of the past have, in fact, slowed down and there is an urgent need for a technological breakthrough to halt this downward trend and sustain productivity in the region. Crop management practices are changing fast. The region has experienced increasing farm mechanization over the last 20 years. Seedbed preparation and harvesting in particular are now commonly undertaken with farm machinery.

This article has identified several key issues and opportunities relevant to current production and future sustainability of RW that warrant further research efforts. Currently, the RW system faces a number of problems that are system-specific and even region-specific. Attempts to import technologies generated elsewhere and for other crops or systems have not found favor. Since conventional breeding is not delivering the expected gains in productivity, there is an urgent need to develop inbred varieties or hybrids that suit conservation agriculture, are more competitive against weeds, and have improved disease and pest resistance. Efforts are needed to improve nutrient-use efficiency and total factor productivity by maintaining or improving soil health, making crop residue management more efficient, and improving water-use efficiency. With the rising cost and non-availability of labor, mechanization will become even more important in the future.

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