Conservation Agriculture in South Asia

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1 Introduction

South Asia (SA) is the southern region of Asia, defined in both geographical and ethnocultural terms. The region consists of Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka and the Maldives. It is home to 1.7 billion people and has achieved high economic growth in the past six decades but still houses around 42% of the world's poorest population, 21% of the malnourished and 41% of underweight children globally (Akhtar, 2016). The combined population of Pakistan, India, Nepal and Bangladesh is

http://dx.doi.org/10.19103/AS.2021.0088.12

expected to reach 2.4 billion by 2050, demanding an almost 50% increase in food production (https://www.eastasiaforum.org/2013/04/06/demographic-dividends-in-south-asia-a-window-of-opportunity/). The food security challenge is further exacerbated by climate-related natural disasters that have already cost around US$2.97 trillion, affecting more than 4.03 billion people between 2000 and 2019 (UNDRR report, 2020, https://www.undrr.org/publication/undrr-annual-report-2020). SA agriculture therefore faces a trio of challenges: to increase production to meet the food demands of a growing human population with a lower environmental footprint; restore and preserve natural resources; and mitigate or adapt to climatic change (Jat et al., 2020a). At the same time, per capita availability of agricultural land and water is declining significantly.

The intensive agriculture practices of the 'Green Revolution' were successful in achieving production goals in the past but simultaneously led to degradation of natural resources, reduced total factor productivity, depletion of water resources and endangered future agricultural production (Kumar et al., 2018). Tillage-based practices have deteriorated soil health by removing crop residues and depleting soil organic matter, degrading the physical structure of the soil, enhancing soil erosion, promoting excessive use of mineral fertilizers and pesticides, reducing water infiltration, using inputs (water, energy, fertilizer and labour) inefficiently and making agriculture a significant source of greenhouse gas emissions and global warming (Parihar et al., 2018a). Furthermore, in Conventional Agriculture (CA), the open burning of crop residues causes atmospheric pollution through the emission of greenhouse gases (GHG), toxic smoke, soot and loss of valuable plant nutrients, which along with inadequate crop rotation and diversity have worsened the agricultural development situation in SA (Yadvinder-Singh and Sidhu, 2014; NAAS, 2017). Intensive and frequent use of tillage with heavy machinery destroys soil structure, compacts the soil, enhances the release of sequestered soil organic carbon (SOC) and releases GHG into the environment from the combustion of fossil fuel. Large yield gaps exist, particularly 'management yield gaps' ranging from 14% to 47%, 18% to 70% and 36% to 77% in wheat, rice and maize respectively, the region's three staple food crops (Jat et al., 2011).

To overcome the current multi-faceted problems of SA's agriculture, there is an urgent need for new science-based sustainable management approaches that are resource-efficient, more productive and environmental friendly. In the past two decades, CA has emerged as an alternative to inefficient tillage-based conventional agriculture across the region. CA is an ecosystem approach to regenerative sustainable agriculture and land management that helps manage agroecosystems in terms of improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment. It is based on the context-specific application of three interlinked principles – continuous minimal soil disturbance, permanent soil mulch (crop biomass and cover crops) and diversification of the cropping system, along with other complementary agricultural production and land management practices (Kassam et al., 2019). Sustainability is one of the major concerns facing the region's agriculture, and CA constitutes a comprehensive approach for moving in that direction. In the past decade, CA-based resource conservation technologies (RCTs) have shown enhanced soil health, better input use efficiency, profitability while promoting conjunctive use of organics (avoiding residue burning), reduced environmental pollution and timely planting in the South Asia region (Ladha et al., 2015).

2 History and status of Conservation Agriculture in South Asia

The history of CA in SA is inextricably linked with wheat production constraints in the rice-wheat system, a dominant cropping system in the Indo-Gangetic Plains (IGP) (Ladha et al., 2003b). Byerlee et al. (1984) reported various problems with wheat production, including late planting, poor plant stand, weed problems, reduced seed replacement rate and poor management (fertilizer and water) in Pakistan Punjab. Randhawa et al. (1981) reported late sowing of wheat as one of the major constraints with a yield decline of about 1% per day after the optimal date. Identifying late planting of wheat as the major problem due to late rice harvesting and prolonged intensive tillage practices for land preparation to sow wheat, zero till (ZT) was recommended as a potential solution. However, ZT was attempted in the IGP in the late 1970s but the technology missed the mark for several reasons. The ZT technology was reintroduced in the early 1980s in Pakistan by using a seed drill imported from New Zealand for the first time in Pakistan and India, but it did not perform well in the first season. In 1996, when the ZT practice was again attempted with local versions of ZT drills from India and Pakistan, it performed better than conventional agriculture. Real-time demonstrations and evaluations of the technology in farmers' fields in a cost-effective manner aided its faster adoption. From 2002 onwards, the rice-wheat consortium (RWC) of the Consultative Group on International Agricultural Research (CGIAR), via its collaborators including the United States Agency for International Development (USAID), introduced and promoted second-generation ZT seeders. Today second-generation CA planters are available, which can be operated with four- or two-wheel tractors and are being adopted at different scales in different countries based on agroecology and socioeconomic conditions. The initiation and spread of CA technology vary among the different SA countries and therefore documentation of skill, knowledge and success stories is an important tool for mutual learning and progress. Historical milestones for CA in South Asia are given in Table 1. The development of a common platform for CA in South Asia can facilitate networking and its further adoption and spread.

2.1 Rice-Wheat Consortium (RWC): a stepping stone for Conservation Agriculture in South Asia

The RWC was formed in 1994 as an ecoregional programme (EP) of the CGIAR with strong support from national partners in India, Pakistan, Bangladesh and Nepal (Table 1). As an EP, the consortium has a special kind of research network to address natural resource management (NRM) issues in a sustainable manner and problems related to agricultural production and within a geographically defined area. The success of the RWC can be attributed to initiatives by the National Agricultural Research System (NARS), CGIAR institutes and other partners, having defined roles and commitment to make it successful. Initially, RWC encouraged tillage and crop establishment methods with a focus on providing a more favourable window for wheat sowing. When the ZT technology was introduced, this was further extended to other RCTs. Although the RCTs were adopted by a large number of farmers in SA countries, they could not cope with the negative effect of traditional agricultural practices, such as loss of SOC associated with high intensity of inversion tillage, in-situ crop residue burning, soil degradation and associated problems, given the level of diversity and endowments prevailing among the farmers in SA.

In SA, the terms 'conservation agriculture' and 'resource conservation technologies' (RCTs) are used interchangeably as if their meanings are similar, but in reality, they differ greatly. RCTs refer to those practices that enhance resource or input-use efficiency (Hobbs et al., 2008). The RCTs in long-term experiments across SA apply minimum soil disturbance and crop residue retention to the dry season crop only and continue with full tillage and puddling of soils for conventional rice transplanting. The limitation of these experiments is that the benefits of RCT/CA take 2 to 5 years of continuous practice for changes in soil properties (Salahin et al., 2021; Alam et al., 2018) and weed ecology (Hossain et al., 2021a,b) to become evident. Therefore, results from the long-term experiments and long-term practice of CA in farmers' fields are most influential in drawing conclusions about its benefits (Bell et al., 2019; Gathala et al., 2021). Overall, CA as a potential alternate land-use system reconciles economic viability, enhances social balance, restores soil health, improves environmental conservation and mitigates climate change and was propagated by the RWC to improve long-term smallholders' living conditions and to alleviate poverty. There are some challenges in large-scale adoption of CA in SA, such as changing farmers' mindsets, weed control, residue management, nitrogen management, availability of ZT planters, socio-economic issues, climate change, irrigation, policy interventions and non-incentives for residue retention/carbon credit. The history and status of CA per country are presented in the following sections.

2.2 India

In India, various state agricultural universities (SAUs) trialled ZT in the 1970s, but their efforts failed due to technical problems including insufficient planting equipment and a lack of solutions to manage weed infestation. In the 1990s, CIMMYT introduced the inverted-T openers in India, which were originally developed in New Zealand by Aitchison industry. In 1991, the first prototype of the Indian ZT seed drill was developed at GB Pant University of Agriculture and Technology, Pantnagar. In 1992–93, a collaborative programme for further development and commercialization of ZT was initiated, involving small-scale industries in the Punjab state of India. Following the significant investment of resources and several rounds of design modifications, the first ZT seed drill was made available for field-testing within 12 months. From 1995, RWC, in collaboration with the National Agricultural Research and Extension System (NARES), provided support for farmer participatory research to accelerate the pace of ZT technology adoption in the rice-wheat systems. The DFID-supported project acquired several ZT drills and donated them to the CCS Haryana Agricultural University for farmer participatory research, providing a much-needed push for this programme. In the late 1990s, Monsanto supported no-till research at the universities but soon reduced its activities when it perceived that the potential for glyphosate marketing was small. In 1997, with further refining of the machines based on feedback received from scientists and farmers, private manufacturers supplied over 150 improved ZT drills to SAUs and the Indian Council for Agricultural Research (ICAR) institutions located in different states. The combined efforts of NARES, private manufacturers, RWC and CGIAR institutes resulted in widespread adoption of ZT in rice-wheat systems during the 1990s in India. Haryana and Punjab were the leading adopters of the ZT technology as it ensured timely planting of wheat, reduced the cost of tillage and increased the wheat yield.

The ZT, along with other resource-efficient technologies such as laser land levelling, bed planting, leaf colour charts etc. which have the potential to save fuel, improve plot-level water productivity and nutrient use efficiency, are considered as RCTs. Currently, the RCTs are being trialled on an area of more than 20 million ha in India alone (VK Singh personal communication during RCTs Vaibhav summit 2020). The RCT practices will be referred to as being CA only when the RCTs are combined with the three interrelated CA principles. The distinction is important because some RCTs, while adoptable in the short term, maybe unsustainable in the longer term. For example, the use of ZT without

Table 1 Historical milestones in Conservation Agriculture in South Asia

Timeframe	Constraint/Problem/Events	Innovation/Technology	Reference
1980-1990	**Transformation from disciplinary to commodity to systems research based on farmer-defined problems and issues**		
1981-1985	• Diagnostic surveys identify wheat production problems - late planting, poor stand, weeds, old varieties and poor management by farmers		Randhawa et al. (1981), Byerlee et al. (1984), Beebe (1985)
1986-1990	• Intensive tillage after rice, main reason for late planting of wheat • Soil physical constraints due to puddling in rice - adverse impact on wheat yields • Diagnostic surveys highlight natural resource degradation (salinization, groundwater contamination), pest build-up and soil nutrient depletion in the rice-wheat cropping system	• Introduction of zero-till (ZT) drill in Pakistan from New Zealand in 1984-1985 by Peter Hobbs from CIMMYT • Successful research and demonstration of ZT drill in 1985-1988 in Pakistan • Shipment of four Aitcheson drills from New Zealand to India in 1988 by Peter Hobbs from CIMMYT. Establishment of Project Directorate for Cropping System Research (PDCSR) in 1989 in India	Byerlee et al. (1986), Khan et al. (1986), Gupta (1989), Flinn and Khokhar (1989), Khuhro (1989), Harrington and Hobbs (2009)
1990-2000	**Consortium to Ecoregional Approach**		
1990-1995	• Isoproturon herbicide resistant *Phalaris minor* weed problem reported and flagged in wheat by R K Malik in 1992-93 under ACIAR project • FAO 'Regional Expert Consultation on sustainability of rice-wheat production system in different agroecological settings in Asia' highlighted in analysing rice-wheat productivity trends and emphasized in rice-wheat research for agroecological zones in 1993 • RWC, along with NARES and CGIAR, identify six research themes to overcome current constraints of rice-wheat system: productivity and sustainability trends, improved crop establishment methods, sustaining soil fertilizer, water management, IPM, and enabling policies for sustainable resource management in 1994	• Descon (Lahore-based implement manufacturer) develops first prototype of local multicrop ZT seedmatic drill • First prototype of Indian ZT drill by GB Pant University of Agriculture and Technology in 1991 'Pantnagar Drill' • National Agro-Industries Punjab India develops own 'T-openers' in 1993 and initiates localized development of ZT drills • First low cost ZT drill prototype developed by NARC Islamabad Pakistan in 1993. • Formation of a Regional Steering Committee and Facilitation Unit (RSC) in 1994 through World Bank meeting of NARES, IRRI and CIMMYT leadership - leading towards RWC along with donor pledge for an Eco-regional programme in New Delhi • RWC for IGP first meeting held in IDRC office as a formal launch of RWC on 19-20 May 1994, attended by NARES, CGIAR and donor leaders	Aslam et al. (1991), Singh and Paroda (1993), Ahmad et al. (1994), Malik and Singh (1995), Malik et al. (1998, 2000), Mehla et al. (2000), Harrington and Hobbs (2009)

1995-2000	• RWC facilitation unit operational in 1995 with Inder Abrol as a permanent facilitator • *Phalaris minor* reported as a major problem in wheat crop in South Asia in 1995-96 under Australian project on *Phalaris minor* resistance operated by HAU, Hisar • Mechanization of small holder farms a major problem in Nepal and Bangladesh • RTCC meeting of 1994 and 1995 prioritizes RWC research agenda on nutrient management, water management, integrated pest management and tillage and crop establishment methods • Visit by RWC team to China in 1995 - introduction to surface seeding and Chinese two-wheel handheld tractor • Long-term soil fertility experiments (LTSFE) highlight decline in rice yields over time and stagnation in wheat yields in 1996, also decline in SOM in chemical fertilizer treatments • Decline in total factor productivity over time reported from long-term experiments in Nepal and India • Decline in ground water table reported from North-western IGP in the late 1990s • Project on herbicide resistance and integrated management in India and Australia implemented 1997-2002. Beginning of accelerated ZT tillage adoption	• ZT farmer participatory research initiation on large scale in rice-wheat system from 1995 onwards • Farmer participatory demonstration of ZT drills on large scale in Haryana through DFID project by CCS HAU and CIMMYT collaboration from 1997 onwards • ZT seeding of wheat helps to reduce *Phalaris minor* problem in wheat and to reduce production cost in upper IGP during 1995-2000. • Chinese two-wheel hand tractor with ZT attachment testing for wheat sowing initiated in Nepal and Bangladesh during 1995 onwards - DFID project • Parachute planting of rice seedlings introduced in Pakistan from 1995 onwards • Strip tillage system developed in Bangladesh in the late 1990s by RWC • ZT drills refined several times based upon farmer and scientist feedback by National Agro-industries, ASS foundry etc • Diversification through legumes introduced by ICRISAT in 1996 through ADB gran • Over 150 ZT drills supplied to NARES for farmers' participatory research and demonstrations in 1997 • Introduction of leaf colour charts (LCC) for nitrogen management by IRRI in the late 1990s • Initiation of two-wheel tractor for ZT wheat in Bangladesh and Nepal in 2000 • ZT wheat exceeds 10 000 ha in upper IGP, and custom hiring of machinery becomes popular in the region	Malik and Singh (1995), Abrol et al. (1996), Abrol et al. (2000), Meisner et al. (1998), Hobbs and Morris (1996), Adhikari et al. (1999), Vincet and Quirke (2002), Ladha et al. (2003a), Tripathi et al. (2006), Malik et al. (2002a), Malik (2005), Harrington and Hobbs (2009)

(*Continued*)

Table 1 (*Continued*)

Timeframe	Constraint/Problem/Events	Innovation/Technology	Reference
2000-2009	**Zero Tillage (ZT) to Resource Conserving Technologies (RCTs) to Conservation Agriculture (CA)**		
2000-2005	• Acceleration of Resource Conservation Technologies ICAR project implemented from 2001 to 2005. Expansion in the areas in EIGP • Identical problems of rice-wheat system identified in the region (Pakistan, India, Nepal and Bangladesh) • Emphasis put on crop-based research rather than cropping system-based research in rice-wheat system • Low water use efficiency depleting ground water table in upper IGP • RWC, along with NARES, initiates research on nutrient management, water management, IPM, nematodes, weeds etc. and develops Resource Conserving technologies (RCTs) • Cornell University project on soil health funded by USAID in RWC countries except for India • World Bank loan to India through NATP enhances the RCTs in IGP. • RWC awarded 'Excellence in Science Award' by CGIAR in 2000, enhancing its profile and credibility • King Baudouin Award to RWC by CGIAR in 2004 for a unique consortium for Government and International research institutions benefiting around 250 000 farm households	• Cropping systems approach with stronger farmer participatory research adopted for RCTs evaluation • Initiation of Resource Conserving Technologies (RCTs) through integrated systems research over six sites in SA, including improved tillage and crop establishment, new varieties in ZT system, site-specific nutrient management, improved irrigation method and diversification jointly by NARES, CIMMYT, IRRI, IWMI, ICRISAT and CIP under ADB funding • Agri-machinery manufacturer visit to Australia in 2002 through ACIAR • Residue management prototype development project with PAU and ACIAR - Happy seeder • Wider usage of IT and GIS for RCTs dissemination and its impact analysis	RWC (2000), Gupta et al. (2000a), Ahmad et al. (2001), Franke et al. (2001), Vincent and Quirke (2002), Malik et al. (2005), Thakur (2005), Laxmi et al. (2007), Franke et al. (2007), Seth et al., 2003

2005-2009	• Farmer-led and contributory research on CA helps to change the perspective of NRM research for development • Tillage project commissioned in India by the ICAR and the Laser and water management project in Pakistan • IRRI/RWC ADB funded project on scaling out RCTs initiated in 2005 • Throwback residue system of Happy Seeder modified to in-situ residue management by Turbo Seeder through RWC • Turbo seeder initiates the double zero till system in rice-wheat system • Shifting of CGIAR focus to challenge programmes • Shifting of RWC Facilitation unit from CIMMYT to IRRI • Integrated crop management using RCTs introduced in Eastern-IGP including unpuddled transplanting of rice/zero-till transplanting of rice, bed planting for rice and wheat • Amar Agro develops two-wheel 5 HP tractor as well as 20HP narrow wheel tractor for zero till • CA machinery pool system developed in the SA as a new model of custom hiring • Inclusion of social science research on RCTs and CA from 2005 onwards • Laser land levelling introduced in India by Joe Rickman from IRRI and locally manufactured by Bery Industries Karnal and promoted by PDFSR and SVBPUAT Modipuram	• By 2006-07, ZT area expands to around 3 M ha in SA through NARES and CG funded research • RCTs' scope expanded to laser land levelling, lining of canals, surface seeding wheat, bed planting, direct seeding of rice, LCC and intercropping from 2000 onwards • Happy seeder for residue management in rice-wheat system developed under PAU-ACIAR project and initiated conservation agriculture in SA in 2007 • Happy Seeder modified to Turbo seeder to suit local rice-wheat system by RWC and Dashmesh Industries India • Turbo seeder machine more compact, lightweight, with depth control wheel and ensured in-situ residue management with less air pollution/dust • Laser land levelling gains importance in India after success in Pakistan from 2007 onwards • Emphasis on stakeholder capacity development on CA, travelling seminars and cross-site visits • RWC and NARES publish packages of practices for DSR to ensure double no-till system in SA during 2006

(Continued)

Table 1 (*Continued*)

Timeframe	Constraint/Problem/Events	Innovation/Technology	Reference
2009-2020	**Conservation Agriculture to Climate Resilient Agriculture**		
2009-2015	• Fourth World Conference on Conservation Agriculture, 4-7 February 2009 in New Delhi • Bill and Melinda Gates Foundation Funding to address cereal systems constraints in South Asia • Changes in front and rear wheels of combines by RWC in collaboration with Sardar Hari Singh of Nabha. • Significant changes in combine harvesters to fit in CA systems • Dismantling of the Rice-Wheat Consortium • Statistical analytical tools for testing significance of adaptive and farmer participatory field trials • Gupta & Prasad from IASRI-ICAR publish first book on adaptive research trials' statistical analysis • Initiation of 'Advance Course on Conservation Agriculture' by CIMMYT 2010 • Shifting of CA focus from upper IGP to lower IGP • Abandonment of RWC to CSISA • ICAR launches CRP on conservation across different parts of India • ACIAR initiates CASI project in Lower IGP	• Adopted resolution on CA for sustainability • Need to start mission mode on CA • Initiation of Cereal System Initiative for South Asia (CSISA) Program by IRRI, CIMMYT, ILRI and IFPRI, along with NARES for four countries • Hub concept of public-private and international centres collaboration for CA • Redesign of the axles of the front and rear wheels of combines aligned at 134 cm spacing to reduce combine compaction in CA • Design change allows controlled traffic movement • Maize combining blade attached to wheat combines • HS Sidhu fits the straw spreader and a sensor for alerting the driver to any interruption in residue throws in the combine back • Dr VK Gupta and Dr R Prasad from IASRI visit farmer fields and develop methodology for statistical analysis of the data from farmers' fields for easy publishing of results • 149 researchers from nine countries train in eight courses • South Asia platform for CA finished • Research and demonstration of CA extended in different cropping systems and agro-ecologies by ICAR-CRP programme • CASI extends CA in new areas of acid soils and covers new cropping systems • CASI emphasizes on small-scale machinery	

2016-2021	• CSISA emphasizes working in lower IGP • Fourth International Agronomy Congress (IAC) November 2016 • TAAS, ACIAR, CIMMYT, NARS (India, Pakistan, Nepal, Bangladesh) meeting on CASI for Sustainable Agriculture (CASI). • Human health problems due to rice residue burning problem recognized • PAU designs new lucky seeder • Private sector supports wide scale adoption of CA through Corporate Social Responsibility (CSR) funds • CA support base extended among different stakeholders (CSR, NGOs, private sector, CGIAR, ICAR, etc) • World Bank funds new project to Punjab Government on saving water through CA and converts residues to electricity • IFDC initiates research work on improving NUE in CA-based systems • Indigrow-CIMMYT-Punjab Government initiates carbon trading through CA in Punjab	• CA extended outside the rice-wheat system • Large-scale adoption of small-scale CA machinery in Bangladesh, Nepal and eastern India • Fourth IAC emphasis on small farm mechanization and the need for a shift in research focus from crop oriented to farming system oriented; focus on innovation in CA • Advocated Neutral platform on CASI • Government provides new policies and funding to extend turbo Happy Seeder in rice-wheat system of Punjab and Haryana • Multi-crop planter in residue retained condition promoted in Punjab and Haryana • Ecosystem-based incentive system for farmers through CA initiated in Punjab, India

residue retention and without suitable rotations, under some circumstances, can be more harmful to agroecosystem productivity and resource quality than a continuation of conventional practices (Thind et al., 2019). The development, testing and refinement of resource-conserving practices are based on the innovative low-cost seed-cum-fertilizer drill (costing US$400–500), which can plant crops with minimal soil disturbance.

With the advancement of CA technology, second-generation no-till drills and seeders were developed, particularly in India, in general for seeding into anchored stubble and loose residue retained soil. During the past few years, a major emphasis has been put on developing CA-based machinery, keeping in mind the needs of small farmers. Sidhu et al. (2015) were successful in developing a no-till seeder, popularly known as 'Happy Seeder', which turned wheat or any other grain crop into heavy loose residue retained on the soil surface. Combine harvesters used in SA led to an accumulation of straw in the rear, which hindered the proper working of the Happy Seeder. An attachment called the Punjab Agriculture University (PAU) Super SMS (straw management system) was developed, which can chop and evenly spread the straw coming out of the rear of a combine harvester (Mahal et al., 2019). In recent times, amid the labour shortage due to the Coronavirus outbreak, PAU has developed a new direct seeding of rice (DSR) machine called the 'Lucky Seeder' to address the issue during the rice transplanting season. Rice is direct seeded with a tractor-operated Lucky seed drill (LSD), which also sprays herbicide simultaneously.

Currently, efforts have focused on expanding CA in rain-fed areas and outside IGP among smallholder farmers. ICAR has ambitiously launched the Consortia-Research Platform on CA (CRP on CA) to adapt and mainstream available best-bet CA technologies across India by covering dominant crops under diverse ecologies, i.e. from a rain-fed to an irrigated system. Recently, the International Fertilizer Development Centre (IFDC) has initiated research work on efficient nutrient management under CA-based cropping systems in different states of India in collaboration with NARES. It is estimated that CA is presently being practised by more than one million farmers in India in an area of around two million hectares (Gupta et al., 2021). Others have indicated a figure of 3.5 million hectares of CA in the IGP in India (Paroda, 2018). No official CA data are available as there is no CA policy to date.

2.3 Pakistan

CIMMYT introduced the inverted-T openers in Pakistan in the 1990s, which were originally developed in New Zealand by the Aitchison industry. Descon Private Limited developed the first ZT drill prototypes in 1990–1991 in Pakistan. During the same season, prototypes were introduced for field testing among farmer groups, but the programme of farmer testing was not entirely successful.

The drills were too heavy to be used with local small tractors, tines were easily broken and frequent blockages of loose straw were reported (Aslam et al., 1991). In 1993, the Farm Machinery Institute, National Agriculture Research Council, Islamabad developed a low-cost drill that was successful in different locations of Punjab and the Sindh province of Pakistan. M/s. Greenland Engineers Daska, a local machinery manufacturer, started fabrication of such drills on a commercial scale, which were subsequently modified according to requirements. At the same time, popular RCTs among the farmers were laser land levelling, ZT, raised-bed planting and crop residue management. RWC and NARES enhanced the promotion and adoption of RCTs among farmers, including soil and water testing, the establishment of a machinery pool for equipment rentals and a village seed bank for provision of certified seed to smallholders. To effectively introduce, validate and promote RCTs, close collaboration among various partners was the key. A win–win partnership was developed among farmers, agricultural implement manufacturers, researchers, extensionists, service providers and private seed and fertilizer companies.

A second key milestone for the adoption of RCTs was via the New Zealand Ministry of Foreign Affairs and Trade funded project 'NZOD/ADAF' launched in April 2000. The project was implemented in irrigated and rain-fed areas of Lahore, Okara and Chakwal districts of Pakistan in 2001–2002. Under this project, ZT wheat was adopted across an area of 442 ha, bed planting on 58 ha and laser land levelling on 183 ha. Human resource development remained an integral component of the project wherein about 2000 farmers/professionals were trained in different RCT interventions. Permanent raised bed (PRB) was a game-changing RCT that saved water and energy, provided timeliness of operations, enhanced yield and soil fertility, reduced soil erosion, facilitated mechanized farming, improved agriculture sustainability and thus improved food security. It was helpful in diversifying crops in the saline and waterlogged rice crop zones of Hafizabad, Sheikhupura and Gujranwala, where growing other non-aquatic crops was not possible due to standing monsoon rainwater, leading to rice being grown as a compulsion rather than choice.

In the changing climatic scenario, with predicted intense and short duration rains, PRB is an effective technology due to larger surface and groundwater storage capacity. Second-generation planters such as Happy Seeder were replicated from India via the Australian Council of Agricultural Research (ACIAR) and Cereal System Initiative for South Asia (CSISA) during 2009–2020. These efforts need to be replicated in other cropping systems including rain-fed, arid, semi-arid and mountainous regions within and outside IGP. The CA expansion in Pakistan is confined to rice-wheat cropping systems through ZT wheat and DSR using the Happy Seeder and covers around 1.3 million ha. The current data is compiled through contacts with manufacturers, provincial agriculture departments and federal Ministry of Food Security and Research. No data on

CA areas from the national bureau of statistics are available as there is no CA policy to date in Pakistan.

2.4 Bangladesh

Research and development on CA in Bangladesh have focused on smallholders (<0.5 ha farm size and small fields of about 1000 m^2) and the two-wheel tractor (12 to 16 hp) as the primary power source for operating seeders (Krupnik et al., 2013; Haque et al., 2018b). The two-wheel tractor-operated ZT seeder and strip-till technology were first introduced by RWC/CIMMYT-Bangladesh in wheat fields during the late 1990s (Hossain and Haque, 2015). Subsequently in 2002, the Wheat Research Centre (WRC) of Bangladesh Agricultural Research Institute (BARI) developed the toolbar-attached raised-bed planter, which was successfully evaluated for other cereal and pulse crops. In 2003–2004, the Food and Agriculture Organization (FAO) initiated CA-based tillage technology to intensify wheat-based cropping systems in Bangladesh. The WRC developed a two-wheel tractor-attached pull-type ZT drill. The FAO, RWC and CIMMYT played a key role in promoting CA technology in farmers' fields during the early 2000. From 2005 to 2007, IRRI-ADB put special emphasis on CA DSR and wheat in Northern Bangladesh. Initial CA work focused on the cool and dry (Rabi) season crops such as wheat, maize, lentil, mustard, chickpea and demonstrated in research plots substantial yield gains (e.g. Bell et al., 2018; Rashid et al., 2019; Vance et al., 2014a) and cost savings (e.g. Miah et al., 2019). From 2006 to 2009, ACIAR, in collaboration with NARS, emphasized improving the quality of the ZT drill and strip-till drills for better adoption by farmers. In 2006 only, the farm machinery division of BARI developed a rotary-type bed planter with a single seed box. While machinery for seeding crops into crop residues with minimum soil disturbance is well developed for four-wheel tractors, there has been limited development of such planters for two-wheel tractors (Johansen et al., 2012). But most cropping systems in Bangladesh involve one or two rice crops per year, and developing a system of CA that is suitable for wetland rice has been a major challenge (Bell et al., 2019). For wetland rice, direct seeding and non-puddled transplanting have been developed to establish rice with minimal soil disturbance and crop residue retention (Haque et al., 2016b; Gathala et al., 2021).

Machinery development for mechanized planting into standing crop residue has therefore been the focus of CA research and development in Bangladesh. Nevertheless, the two-wheel tractor planters can only reliably sow into 40–50% standing rice and wheat residue (Haque et al., 2018a). Considering the ease of bed formation, the WRC-BARI-Cornell University (2010–2014) Food for Progress project further improved the rotary type of bed planter with the introduction of an inclined plate seed metering system, separate seed and fertilizer box, split power transmission chain and set-up of the operator's seat for easy movement and greater adoption in the farmer's field. Adaptations of imported Chinese seeders are available in Bangladesh for mechanized strip planting (Krupnik et al., 2013), but most of this machinery is used for full tillage rather than minimum soil disturbance planting (Haque et al., 2018a). The VMP is a planter developed in Bangladesh for operation on the two-wheel tractor (Haque et al., 2016b, 2018a). It can sow the seed and place fertilizer in rows using strip planting and zero tillage modes and sow into 40 cm high cereal residues (equivalent to 5 t of cereal residue/ha). Following a decade of research and development to improve seed metering, seed delivery and cover, for a range of seed sizes, and with continuous or spaced seed placement, the VMP is now in a machinery commercialization phase with a private sector manufacturer.

The CSISA and ACIAR-SRFSI projects are further expanding these tillage technologies in the Southern and Central parts of Bangladesh. Moreover, leading NGOs such as RDRS, IDE, CARITAS and PROVA are also expanding CA-based technology in the farmer's field. Current adoption levels of CA are not available in the country, but in 2015–2016, an area of around 1500 ha was under CA (Kassam et al., 2019). However, CA literature in Bangladesh is still dominated by experiments reporting on a single crop established using minimum soil disturbance and residue retention in a field previously under conventional tillage. While the Government of Bangladesh has implemented a series of machinery subsidy schemes, no special consideration is given to CA planters. The scale out of CA is ready for investment in widespread demonstrations of the CA planters on farmers' fields with a diverse range of crops. Initial pilot testing of the market suggests that a mixture of individual farmers and small entrepreneurs operating planting businesses will be attracted to the purchase of planters such as the VMP, but targeted incentives to decrease the net purchase price will accelerate the scale out. Business models for the service providers appear to be highly profitable when >20 ha per year is planted, but for an individual operator, 8–9 ha ensures a breakeven position (Miah et al., 2019).

2.5 Nepal

The ZT was first introduced in the wheat crop of the Terai region of Nepal in the late 1990s through RWC in order to reduce yield losses due to late planting of wheat (Giri, 1998). Over time, other RCTs such as bed planting and laser land levelling, along with CA, were introduced in Nepal. The NARC, in close collaboration with CIMMYT, initiated ZT maize in central Terai and the western mid-hills of Gulmi and Palpa in 2010. Many studies of the rice-wheat and rice-maize system in Terai and maize-based system in the hills have been carried out by CIMMYT to evaluate the effectiveness of RCTs. Upland and lowland maize under CA-based practices were found to be superior to conventional practices. For successful adoption of DSR, many efforts have been made by NARC, CIMMYT's Cereal System Initiatives for South Asia (CSISA) and IRRI and local agriculture-based NGOs such as LIBIRD, Pokhara and FORWARD, Chitwan. The CSISA was first initiated in 2009 by IRRI and CIMMYT in the central Terai region, with a focus on the rice-wheat system to promote widespread adoption of RCTs to increase productivity with less water, labour and input costs, and efforts were further extended to Western Terai of Nepal. Through the 'Sustainable and Resilient Farming Systems Intensification' (SRFSI) project (2014–2020), CIMMYT conducted research and promoted CA-based Sustainable Intensification (CASI) and efficient water management practices to increase crop productivity and resilience in the Eastern Terai of Nepal.

To date, CA-based practices have been tested and verified at the farm level, but the rate of upscaling is very poor. A dozen of postgraduates have been granted scholarships by CIMMYT for MScs and PhDs in CA from Nepalese universities. The Agriculture and Forestry University in Nepal has run a course on CA in both graduate and post-graduate studies since 2011. The momentum has not been as expected in Nepal compared to other parts of the globe. However, of the total rice-growing area of 1 497 744 ha, wheat area of 703 992 ha and maize area of 956 447 ha, an estimated 800 ha are covered under DSR, 500 ha under ZT maize and 1000 ha under ZT wheat in Nepal. In the hills, legumes are planted as relay or intercropping with maize on an area of about 30% of the total maize growing area. Of the total fruit growing area of 120 028 ha, about 15% ha is under legumes mulching. Mulching has become common in vegetables, and ginger and turmeric are 100% mulched. Garlic in western Terai is commonly grown under a no-till field with anchored rice residue after rice harvesting. Almost all of the cardamom growing area of 1555 ha is under the agroforestry system. Similarly, of the total vegetables grown under tunnels, about 30% are mulched with polythene. Currently, the International Fertilizer Development Centre (IFDC) is evaluating efficient nutrient management technology under CA-based cropping systems in collaboration with CIMMYT through a USAID-funded project. The uptake of CA is limited in Nepal despite tremendous potential. The key constraints are the fixed mindset of farmers and extension for intensive tillage, lack of knowledge, expertise and inputs (especially equipment and machinery), inadequate financial resources and infrastructure and poor policy support (Karki and Shrestha, 2014). The current area of CA in Nepal is estimated at 1000 hectares.

2.6 Sri Lanka

Traditionally, shifting cultivation was the predominant practice in Sri Lanka but, due to population growth, farmers started to settle in one place and practiced subsistence agriculture. This form of cultivation was not for large-scale commercial use but for limited small-scale farming to meet family needs. Since farmers had to settle at a particular location, the land was continuously used for cultivation, where land degradation, particularly soil erosion, was unavoidable, thus productivity declined. The Department of Agriculture launched research studies in 'Conservation Agriculture' way back in the early 1980s with the intention of incorporating such practices into farmers' fields to form a stabilized rain-fed cultivation system. The CA research programme commenced activities in 1980, led by Ray Wijewardena at Maha-illuppallama in collaboration with a Nigerian institution (Weerakoon, 1983).

CA was tried elsewhere in the dry zone of Sri Lanka to address problems associated with rain-fed upland farming. In Sri Lanka, CA includes diversified components – a combination of agriculture with forestry through mixed cropping, integration of perennials, green manuring, biological N_2 fixation, use of live crop or crop residue mulching, integration of botanical pesticides, integrated pest management, integration of crops with livestock, supplementary mineral fertilizer and use of low-cost energy-conserving tools. During the subsequent two decades, many field experiments were conducted and most produced encouraging results.

CA is a very promising approach, and a wealth of research findings and information are available based on two decades of research in the 1980s and 1990s. However, it must be stated that, although the research information is available, farmers did not fully accept the technology, probably because the programme was research-biased with no extension arm to upscale the technology. Moreover, social problems have not been adequately addressed. The Department of Agriculture is presently the authority for the implementation of the Soil Conservation Act of Sri Lanka. The Natural Resources Management Centre (NRMC) is responsible for the implementation of the Soil Conservation Act. The NRMC is launching an annual soil conservation programme in collaboration with Provincial Departments of Agriculture on 1000–1200 ha of farmers' fields supported by technical and financial assistance. In this programme, mechanical soil conservation, along with biological and agronomic measures, are being promoted. Lessons learned during conservation farming research programmes need to be incorporated into the above programme, especially for the rain-fed uplands in the dry zone.

In 2019, the FAO's 'Save and Grow' and 'Climate-Smart Crop and Mechanization Systems Scaling Up' projects started to introduce CA again in collaboration with the Department of Agriculture. The approach will create opportunities for profit by way of using CA combined with sustainable mechanization services and high-quality inputs (seed varieties and selected fertilizers). The projects operate in the dry zone of Sri Lanka, targeting small- and medium-scale farmers, who cultivate lowland paddies under minor irrigation systems and maize-based crops in rain-fed conditions. The project promotes a switch from maize monoculture to maize produced in rotation with groundnut and a 'sandwich crop' between the two main crops.

To control weeds in the off-season and to get additional income, sun hemp and sesame are used as sandwich cover crops. Crop residues are maintained. This production system is being promoted in farmers' fields and in the climate-smart agriculture village that is run by researchers of the Department of Agriculture. As the main objective of the project was to provide the necessary guidance for agricultural mechanization, which is an essential component of CA, several activities were carried out as well. Mechanization is not common among farmers due to the high cost of agricultural machinery, lack of machinery availability and lack of knowledge of mechanization practices. The usual farmer practice is to use only tractors for land preparation and harvesting machineries to harvest. The remaining operations are done manually. Most of the time, female farmers are involved in operations such as collecting, threshing, drying and haulage operations. The FAO and the Department of Agriculture have worked together to develop a programme to rent agricultural machinery at affordable prices, and the construction of the building was done by the department at one of the most suitable locations in the dry zone. The necessary machinery was selected, procured and provided by the project. The technical contribution of the engineers and extension officers of the department was invaluable in terms of providing mechanized training and demonstrations. Under the machinery hub concept, machinery was introduced for paddy cultivation, maize, groundnut, finger millet and other supplementary food crops grown in the dry zone. A television programme was also aired to promote the practice among farmers. More information is available at: http://www.fao.org/in-action/save-grow-climate-smart/our-approach/en/. The area of CA is about 50 ha (Sandra Corsi and Priyadharshanee Herath, FAO, 21 June 2021).

2.7 Afghanistan

In war-torn Afghanistan, agriculture is the backbone of the country's GDP and source of livelihood for more than 74% of the population. The country has made significant progress in the agriculture sector during the past two decades, but its sustainability and food security are still challenged by multiple intermingled factors, including limited access to technology, lack of trained human resources and insufficient policy support. Farming conditions are more traditional, with more than 50% of agriculture production from dryland conditions, which could be attributed to a lack of resources, ageing scientific institutions and unskilled human resources in the agricultural production system, which is still very traditional.

During 2008–2009, ZT technology was first introduced in Afghanistan through International Fertilizer Development Centre under the USDA-funded project. The ZT trials were conducted in the Nangarhar province of Afghanistan in rice crops, along with different nutrient management options. The ZT technology performed better than traditional rice cultivation. The IFDC organized the first CA study tour of Afghanistan stakeholders at RWC and Punjab Agricultural University (PAU) and other sites in Haryana and Punjab in India during 2009. During 2011–2019, CIMMYT and ICARDA organized several in-country and out-country trainings on CA for different stakeholders and introduced the ZT drill and Happy Seeder. ZT and laser levelling technologies have been adopted on a small scale in the country.

2.8 Conservation Agriculture in rain-fed areas: an emerging avenue in South Asia

Rain-fed farming soil health and moisture conservation practices directly influence the extent of potential crop production (Singh et al., 2015b). Healthier soil is more resilient to climate extreme events such as excess rainfall or drought, high or low temperatures etc. The adoption of CA is an emerging dimension that improves the SOC stock in the soil by recycling crop residues into the soil system. The competitive need for biomass for fodder must be taken care of in rainfall-deficit conditions. CA systems improve yields in rain-fed conditions on alfisols, which are shallow, often with compacted subsoil horizon and susceptible to hard setting. Traditionally, the area under degraded alfisols of Southern India is a mono-cropped area with maize being cultivated during the rainy season, but with adoption of CA, there is the potential to produce a post-rainy legume crop (e.g. horse gram, *Macrotyloma uniflorum*).

To harness the advantages of CA systems in SA's semi-arid tropics, it is essential to retain crop residues on the surface as mulch, which during the early years of transformation to CA can be a major challenge in rain-fed regions of South Asia due to the competing demands of crop residues for livestock. The potential for CA exists in rain-fed cropping systems involving crops such as maize, pigeon pea, mung bean, castor, cotton and sunflower, where crop residues are not used as feed. Ensuring good seed germination and crop stand establishment are major challenges to be addressed by CA management. Being the only source of water, interactions between rainwater conservation and CA must be studied in an integrated manner. Sharif et al. (2017) reported that studies on CA conducted to date in dryland areas of Pakistan have been short term and CA has the potential to improve soil structural stability by enhancing organic matter content, providing equal yield and economic benefit by reducing input cost. There is great potential for CA in dryland areas of Afghanistan, Pakistan and India as the climate, soils and crop diversity are conducive to adoption of CA systems.

3 Crop productivity and income in Conservation Agriculture

Long-term studies in SA show that CA has the potential to improve sustainability, profitability and input use efficiency in both irrigated and rain-fed regions. A meta-analysis by Jat et al. (2020b) showed that CA has the potential for 11.1% yield enhancement in on-station trials compared to 4.6% in on-farm CT. In EIGP, the yield advantage of 19.4% has been reported from ZT compared to CT in wheat as reported in the survey conducted in Bihar (Keil et al., 2015). The results from a long-term experiment in upper IGP covering India and Pakistan showed higher system productivity in CA-based rice-wheat/maize-wheat-mungbean systems compared to CT-based rice-wheat system. This might be due to the legume effect (integration of mungbean crop into the cropping system) and better thermal regime with reduced terminal heat stress in wheat crop (Gupta et al., 2010), higher soil water availability (Gathala et al., 2013; Jat et al., 2018; Sharma et al., 2019a) and regulation of soil moisture retention and release, thus avoiding extreme moisture conditions such as waterlogging and soil dryness in the absence of rainfall (Parihar et al., 2019a) and improved soil health, including increased plant nutrient availability (Singh et al., 2016; Choudhary et al., 2018a,b). In addition, it was found that the quality of wheat grain was improved under ZT compared to CT. For example, wheat grain grown under ZT had a higher protein, grain hardness and chapatti (Indian bread) score from all four rotations (rice-wheat, sugarcane-wheat, pearl millet-wheat and cluster bean wheat) than CT (Coventry et al., 2011).

In Pakistan, the use of village seed-bank-supplied good-quality seed alone increased wheat yield by 297 kg ha^{-1}. Laser levelling adopted on an area over 2080 ha improved seed germination by 15–25% and reduced irrigation water use by 20–30% and labour for irrigation by 30%. The ZT wheat planting saved 60 L of diesel fuel per hectare and produced an additional grain yield of 141 kg ha^{-1}. Bed planting of wheat increased yield by 566 kg ha^{-1} and reduced irrigation water use by 33%. With the integration and adoption of these technologies in pilot villages, farmers earned an estimated additional income of US$3 million in 2005–2008.

A diverse range of CA research has been carried out in Bangladesh, and much of it was reported in two international conference proceedings (Vance et al., 2014b; Haque et al., 2017a). In addition, regional studies on CA in the Eastern Gangetic Plain have included sites in Bangladesh (Gathala et al., 2021). Based on over a decade of research, the best practices for CA in rice-based cropping systems have recently been assembled in a manual for operators, extension officers and researchers (Haque et al., 2018a). The manual addresses site selection including the important issues of pre-existing weeds and the height of crop stubble from the previous season, seed quality, types of planters including their merits and limitations, crop management guidelines, weed control, best practice for a range of crop species, as well as the overall benefits of adopting CA in Bangladesh. For dry season crops, there are generally significant and immediate increases in crop yield when switching to CA (Bell et al., 2018; Salahin et al., 2021). With rice, there may be no significant effects on yield for 2–5 years. However, even when there are no increases in crop yield, as in the case of non-puddled transplanted rice, profit increases are generally (Haque et al., 2016a) even on farmers' fields (Haque and Bell 2019) but not on sandy loam soils (Chaki et al., 2021). Mechanized non-puddled transplanting of rice has been reported to increase crop yield and profit (Hossen et al., 2018).

The larger yield response of winter crops (wheat and maize) to crop residue retention and ZT (wheat only) might be associated with the higher conserved soil moisture, improvement in physical properties of the soil, increased SOC and moisture-dependent plant nutrient accessibility (Laik et al., 2014; Gathala et al., 2017; Nandan et al., 2019). In the rice-maize-mungbean system in Bangladesh, Rashid et al. (2019) reported that maize yields were significantly higher under the permanent bed (PB) method than in the conventional till method, but no differences were observed in mungbean and rice yields. Haque et al. (2018b) in Bangladesh reported a yield increase of 28% for lentils, 19% for mustard and 6% for wheat by farmers who adopted CA planting. Profits increased by 47% for lentil, 55% for maize, 46% for mustard and 76% for wheat due to the adoption of CA. In studies that recorded improvements in soil health under CA management systems, significant increases in yield have been obtained.

On a cropping system basis, the highest yield enhancement was observed in CA-based maize-wheat systems (18.6%) (Jat et al., 2020b), followed by rice-wheat (5.1%) and rice-maize (3.6%). The CA systems provided higher profitability due to reduced labour cost, reduced input cost for land preparation and lower water requirements, and partly from increased yield in irrigated systems (Jat et al., 2014; Kumar et al., 2018; Devkota et al., 2019). Increased yields due to retention of crop residues in established CA systems are attributed to (a) conservation of soil moisture and nutrients; (b) improved soil water infiltration; (c) improved soil biological activities and nutrient cycling; (d) better weed control; (e) improved soil quality through increased soil organic matter content; and (f) regulation of soil temperature, thereby minimizing high-temperature effects during the wheat grain filling period.

4 Soil health in Conservation Agriculture

Soil organic carbon (SOC) is one of the most important indices of soil health and sustainability in agriculture. Soils of semi-arid and arid regions of SA are generally low in OC content. Carbon sequestration in soil is an important strategy to improve soil quality, mitigate climate change and improve soil quality associated with higher crop productivity in CA (Parihar et al., 2020). Potentially one-third of the C emitted in current fossil fuel use could be offset by implementing CA globally in the next decade. A significant build-up in SOC in 0–20 cm under CA (ZT+ residue) compared to the CT system was recorded by Paudel et al. (2014). In Nepal, ZT+ residue-retained plots sequestrated 0.91g kg^{-1} $year^{-1}$ SOC, which was 23% higher than CT after five cycles of rice-wheat system. Several other studies from SA also recorded significant increases in SOC contents in CA treatments over CT (Choudhary et al., 2018a,b; Bera et al., 2018; Sharma et al., 2019b; Bhattacharyya et al., 2013; Singh et al., 2016; Jat et al., 2014, 2019; Thind et al., 2019; Yadvinder-Singh et al., 2009, 2014). From long-term on-farm trials maintained since ACIAR project in 1997, it was found that soil health of ZT plots was superior to CT as studied by Singh et al. (2015a). Data show that the carbon stock in surface 0.4 m soil depth increased by 19.0%, 34.7% and 38.8% over CT in 15 years in sandy loam, loam and clay loam soil, respectively.

Ghimire et al. (2012) concluded that the R-W system would serve as a greater sink of SOC under the ZT system with plant residues retained than with the CT system without residues. Sharma et al. (2019b) reported the highest carbon management index (CMI) values under the CA-based rice-wheat system, which provided better options for C sequestration in soils than conventional rice-wheat systems. CA improves the physical properties of soil, such as structure, aggregate stability, infiltration rate and plant available water capacity, as well as biological quality. In medium-term CA-based experiments, Parihar et al. (2018a) recorded a 34% and 21% increase in SOC under CA in maize-based cropping systems compared to CT systems, respectively. Based on research in Bangladesh, Bell et al. (2019) reported that CA practices decreased soil bulk density and increased soil porosity. The release of polysaccharide compounds during the decomposition of crop residue acts as a cementing agent and has a crucial role in micro- and macro-aggregate formation (Six et al., 2002; Bhattacharyya et al., 2013).

CA-based agricultural practices significantly influence infiltration rate and soil water retention. The lower infiltration in conventional tilling as compared to ZT is due to a breakdown of aggregates and formation of surface seal by the impact of raindrops, increased compaction and reduction in pore volume of the surface soil. CA leads to the formation of stable soil aggregates and ultimately results in less soil erosion. The majority of the reports from SA showed a decrease in bulk density under CA over CT in different cropping systems and soil types (Jat et al., 2018b; Choudhary et al., 2018a,b, Parihar et al., 2020). Crop residue cover in CA buffers the soil temperature regime in the surface layer by lowering the maximum soil temperature (often between 2°C and 8°C) and increasing the minimum soil temperature (by 1–3°C) compared to CT (Singh et al., 2016). The decreased soil temperatures in residue mulched wheat plots at grain filling stage resulted in a positive effect on reducing canopy temperature (by 1–3°C) and ultimately decreased the adverse impact of terminal heat on the yield (Balwinder-Singh et al., 2011; Yadvinder-Singh et al., 2014).

In Sri Lanka, CA, crop residues and live mulch are used to control weeds and protect soils. Studies revealed that the application of sun hemp mulch at the rate of 1.5–3.5 t/ha can reduce soil loss to 1.8–3.5 mt ha^{-1} $year^{-1}$ (Weerakoon, 1983). Investigations into the effects of tree components on upland soil fertility in the dry zone revealed improvements in bulk density, organic matter content, exchangeable K, Ca and Mg, N and earthworm activities in soils in Sri Lanka. Suppression of grass weeds and dominance of broad-leaved species were also observed between Gliricidia rows. However, available P in soil was depleted with continuous cropping on the land (Handawala and Kendaragama, 1991). The inclusion of a grass component on the tree row has become necessary in order to improve alley cropping as a grass-tree alley system, which would be more beneficial than tree alley cropping (Dharmasena, 1996).

SOC improvements in CA systems can have a significant effect on plant nutrient availability, due to both changes in the quantity of nutrients available and their distribution in the soil profile. The continuous addition of large quantities of crop residues in CA is associated with the addition of plant nutrients in residues to the soil, resulting in increased storage and availability of macronutrients (Jat et al., 2013, 2019; Bera et al., 2018; Nandan et al., 2019) and micronutrients (Gupta et al., 2007; Nandan et al., 2018; Rashid et al., 2019). Soil microorganisms appear to be excellent indicators of soil health as they respond quickly to changes in the soil ecosystem. Jat et al. (2019) recorded 35% and 54% higher microbial biomass carbon and nitrogen in CA-based rice-wheat-mungbean system and 50% and 110% in the CA-maize-wheat-mungbean system, respectively, than in CT-rice-wheat from a 7-year-old field experiment. The CA approach improves soil health, decreases costs of production and increases crop profitability.

5 Water productivity under Conservation Agriculture

CA-based cropping systems require 30–71% less irrigation water and use 24–47% less energy compared to CT-rice-wheat (Kumar et al., 2018). The CA-based maize-wheat-mungbean system improved productivity by 16% and profitability by 50%, using 71% less irrigation water and 47% energy input compared to the conventional rice-wheat system/farmers' practice (Kumar et al., 2018). In a cotton-wheat system, Choudhary et al. (2016) reported that mean system water productivity and energy output were 131% and 21% higher with permanent broad bed (PBB)-mungbean, respectively, compared with CT. Surface retention of crop residues reduced evaporative loss and contributed to moisture conservation, thus requiring less irrigation water than in the CT system with no residues (Jat et al., 2016). Mustard (*Brassica juncea* L.) can be an economically alternative crop to wheat in both irrigated and rain-fed agroecologies in SA, while grown under the CA-based system.

Devkota et al. (2019) evaluated the performance of ZT wheat in the Western Terai region of Nepal. ZT wheat produced a similar or higher grain yield with lower total production cost by \$70 ha^{-1} and higher water productivity by 30% and net profit by US\$115 ha^{-1} as compared to CT in rain-fed or limited irrigation areas. From a study conducted in Pakistan, Nawaz et al. (2017) concluded that DSR followed by ZT wheat was the best RCT to sustain the productivity of the rice-wheat system and improve net profit and soil properties. In conclusion, CA-based systems generally enhance crop productivity, water productivity and profitability, while reducing irrigation water and energy requirements compared to CT systems. Therefore, CA should be out-scaled to improve soil and environmental quality in SA.

6 Climate change mitigation and adaptation in Conservation Agriculture

Projections state that almost half of the IGP in SA – the major food basket of the SA region – may become inappropriate for wheat production by 2050 due to heat stress as a result of higher temperatures associated with GHG emissions (Ortiz-Monasterio et al., 2010). CA is reported to reduce GHG emissions and promote C sequestration in soil and play an important role in contributing to mitigation and adaptation/resilience to climate change for food security (Nandan et al., 2019). In medium- and long-term CA-based experiments, the CA components had higher SOC sequestration potential and the sequestered SOC has greater stability against higher temperatures as evident from twice less Q_{10} value as compared to CT (Parihar et al., 2019b). According to Ashraf et al. (2015), improved production practices under CA improve SOC and N storage while reducing soil erosion and N leaching from the soil profile without significantly altering crop yields and has GHG mitigation potential as compared to CT. Parihar et al. (2018b) estimated annual N_2O emissions using gas chamber methods and concluded that GWP per year or per hectare, associated with nitrate-N emission, was less in an intensive CA-based system as compared to CT. Arshad et al. (2017) suggested that agronomic management such as ZT with residue retention will help alleviate the period of critically high heat during flowering in wheat, which can advance sowing dates while conserving soil moisture in SA.

Carbon sequestration under CA helps to mitigate GHG emissions and increase soil productivity and avoid further environmental damage from the unsustainable use of intensive tillage systems. CA helps reduce CO_2 emissions via energy savings through less fuel consumption and reduction of the mineralization of soil organic matter, leading to a markedly less negative effect on climate change. Improved soil nutrient availability in CA systems lowers external N and other fertilizer requirements, which means less potential for N_2O emissions and energy saving from the manufacture of fertilizers. CA systems also mitigate climate change by enhancing soil moisture conservation, thereby helping save electricity costs and reduction in GHG associated with energy production consumed in irrigation. A study by Ladha et al. (2015) showed that adoption of CA practices in rice can reduce total global warming potential (GWP) for rice by 23% annually. Diversifying rice with maize has the potential to reduce GWP by 38%. On a system basis, CA-based rice-wheat and maize-wheat systems have the potential to reduce GWP by 16–26% compared with the CT-RW system. A significant reduction in GWP in CA-based maize-wheat system suggests that in areas where diversification of rice-wheat system is feasible, there is great scope for mitigation of GHG emissions. Soil organic carbon (Alam et al., 2018) and total nitrogen (Alam et al., 2020) concentration (0–10 cm) increases of up to 65% were reported after 5 years of continuous CA relative to the current practice of intensive tillage and <20 % crop residue retention. According to Alam et al. (2020), a 26% increase in soil organic carbon stock, equivalent to 5.1 t ha^{-1} after 5 years, was achieved with CA practices. Continuous strip planting plus increased crop residue retention decreased life cycle greenhouse gas emissions by 35%, equivalent to a savings of 0.25 t emissions per metric tonne of rice production relative to current practices (Alam et al., 2019a,b). Another study from Northwest India shows that the CA-based rice-wheat system reduced CH_4 emissions and resulted in the lowest GWP (CO_2-eq ha^{-1} $year^{-1}$) compared with CT systems (Jat et al., 2020a).

7 Nutrient management in Conservation Agriculture

Nutrient management is an important aspect of CA for enhancing crop productivity and its adoption by farmers. The conventional nutrient recommendations are not necessarily a valid basis for fertilizer recommendations in CA. Nutrient management can become more complex with CA due to higher residue levels at the soil surface, which makes the surface broadcasting and band placement application of fertilizer less efficient. In addition, deciding the timing and amount of fertilizer application must include the nutrient release pattern from crop residue and the soil pool. Thus, nutrient management should focus on local site-specific conditions, not only to achieve the full benefit of available resources but also to overcome crop yield barriers. Site-specific nutrient management (SSNM) captures the spatial and temporal variability in soil fertility and provides an approach to 'feeding' crops with all the required nutrients based on crop needs and thus improving the crop yield. As the concept of CA is a relatively recent introduction in SA, only a few studies are available on nutrient management in different crops and cropping systems. In CA, organic mulch will improve the soil moisture regime and nutrient dynamics that in turn will influence nutrient response and economic profitability. Yadvinder-Singh et al. (2009) found that rice straw mulch containing 40 kg N ha^{-1} released only a small fraction of N during the life span of the wheat crop (~150 days). With such small amounts of N released from the residue, significant savings in fertilizer N in wheat are unlikely in the first 2 to 3 years. CA in most cases improves the availability of P and K in the surface soil layer due to reduced mixing of fertilizer and surface retention of crop residues. The reduced mixing of P and K fertilizers with the soil in CA is expected to lower P-fixation (Gupta et al., 2007).

In CA production systems, innovations are needed in no-till seeding equipment to allow separate seed and fertilizer band placement. Major technologies focused on the adoption of new diagnostic tools for nutrient management under CA include the use of a leaf colour chart, Green Seeker and Nutrient Expert® (NE®) Software tool (a fertilizer decision support tool based on SSNM principles) and use of fertigation through micro-irrigation. As applicable under the conventional system, NUE under CA could be improved through the '4Rs' nutrient stewardship (right rate, right source, right timing and right place) and precision nutrient management practices that are specific to field soil, climate and crop management. Improvements in soil organic matter content and nutrient availability will have a significant bearing on nutrient management under CA (Kakraliya et al., 2018; Parihar et al., 2016). Parihar et al. (2016) reported that a combination of ZT/PB and SSNM increased maize-wheat productivity by 23% and 41% compared with CT recommended fertilizers and farmer's practices, respectively. Nayak (2019) and Nayak et al. (2019) addressed the right placement issues under long-term CA and concluded that point placement of second urea split enhances the maize grain yield, energy output and profitability as compared to CT. The layering of CA-based management practices with precision nutrient prescriptions using SSNM-based decision support tools offers a new management paradigm for scaling up the CA-based system.

8 Weed management in Conservation Agriculture

Traditional intensive tillage practices eliminate early crop weed competition, whereas under CA, weed control with tillage is not possible. The adoption of the full CA package of practices (CA with all three principles) modifies the soil environment, while some favour weed control, while others exaggerate weed proliferation. In the no-till CA environment, about 60–90% of the weed seed lies within 5 cm of the soil profile, as seeds move through the cracks and by fauna (Bàrberi et al., 2001). The chances of higher weed seed germination during the initial years of CA adoption are greater. Gradually, the soil seed bank depletes due to less soil disturbance/inversion (deeper weed seed does not come to the surface), increased predation due to more accessibility, reduced viability due to greater fluctuating environment at surface soil layers, etc. (Nichols et al., 2015).

Several field experiments and modelling-based findings suggest, if carefully managed, the higher weed germination during the initial year of CA adoption provides an opportunity for long-term weed control. Preventing weed establishment is more crucial under CA than the conventional till (CT) system. The less disturbed CA system favours perennial weeds, whereas intensive tilling under CT favours the dominancy of annual broad-leaved weeds. Due to no tillage, the reproductive structures of perennial weeds are neither buried too deep to avoid emergence nor come to the surface for desiccation (Sharma and Singh, 2014). Along with tillage, the nature/type of crop rotation dictates the nature of weed communities. The residue retention under CA decreases or delays the weed seed germination by moderating daily soil temperatures (weed seed requires certain threshold temperatures for germination), allelopathic effects seem to encourage seed decay (residue maintains a moist environment) and by acting as a physical barrier (avoids light penetration and seedling emergence), but the timing, form and application methods of herbicides must be chosen wisely as surface-retained residue intercepts the applied herbicide to the tune of 15–80% (Chauhan et al., 2012). The granular form of pre-emergence herbicide may be more effective under CA systems.

The principle of crop rotation under CA was historically advised as a component of integrated weed management. Crop-specific weeds are effectively controlled by efficient crop rotation, as well as the rotation of an allopathic crop, a weed-resistant crop and smothering crop, which favours less weed germination. Although all three principles of CA favour reduced weed growth, the transitioning phase to CA during the initial 4 to 10 years is important, and perennial weeds should be effectively controlled using glyphosate or other non-selective herbicides. Therefore, a greater amount of herbicides might be needed during the initial years in CA. Strip planting and crop residue retention for 2–5 years continuously has been reported to decrease the size but increase the diversity of the weed seed bank, particularly the dominance of perennial species, under intensive rice-based crop rotations in Bangladesh (Hossain et al., 2021a,b). In recent years, several low-dose, high-potency, selective, post-emergence herbicides and their mixtures have become available in India and South Asia and can effectively manage weeds in crops like rice and wheat grown in sequence under CA. Herbicide use must be complemented by other measures such as fertilizer placement, planting dates, microbial weed control, implementing 4+ year rotation, etc. Weed control is more challenging when CA is adopted partially, where the benefits of synergism between the three principles are not achieved. In northwest India, reduced *Phalaris* infestation has been reported under zero-till-wheat. CA involves the implementation of many skilful techniques such as the use of appropriate machineries, herbicides, proper crop rotation, soil and residue management. No doubt CA has multiple advantages, but its adoption is still not widespread with the full package of practices.

9 Further upscaling of Conservation Agriculture in South Asia

The total cropland area under CA globally in 2015/16 was estimated to be about 180 M ha in more than 75 countries (Kassam et al., 2019). The area under CA cropland is expanding worldwide at an average rate of around 10.5 M ha year^{-1} since 2008–2009. In SA across India, Pakistan, Bangladesh and Nepal, in the R-W system in the IGP, the estimated adoption of ZT wheat was about 5 M ha area, which has increased since. The adoption of various CA systems has been reported to be over 4 M ha (Paroda, 2018; Kassam et al., 2019). The success of CA spread in SA is attributed to a multi-stakeholder approach and low-priced drills. The success of CA drills from within the region has created demand for CA in other countries and regions. According to Devkota et al. (2019), while the benefits are clear, coordinated efforts are required to overcome technology-scaling bottlenecks that have kept adoption rates of these technologies at a nascent state in SA. The double no-till CA system of rice and wheat has not yet become mainstream in South Asia. The main barriers to the adoption of CA practices could be due to competing uses for stover/straw as forage, particularly under rain-fed situations, the large-scale practice of open residue burning in the IGP, lack of suitable machinery for no-till seeding of rice, lack of skilled manpower and scarcity of trained service providers (SPs) with the right equipment. This is partly because policy environments are not favourable and poor understanding of the CA practices by farmers due to the prevailing tillage mindset. These challenges relate to development, standardization and adoption of farm machinery for seeding with minimum soil disturbance and developing crop harvesters with effective residue management systems. Bell et al. (2019) concluded that CA in Bangladesh is feasible and a profitable venture for smallholder farmers and that the local service provider business is profitable for ZT planting. However, suitable planters should be made available at an affordable price. Several manufacturers were reluctant to invest without evidence of demand. Low-quality machinery will hamper efforts to develop farmer confidence in CA.

The lack of subsidies and incentives in a context of high poverty in rural areas does not create a favourable environment for CA adoption. Farmer participatory on-farm research to evaluate/refine the technology in the initial years, followed by large-scale demonstration in subsequent years is needed. Due to the wide range of agroecological conditions ranging from arid, semi-arid to sub-humid zones in SA, it is important for the promotion and development of CA to continue to identify entry points for its adoption and spread. There is a need to think about the problems faced at the implementation level and devise a strategy involving all concerned stakeholders. The potential limitations for future wide-scale adoption of CA include the high initial cost of no-till seeders, inability of ZT seeders to handle large amounts of loose straw left on the surface after combined harvesting of the previous crop and a lack of scale-appropriate and locally adapted machinery for smallholders in some locations (Sapkota et al., 2015; Mishra et al., 2021). Promotion of farm mechanization for CA through custom hiring centres (CHCs), private entrepreneurs and farmers' organizations does benefit small and marginal farmers, and this strategy must be expanded. Many medium- and large-scale farmers who purchase CA machinery in turn also become service providers to smallholder farmers. These farmers have the opportunity to supplement their farm income with the purchase of CA machinery for use on their own farms as well as neighbouring fields. They should be encouraged and supported to acquire CA machinery, leading to a successful business model for large-scale adoption of CA by all types of farmers. Agencies like Krishi Vigyan Kendras (KVKs) in India and extension wings of universities need to increase their involvement in introducing farmers to the custom hiring adoption of CA systems.

Policy barriers that constrain the adoption of CA technologies include issues such as farmers' financial capacity, short timeframes for economical use of ZT seeders, a serious lack of farmer training opportunities and resources and poor enforcement of the crop residue burning ban. Success stories and technical discussions generated by the growing spread of CA technology, as told by farmers and others, could be garnered to make government department heads, policymakers, institutional leaders and others aware of the benefits and desirability of backing initiatives to help farmers adopt CA systems. Training and capacity development are the core areas for out-scaling of CA. Consideration of extension approaches such as the 'Lead Farmer Approach' should also be made as a way to mitigate extension shortages at the local level. Targeting key policymakers, advisors and engaging governments/decision makers' policy in events related to CA can also create public awareness and knowledge. There is also a need for more private sector investment and government funds to refine and develop farm equipment and machinery to promote CA and complementary precision agriculture practices.

10 Where to look for further information

Volumes 1 and 2 of this book have more information related to CA in SA. The main global website for more information is the FAO at: http://www.fao.org/conservation-agriculture. Information is also available at the websites of regional CA organizations and they are: http://www.act-africa.org/ for Africa; https://ecaf.org/ for Europe and http://www.caa-ap.org/ for Asia-Pacific. More information is available at the national level in several countries that have CA organizations. The CIMMYT website (https://www.cimmyt.org/tag/conservation-agriculture/) also has information about CA in SA and generally. Research papers on CA from SA countries can be found in international journals.

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