Somasundaram Jayaraman
Ram C. Dalal
Ashok K. Patra
Suresh K. Chaudhari *Editors*

Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security

Conservation Agriculture for Sustainable Agriculture

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Foreword

Humanity has witnessed many catastrophes and disasters in the past which occasionally threatened existence of human population. However, this Pandemic (COVID-19) is really testing the capability of the societies to survive in global crisis situation. Despite these difficulties, we need to feed 10 billion people by 2050, about an increase of 2 billion people in the next 30 years. However, it is equally important to increase food production while maintaining the sustainability of the environment. Therefore, *SOIL RESOURCE* has often looked for greater opportunities and possibilities not only for food production but also for curing diseases and infections (i.e. *'drug from dirt', e.g. Penicillin, Rifamycin*). Thus, Conservation Agriculture (CA) is a sustainable approach to manage agro-ecosystems in order to improve productivity, increase farm profitability and food security, and also enhance the resource base and environment. Worldwide, various benefits and prospects in adopting CA technologies in different climatic conditions have been reported.

CA technologies are promising, but it is in infancy stage in India. It is a system of raising crops without excessively disturbing the soil along with crop residue retention and diversified crop rotations. Retaining and managing adequate amount of crop residues on the soil surface under CA is the key to realize long-term benefits and to reverse the process of soil degradation (~121 m ha affected in India), carbon storage, and mitigation of climate change. Worldwide, CA has been successful in rainfed regions which have spread to ~180 m ha, whereas in India it has been mainly concentrated in the irrigated areas (~5 m ha) for sustaining productivity, natural resource base, and economic growth of farmers. Though CA has become an exciting option for farmers to manage the natural resources, less than 1% of farmers have adopted these technologies in the rainfed ecosystems where the challenges to improve soil quality and crop productivity are enormous. There is an urgent need to mainstream CA technologies to the doorstep of the farmers through strong institutional mechanisms involving innovative participatory approaches and on-farm demonstration of best-bet technologies.

I believe that this book on *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security* gives a comprehensive understanding of the subject having more than 25 chapters covering various facets of CA, latest development in the area of CA on soil health, carbon sequestration, and mitigation of climate change. Besides, this book also sheds light on the impact of CA vis-à-vis irrigated and rainfed region, which will be highly useful to researchers, teachers, land managers, and students.

I compliment all the editors and authors for publishing this book.

13 July 2020

Trilochan Mohapatra
Secretary and Director General
Department of Agricultural Research & Education, and
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New Delhi, India

Preface

Indian agriculture has witnessed a radical shift in food production from 'begging bowl to bread basket' through intensification of agriculture with high-yielding varieties, fertilizer application, and improved agronomic practices during post-green revolution. Although our country has attained self-sufficiency in food grain production and recorded the highest food grain production (~297 million tonnes) during 2019–2020, the productivity remains low and stagnating. At present, the agriculture sector accounts for ~15% of the country's GDP and employs about 60% of the labour force.

In fact, the natural resources such as soil and water are under great pressure to meet the food and nutritional demand. India has to produce 350 Mt by 2030, and this can be achieved only through sustainable soil and water management practices. But the conventional farming practices such as intensive tillage operation, and widespread residue burning accelerate oxidation of soil organic carbon (SOC), which is otherwise crucial for sustainable soil quality and food production systems. Simultaneously, these losses add to elevated levels of CO_2 into the atmosphere, thereby contributing to the greenhouse effect and global warming of the planet. Rising atmospheric concentrations of greenhouse gases (GHGs) such as CO_2, N_2O, and CH_4 are global threats to the agriculture and the future generations. Agricultural activities around the world contribute about 15–18% to the annual emissions of these GHG. Research during the past few decades has demonstrated the significant contribution that conservation agricultural systems on soil health, sequestering carbon, and efficient utilization of water and nutrients in soil as well as reducing emission of GHG.

Due to rise in fertilizer price and declining native mineral nutrient sources, there is an urgent need to recycle surplus crop residues (~140–200 Mt) left and burnt in the field itself to take up succeeding crop. Worldwide conservation agriculture (CA) is being adopted on more than 180 million hectare (m ha) area and increasing at the rate of 7–10 m ha per year, whereas in India, it is expanded to only about 5 m ha. Crop residue retention through conservation agriculture (CA) is able to revert the soil degradation process such as soil erosion, compaction, and surface sealing, through the system of raising of crops in rotation without tilling the soil while retaining crop residues (at least 30%) on the soil surface. However, challenges such as weed and crop residue management, herbicide tolerant weeds, and non-availability of suitable machinery to small farmers need to be addressed properly.

The CA is aimed to conserve, improve, and make more efficient use of natural resources through integrated management of available soil, water, and biological resources combined with external inputs. According to FAO, CA system contributes to environmental conservation as well as economically, ecologically, and socially sustainable agricultural production. It can also be referred to as ‘resource efficient or resource effective agriculture’.

This book comprises more than 25 chapters dealing with various issues, prospects, and importance of CA practices under different agro-climatic conditions, particularly India, and also covers other countries such as Australia, Europe, and the USA. We place our sincere thanks on record to all the authors for their fine contribution and support.

We sincerely express our gratitude to Hon’ble Dr. Trilochan Mohapatra, Secretary (DARE) and DG (ICAR); Dr. Alok K. Sikka, Former DDG (NRM), ICAR for their inspiration and motivation.

First Editor also thanks all the Teachers and Professors who have inspired him with their great knowledge and wisdom that has reformed his understandings on Soil Science vis-à-vis Natural Resource Management.

We hope this book *Conservation Agriculture: A Sustainable Approach for Soil Health and Food Security* will be highly useful to researchers, scientists, students, farmers, and land managers for efficient as well as sustainable management of natural resources.

Bhopal, India — Somasundaram Jayaraman
Brisbane, QLD, Australia — Ram C. Dalal
Bhopal, India — Ashok K. Patra
New Delhi, India — Suresh K. Chaudhari

Contents

About the Editors

Somasundaram Jayaraman has graduated from the Faculty of Agriculture at Annamalai University (1995) and completed his postgraduation (1998) and doctoral studies (2001) at Tamil Nadu Agricultural University (TNAU) in Coimbatore, Tamil Nadu, India. Presently, he is a Principal Scientist at the division of soil physics, ICAR–Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India. He has more than two decades of experience in research and training in the field of natural resource management/conservation agriculture on soil properties and carbon sequestration. Dr. Jayaraman has developed conservation agricultural practices for enhancing soil health and crop productivity in Western and Central India. In addition, farmers in rainfed regions of Central India were also sensitized about soil health and developed low-cost farmer-friendly tools for assessing soil health in a participatory mode through field demonstrations. Dr. Jayaraman has published more than 75 research papers of national and international repute. In addition, he has authored/edited 5 books and published more than 25 book chapters. Besides, he has mentored postgraduate students, PhD scholars, and young scientists. Dr. Jayaraman received Endeavour Research Fellow by Australian Government in 2015, Australian Awards Ambassador by Australian High Commission to India in 2018, the Scientist Award in 2018 and Leadership Award by SCSI, New Delhi in 2019.

Ram C. Dalal has graduated from the Punjab Agricultural University (1964) and completed his master's and doctoral studies at the Indian Agricultural Research Institute (1969). Presently, he is a Professor/Adjunct Professor in the School of Agriculture and Food Science at the University of Queensland, Brisbane, Australia, and Adjunct Professor at Uttar Banga Krishi Vishwavidyalaya, Pundibari, Cooch Behar, India. Throughout his five decades of research and teaching experience, Prof. Dalal has contributed significantly to create awareness in the farming, scientific and general community on the seriousness and insidious nature of soil degradation. Since the last 25 years, landscape restoration, soil organic matter management, carbon sequestration and nitrogen management, site-specific management for soil and subsoil and other constraints, and sustainable crop and pasture rotations and vegetation management have been the central research platforms across cropping, rangelands, and forestry ecosystems. In addition, he is recipient of several awards and honours and also mentored more than 25 PhD scholars in the span of four decade as well as published more than 400 publications with more than 17000 citations. Prof Dalal was made a member in the general division of the 'Order of Australia (AM)' in 2018 and also awarded 'Medal of Agriculture' by Ag Institute Australia in 2021 for outstanding service to science, and to farming through research and sustainable farming practices.

Ashok K. Patra acquired his BSc (Agri) from Banaras Hindu University (Varanasi) and MSc and PhD from the Indian Agricultural Research Institute (IARI), New Delhi. He is presently serving as Director of the ICAR–-Indian Institute of Soil Science, Bhopal. During his scientific career, he has also worked as a postdoctoral fellow at ICRISAT, Hyderabad, and as a visiting study fellow at the Institute of Grassland and Environmental Research (IGER), Devon, UK. He was a recipient of the prestigious INRA Fellowship of the French Research Ministry for work on molecular soil ecology in N cycling at the CNRS-Claude Bernard Université Lyon, France. He developed integrated soil quality index, assessed impacts of climate change on soil–plant systems, advanced nanoparticle research as nutrient source, and developed a digital soil-testing mini-lab *Mridaparikshak* for soil health assessment and fertilizer advisory. He has published more than 350 publications, which have been widely cited throughout the world (~4600 citations). Dr. Patra was a faculty of Post Graduate School, IARI, New Delhi, and has been actively involved in teaching and guiding of postgraduate students at IARI for 15 years. Dr Patra is a recipient of several awards and honours, of which Fellow of the National Academy of Agricultural Sciences (2010); Fellow of the Indian Society of Soil Science (2013); Fellow of West Bengal Academy of Science & Technology (2018); Fellow of the Range Management Society of India (2007); and Fellow of the National Academy of Sciences, India (2020) are notable.

Suresh K. Chaudhari acquired his BSc (Agri) from JNKVV, Jabalpur, and his MSc (Agri) and PhD from MPKV, Rahuri. He is presently serving as Deputy Director General (NRM), Indian Council of Agricultural Research, New Delhi. Earlier, he served as Scientist and Senior Scientist (SS) at various institutes as well as Principal Scientist and Head (Soil and Crop Management Division) at ICAR–Central Soil Salinity Research Institute, Karnal. His areas of research are dynamics of irrigation-induced land degradation, soil hydraulic properties under different quality waters, influence of poor and marginal quality waters on soil properties and plant growth, direct and indirect estimations of soil hydraulic properties, pedo-transfer functions to describe soil hydraulic properties, and irrigation water management in field crops. Dr Chaudhari is a recipient of several awards and honours, of which ICAR–Rafi Ahmed Kidwai Award, 2015; Salinity Excellence Award, 2010–2011; Fellow of the Indian Society of Soil Science; Maharashtra Academy of Sciences; National Academy of Agricultural Sciences; and Fellow of the National Academy of Sciences, India are notable.

Conservation Agriculture: Issues, Prospects, and Challenges in Rainfed Regions of India

1

Somasundaram Jayaraman, A. K. Naorem, N. K. Sinha, M. Mohanty, K. M. Hati, A. K. Patra, S. K. Chaudhari, Rattan Lal, and Ram C. Dalal

Abstract

In India, out of total cropped area (142 Mha), 86 Mha is under rainfed agriculture. These rainfed areas are prone to land degradation, dry spells, water scarcity, and increased poverty and malnutrition. Therefore, it is the urgent need for adopting cost-effective resource conservation technologies such as conservation agriculture (CA) that can act as an essential prerequisite for achieving enhanced productivity in the region. The crop residue burning not only deteriorates soil health but also has adverse environmental and ecological impacts. This is minimized with the retention/incorporation of the crop residue with minimal soil disturbances in CA technologies. It not only returns much needed C and other nutrients to the soil but also improves soil aggregation and reduces soil erosion. Availability of specialized machinery in CA is a greater problem as it is difficult to sow a crop in the presence of residues of preceding crop. However, with the widespread adoption of CA in India, new variants of zero-till seed-cum-fertilizer drill/planters have been developed for direct drilling of seeds even in the presence of surface

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residues. In order to generate benefits from CA, untapped area of rainfed regions needs to be explored and utilized for CA interventions for carbon sequestration and enhancing the productivity of those areas. Appropriate location-specific CA technologies need be developed for the dominant cropping systems in the rainfed regions.

Keywords

Conservation agriculture · Prospects and challenges in adoption of CA · Soil health · Carbon sequestration · Sustainable Soil Management

1.1 Introduction

Agriculture is one of the primary sources of livelihood for about 58% of India's population (IBEF 2020). The growth in gross value added (GVA) by agriculture and allied sectors in India stood at 3.7% during the year 2019–2020 (IBEF 2020). It is estimated to reach food grain production of 291.95 million tonnes during 2019–2020 (IBEF 2020). The mission of increasing food grain production, though realized to a commendable extent at present, is under risk due to climatic aberrations and reduced availability of land, water, and nutrients along with poor and continuous degradation of the resources to cope up with the demands of increasing population. Although India had attained self-sufficiency in food grain production through intensification of agriculture with high-yielding varieties, fertilizer application, and chemical pest control during the green revolution, productivity is still low and is stagnating.

Conservation agriculture (CA) is a set of management practices for sustainable agricultural production without excessively disturbing the soils while protecting it from the processes of soil degradation like erosion, compaction, aggregate breakdown, loss of organic matter, leaching of nutrients, and processes that are accentuating due to anthropogenic interactions in the presence of extremes of weather and management practices (Hobbs et al. 2008; Dalal et al. 2011; Sinha et al. 2019; Somasundaram et al. 2020). The organic materials conserved through this practice are decomposed slowly, and much of materials are incorporated into the surface soil layer, thus reducing the release rate of carbon into the atmosphere. In the total balance, carbon is sequestered in the soil and turns the soil into a net sink of carbon (Dalal et al. 2011, Page et al. 2020, Somasundaram et al. 2017, 2018). This could have profound consequence in our fight to reduce greenhouse gas (GHG) emissions into the atmosphere from agricultural operations and thereby helping to forestall the calamitous impacts of global warming. CA helps in improving soil aggregation, reducing compaction through promotion of biological tillage, increasing surface soil organic matter and carbon content, and moderating soil temperature and weed suppression. CA reduces cost of cultivation, saves time and energy, increases yield through timelier seeding/planting, reduces pest and diseases through stimulation of biological diversity, and reduces greenhouse gas emissions. In this chapter, various facets of CA vis-à-vis rainfed region have been discussed.

1.2 Conservation Agriculture

Human efforts to produce ever-greater amounts of food leave their mark on our environment. Persistent use of conventional farming practices based on extensive tillage, especially when combined with removal or in situ burning of crop residues, has magnified soil erosion losses, and the soil resource base has been steadily degraded (Montgomery 2007; Singh et al. 2020). One of the glaring examples for the aforementioned statement is the dust bowl in the United States during 1930s in Great Plains, where 91 Mha of land was degraded by severe soil erosion (Montgomery 2007; Utz et al. 1938). The land is becoming a diminishing resource for agriculture, in spite of a growing understanding that future of food security will depend upon the sustainable management of land resources as well as the conservation of prime farmland for agriculture (Swaminathan 2011). The main threats to soil resource are soil erosion, loss of organic matter (OM), soil compaction, soil sealing, soil acidification, and soil salinity and sodicity. It has been realized worldwide that crop residue retention on soil through conservation agriculture is able to revert the soil degradation process. As the food demand is ever increasing due to population explosion coupled with fertilizer price rise and declining native mineral sources, there is a need to reuse the crop residues left in the field as well as other options for reviving the agriculture sector's growth.

Conservation agriculture has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production (Hobbs 2001, 2007). The CA is aimed to conserve, improve, and make more efficient use of natural resources through integrated management of available soil, water, and biological resources combined with external inputs. It contributes to environmental conservation as well as economically, ecologically, and socially sustainable agricultural production (FAO 2014). It can also be referred to as resource-efficient or resource-effective agriculture (FAO 2014). The name "conservation agriculture" has been used to distinguish this more sustainable agriculture from the narrowly defined *conservation tillage* (Wall 2007; Reicosky 2015).

1.3 Conservation Tillage

Tillage, the mechanical manipulation of the soil and the leftover plant residues to prepare seedbed where crop seeds are planted, has been an integral part of modern agricultural production and also a major input for conventional cropping systems due to high requirements in energy and time, which increases production cost. Although tillage can help in temporarily overcoming a few soil-related constraints such as surface sealing to crop production, it can result in deterioration of soil structure, reduced infiltration, increased runoff and erosion, water pollution, and degradation of the soil (Lal 1991).

Conservation tillage is often defined as any tillage system that leaves enough crop residues (at least 30%) in the field after harvest to protect the soil ranging from no-tillage to intensive tillage depending on soil conditions (Uri 1998). Similarly, Jarecki and Lal (2003) described it as a widely used terminology to denote soil management systems that results in at least 30% of the soil surface being covered with crop residues after seeding of the subsequent crop and often regarded as an essential tool for conservation of soil and water (Baker et al. 1996) (Fig. 1.1).

Conservation tillage practices such as zero-tillage practices can be the transition steps toward conservation agriculture. *Conservation farming* or *conservation agriculture* removes the emphasis from the tillage component alone and addresses a more holistic concept of the complete agricultural system. It combines the following key basic principles:

1.4 Key Principles of CA

The CA in the arid and semiarid regions of India needs to be understood in a broader perspective. The term CA refers to the system of raising of crops in rotation without tilling the soil while retaining crop residues on the soil surface (Abrol and Sunita 2005, 2006, http://www.conserveagri.org/understanding.htm, FAO 2014) that has three key principles (Fig. 1.2):

- Minimal soil disturbances enabled through no-till/reduced tillage.
- Maximum soil cover/residues.
- Diversified crop sequences/rotations (spatial and temporal crop sequencing).

The CA system constitutes a major departure from the past ways of doing things (Fig. 1.2). Besides, integrated nutrient management (INM) is a fourth principle, especially having much relevance for the resource-poor farmers (Lal 2015). These CA principles are applicable to a wide range of crop production systems from low-yielding, dry, rainfed conditions to high-yielding, irrigated conditions. However, the techniques to apply the principles of CA will differ in different situations and will vary with biophysical and system management conditions and farmer circumstances (Verhulst et al. 2010). This implies that the whole range of agricultural practices, including handling crop residues, sowing and harvesting, water and nutrient management, disease and pest control, etc., need to be evolved and evaluated through adaptive research with active farmers' involvement. The key challenges relate to the developing, standardizing, and adopting farm machinery/implements for seeding amid of crop residues with minimum soil disturbance, developing crop harvesting and management systems with residues maintained on the soil surface, and developing and continuously improving site-specific soil, crop, nutrient, and pest management strategies that will optimize the benefits of the new CA systems.

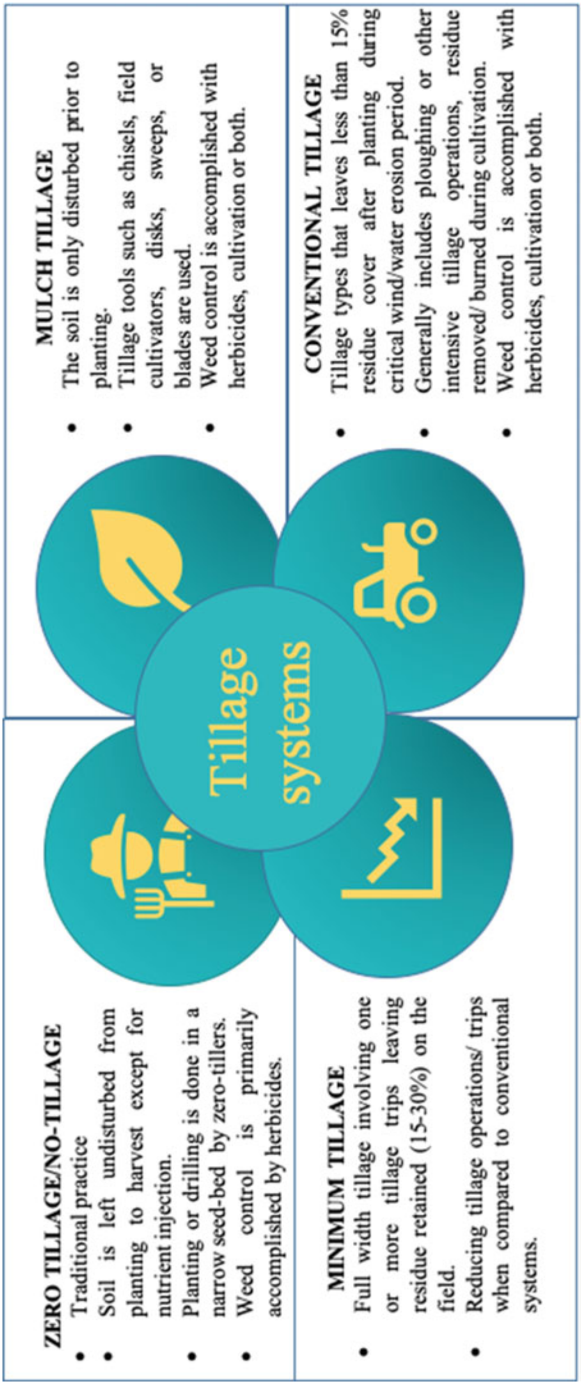

Fig. 1.1 Descriptions of different tillage systems (Conservation Technology Information Centre 2002)

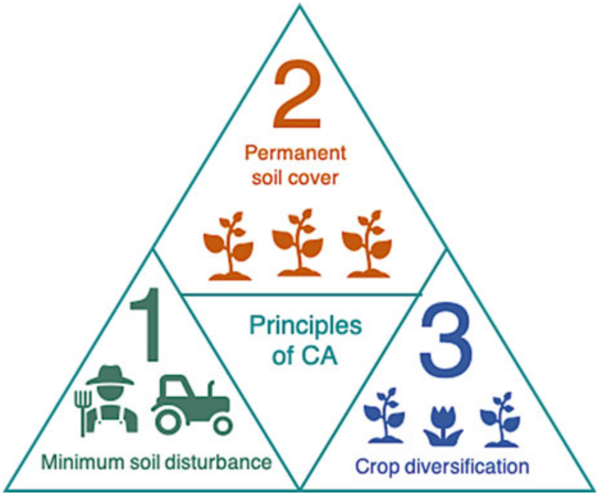

Fig. 1.2 Principles of conservation agriculture

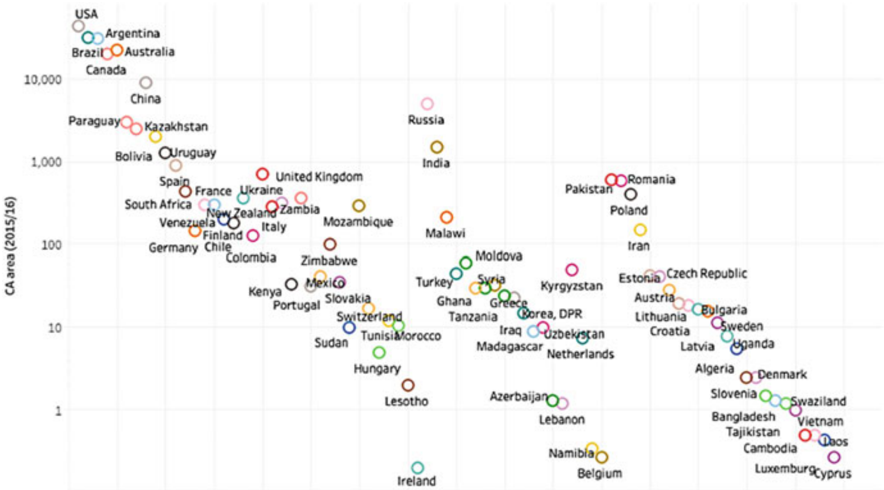

Fig. 1.3 Global overview of CA adoption area (ha) country-wise by 2015–2016 (Data is plotted on a logarithmic scale to compare the extent of CA adoption area among countries) (Figure constructed using dataset of Kassam et al. 2018)

1.5 Status of Conservation Agriculture

Conservation agricultural practices are gaining increased attention worldwide. CA is practiced globally on about 180 Mha of cropland (12.5% of total global cropland) during 2015–2016 (Kassam et al. 2018) (Fig. 1.3). In Asia, 13.93% of cropland is under CA practices out of which 1.5–2.10 Mha is CA adopted area during 2015–2016 (Kassam et al. 2015), and another study reported <5 Mha (Kassam et al. 2018) (Fig. 1.3). The CA is a way to reduce the water footprint of crops by improving soil water infiltration, increasing soil water retention, and reducing runoff and contamination of surface and groundwater. South American countries (e.g., Brazil, Argentina, and Colombia) practicing CA reported to have a remarkable positive effects on water footprints of crops. Unlike in the rest of the world, CA technologies in India are spreading mostly in the irrigated areas of the Indo-Gangetic Plains (about 2–3 Mha) where rice-wheat (RW) cropping system dominates (WCCA 2009). Evidently, yields in the rice-wheat (RW) system of the Indo-Gangetic Plains of India are higher with no-till because of timelier planting and better stands. Increase of yields about 200–500 kg/ha was found with no-till wheat in this system (Hobbs and Gupta 2004). It is also popular in the region because it costs less in terms of money, labor, and time. No-till wheat significantly reduced the costs of production; farmers estimate this at about 2500 rupees/ha (US$ 60/ha), mostly due to saving in diesel fuel, less labor, and less pumping of water. Since planting can be accomplished in one pass of the seed drill, time for planting was also reduced, thus freeing farmers to do other productive works. However, CA systems have not been extensively tried or promoted in other major agro-ecoregions like rainfed semiarid tropics, the arid regions, and the mountain agro-ecosystems.

In contrast to the homogenous growing environment of the IGP, the production systems in semiarid and arid regions of India are quite heterogeneous in terms of land and water management and cropping systems (Kumar et al. 2011). These include the core rainfed areas which cover up to 60–70% of the net sown area and the remaining irrigated production systems. The rainfed cropping systems are mostly single cropped in the Alfisols, while in Vertisols, a second crop is generally taken on the residual moisture. In *rabi* black Vertisols, farmers keep lands fallow during *kharif* and grow *rabi* crop on conserved moisture. Sealing, crusting, subsurface hard pans, and cracking are the key constraints which cause high erosion and obstruct infiltration of rainfall. The choice and type of tillage largely depend on the soil type and rainfall. Leaving crop residues on the soil surface in CA is a major concern in these rainfed areas due to its competing uses as fodder, leaving very little or no residues available for surface application. Agroforestry and alley cropping systems are other options for CA practices. This indicates that the concept of CA has to be adopted in a broader perspective in the arid and semiarid areas. Experience at Indian Institute of Soil Science (IISS) showed that reduced tillage in soybean-wheat system is a suitable option for growing soybean and wheat crops on Vertisols with saving of energy and labor (Subba Rao et al. 2009). This practice also improves soil organic carbon and physical and biological properties.

Due to less biomass production and competing uses of crop residues, the scope of using crop residues for conservation agriculture is limited in dryland ecosystems. The Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, has shown that in dryland ecosystems, it is possible to raise a second crop with residual soil moisture by covering the soil with crop residues. In a network project on tillage conducted since 1999 at various centers of the All India Coordinated Research Project for Dryland Agriculture, it was found that rainfall and soil type had a strong influence on the performance of reduced tillage. In arid regions (<500 mm rainfall), low tillage was found on par with conventional tillage, and weed problem was controllable in arid Inceptisols and Aridisols. In semiarid (500–1000 mm) region, conventional tillage was superior. However, reduced tillage with interculture was superior in semiarid Vertisols, and reduced tillage with herbicide was superior in Aridisols. In subhumid (>1000 mm) regions, weed problem was severe due to rainfall, and thus there is a possibility of reducing the weed population by using herbicides in reduced tillage condition.

1.6 Challenges in Adoption of Conservation Agriculture

The CA systems are quite different from the conventional farming practices. This implies that the whole range of agricultural practices, including handling crop residues, sowing and harvesting, water and nutrient management, and disease and pest control, need to be evolved and evaluated. The key challenges relate to developing, standardizing, and adopting farm machinery for seeding/planting amid crop residues with minimum soil disturbance, developing crop harvesting and management systems with residues maintained on the soil surface, and developing and continuously improving site-specific crop, soil, and pest management strategies that optimizes the benefits of the new systems.

1.7 Rainfed Agriculture Scenario

Rainfed area is not only characterized by low and uncertain returns, land degradation, frequent mid-season dry spells, and water scarcity but also by hotspots of poverty, malnutrition, and child mortality. The total cropped area in the country is lingering around 142 million hectares, out of which about 86 Mha are rainfed (Srinivasarao et al. 2015). Rainfed farming area falls mainly in arid, semiarid, and dry humid regions. To meet the requirement of growing demand of food grains, it is imperative to increase the production potential in perpetuity in rainfed region besides the irrigated region. The country's first green revolution had greater benefits on irrigated lands where wheat and rice are grown, while the drylands growing coarse cereals were unattended. The yields of the latter remained very low (<1 t ha^{-1}), and this requires the immediate attention. Depletion of soil carbon and nutrients from these fields is one of the major threats to the soil productivity and land degradation.

Rainfed agriculture is practiced under a wide range of soil and climatic conditions. Rainfall regimes, amount and distribution of rainfall, and soil characteristics are the key determinants of rainfed cropping potentials, and these vary widely in rainfed regions. About 74% of annual rainfall occurs during southwest monsoon (June to September) (Venkateshwaralu and Shankar 2009). Due to lack of widespread adoption of cost-effective moisture retention and conservation technologies, the soils suffer from rapid rainfall runoff and erosion, reducing their productive capacity and agronomical potential. Realizing this potential essentially hinges on our ability to reverse processes of degradation—processes that contribute to institutionalize water conservation and reduce runoff and erosion. Thus, conservation agriculture practices are essential prerequisite for achieving enhanced (sustained) productivity in the region. It is also important to understand the farming systems of the region and particularly how the crop and livestock sectors interact and prevailing socioeconomic conditions/factors are impacting resource use and dynamics.

1.7.1 Residue Burning

Worldwide, many farmers conduct burning of field crops residue for variety of real and perceived benefits. *Residue burning* is a quick, labor-saving practice to remove residue that is viewed as a nuisance by farmers (Prasad et al. 1999) (Fig. 1.4). According to Directorate of Economics and Statistics, MoA, DAC, New Delhi (2012–2013), India produced 93.51 million tonnes (Mt) of wheat, 105.24 Mt. of rice, 22.26 Mt. of maize, 16.03 Mt. of millets (jowar, bajra, ragi, and small millet), 341.20 Mt. of sugarcane, 7.79 Mt. of fiber crops (jute, mesta, cotton), 18.34 Mt. of pulses, and 30.94 Mt. of oilseed crops (MNRE 2009;NPMCR 2014). Out of all these crops grown, wheat, rice, and sugarcane are those crops that are most prone to crop residue burning (NPMCR 2014). These crop residues are also used as animal feed,

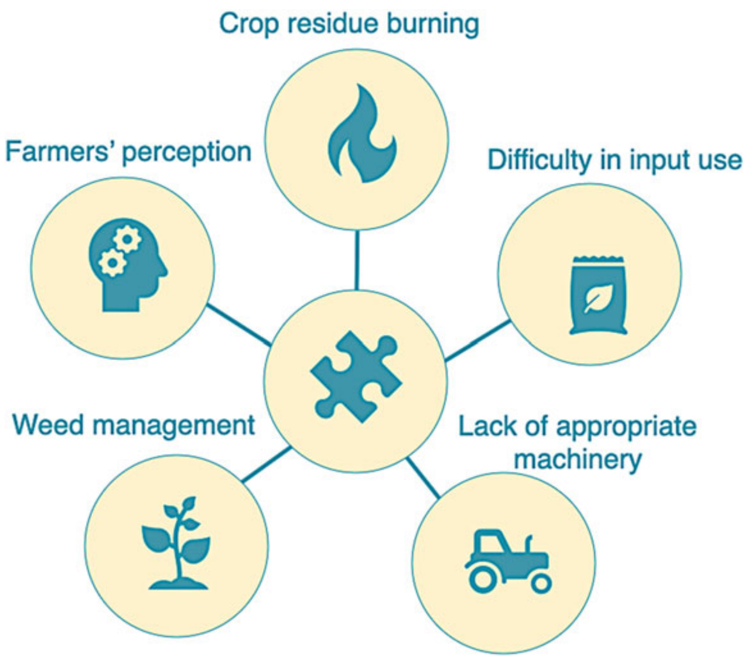

Fig. 1.4 Challenges in the adoption of CA in rainfed areas of India

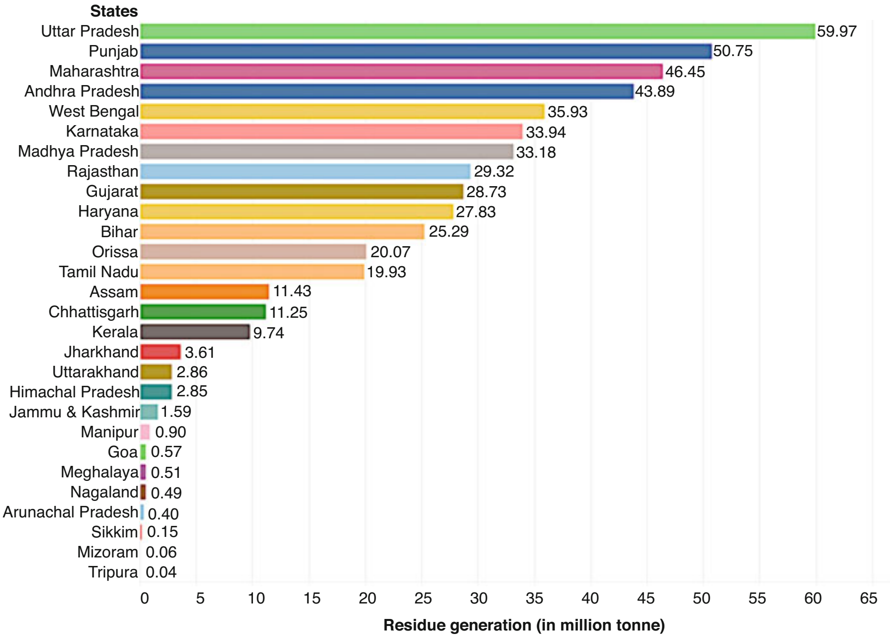

Fig. 1.5 Crop residue generation (in million tonne) in different states of India (Figure constructed using data of NPMCR 2014)

soil mulch, manure, thatching for rural homes, and fuel for domestic and industrial purposes. However, a large portion of these crop residues is burnt on farm primarily to clear fields to facilitate timely planting/seeding of succeeding crops (NAAS 2012) (Fig. 1.5). Ministry of New and Renewable Energy, Government of India, had estimated that about 500 Mt. of crop residues are generated annually. Uttar Pradesh (60 Mt) is leading in the generation of crop residues, followed by Punjab (51 Mt) and Maharashtra (46 Mt) (Figs. 1.6 and 1.7). Out of the major crops grown in India, cereals generated maximum residues (352 Mt), followed by fibers (66 Mt), oilseeds (29 Mt), pulses (13 Mt), and sugarcane (12 Mt). Cereal crops (rice, wheat, maize, millets) contribute 70%, while rice crop alone contributes 34% to the crop residues. Sugarcane residues consisting of tops and leaves generate 12 Mt., i.e., 2% of the crop residues in India (Fig. 1.7).

Residue burning reduces crop disease infestations (phytosanitary) and improves weed control; however, it causes considerable loss of organic C, N, and other nutrients by volatilization and aerosolization, which may affect soil microorganisms detrimentally. Moreover, residue burning has several adverse environmental and ecological impacts as it leads to release of soot particles and smokes causing human health hazards and adds a considerable amount of CO_2 and particulate matter to the atmosphere and can reduce the return of much needed C and other nutrients to the soil. The lack of a soil surface cover may also increase the loss of soil nutrients via runoff. Crop residues returned to the soil maintain OM levels and provide substrates

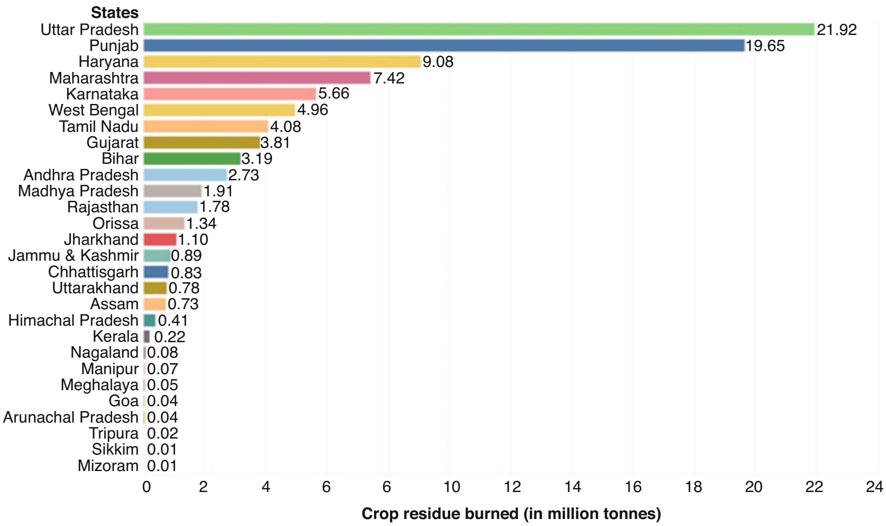

Fig. 1.6 Crop residue burned (in million tonne) in different states of India (Figure constructed using data of NPMCR 2014)

for soil microorganisms. In comparison to burning, residue retention increases soil carbon and nitrogen stocks, provides organic matter necessary for soil macroaggregate formation, and fosters cellulose-decomposing fungi and thereby carbon cycling.

1.7.2 Lack of Appropriate Machinery

Permanent crop cover with recycling of crop residues is a prerequisite and an integral part of CA system. However, sowing of a crop successfully in the presence of residues of preceding crop is a problem that needs to be resolved. Recently, new variants of zero-till seed-cum-fertilizer drill/planters such as Happy Seeder, Turbo-Seeder, and Rotary Disc drill have been developed for direct drilling of seeds even in the presence of surface residues (loose and anchored up to 10 t ha^{-1}). These machines are found to be very useful for managing crop residues for conserving moisture and nutrients as well as controlling weeds (IARI 2012). In addition to moderating soil temperature, these machines are now adopted in the Indo-Gangetic Plains under the rice-wheat system. There is an increasing awareness and concern for affordable and energy-efficient equipment and technology for cost-effective production of crops (Fig. 1.3). Thus, more emphasis is on increased yield, reduced cost of cultivation, and efficient utilization of input resources to raise farm income. Agricultural machinery or tools, which support CA, generally refer to the cultivation systems with minimum or zero tillage and in situ management of crop residues (Fig. 1.8). Different designs of direct drilling machines, viz., zero-till seed drill, no-till plant drill, strip-till seed drill, roto till drill, and rotary slit no-till drill, have

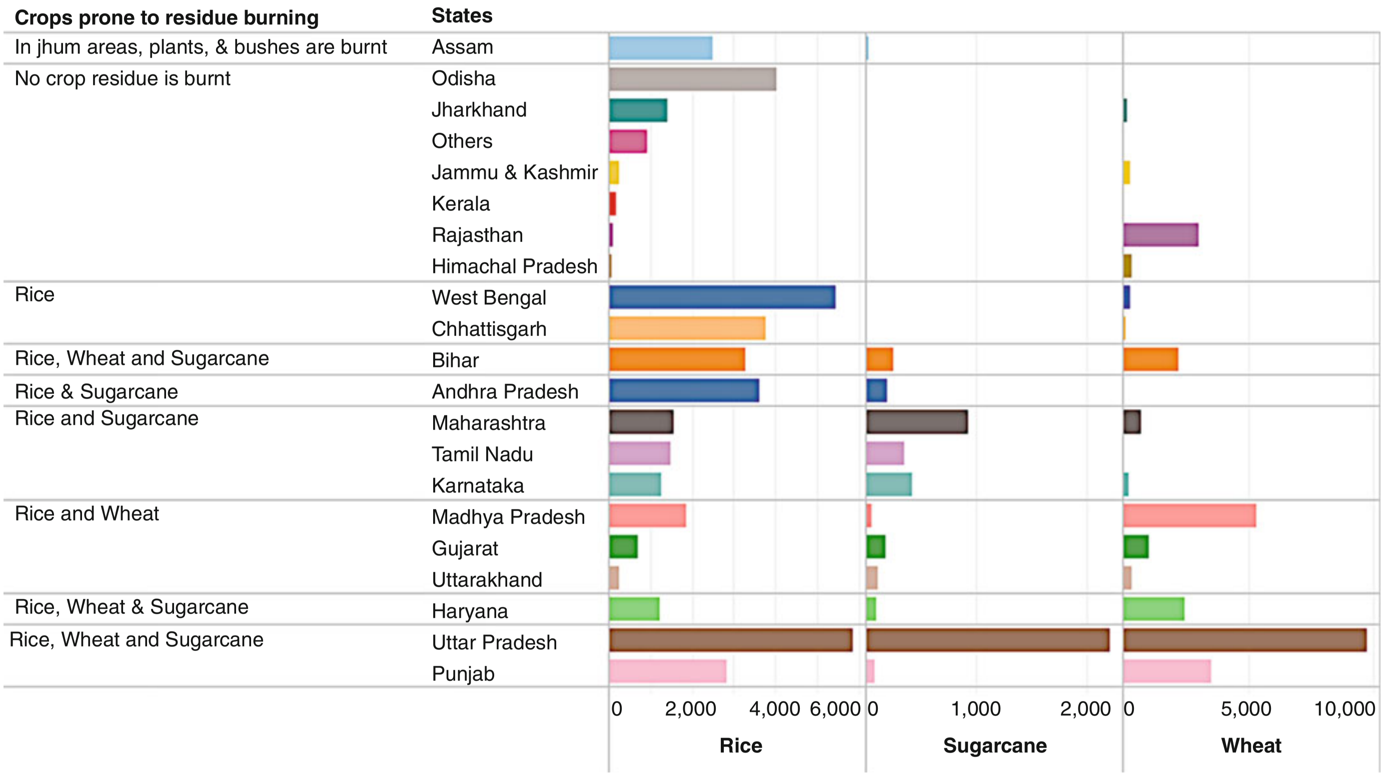

Fig. 1.7 Crops prone to residue burning in different states of India (The column chart represents the state-wise major cropped area in thousand hectare under rice, wheat, and sugarcane) (Figure constructed using dataset from NPMCR 2014)

Fig. 1.8 Soybean sown by no-till seed drill

been developed with controlled traffic measures for energy-efficient and cost-effective seeding of crops with less soil disturbances.

Package of equipment and technology for residue incorporation and bed planters have been developed for higher productivity with reduced irrigation water requirements. Recent development and performance of agricultural machinery have concentrated both on biological and mechanical parameters. Selection of most appropriate equipment for a specific situation is essential for maintaining soil physical environment. Besides, the chosen equipment should be fuel efficient. Tractor-operated/self-propelled machinery/technologies used in CA have the potential to meet the challenges encountered in CA under field conditions. Zero-tillage farming on 1.2 million ha Indo-Gangetic Plains reportedly saved 360 million m^3 water. It also reduces the number of operating hours of the pumps, thus reducing CO_2 emission and consumption of electrical energy.

1.7.3 Weed Management

Weed control is the other main bottleneck, especially in the rice-wheat system (IARI 2012). Continuous and high-intensity downpours during the rainy season also create a problem in effective weed management through herbicides. Thus, increased use of herbicides is prerequisite for adopting CA (Fig. 1.3). Countries that use relatively higher amounts of herbicides are already facing such problems of pollution and environmental hazards. Nutrient management may become complex because of higher residue levels in surface layers and reduced options for application of nutrients, particularly through manure. Application of fertilizers, especially N, entirely as basal dose at the time of seeding may result in a loss in its efficiency and environmental pollution. Sometimes, increased application of specific nutrients may be necessary and specialized equipment are required for proper fertilizer placement, which contributes to higher costs.

1.7.4 Difficulty in Input Use

There are difficulties in sowing and application of fertilizer, water, and pesticides under residue-retained conditions. The conservation agriculture with higher levels of crop residues usually requires more attention on the timing and differential placement of seed and nutrients and application of pesticides and irrigations (Fig. 1.4). Precision agriculture (PA) using digital technologies such as moisture and nutrient sensors can be used under CA. While adopting PA, application of herbicides and nutrients as and when required using GPS and remote-operated drones can be potentially explored. Similarly, agro-services could provide custom hiring services such as farm machinery and recommendation on the choice of crop, cultivars, seed, and fertilizer to farming community.

1.7.5 Farmers' Perception

Limiting factors in adoption of residue incorporation systems in CA by farmers include additional management skills, apprehension of lower crop yields and/or economic returns, negative attitudes or perceptions, and institutional constraints. In addition, farmers have strong (historical and conventional) preferences for clean and good-looking tilled fields vis-à-vis untilled shabby-looking fields. In addition, pest infestation, particularly termite and rodent infestations under residue-retained fields in CA pose greater challenge to farmers for adoption (Fig. 1.4).

1.8 Technological Gaps

In India, efforts to adopt and promote CA practices are in increasing demand among stakeholders in intensively cropped areas as in IGP (Hobbs et al. 1997; Hobbs et al. 2008). There is also limited use in other parts of India due to inappropriate knowledge about CA technologies (Shukla et al. 2012). Concerns about stagnating productivity, increasing production costs, declining resource quality, depleting water tables, and increasing environmental problems are the major factors to look for alternative technologies for improving production potential in diverse agro-ecological regions of the country. The Northern and Eastern IGP, black soil belts of central plateau, Odisha upland systems, coastal high rainfall regions, and rainfed regions are the areas where there is a potential to improve crop productivity through CA technologies. In IGP, some of the CA components have gone to field implementation, whereas in other parts (rainfed regions) of India, efforts are made to popularize such technologies. Developing location-specific CA practices in these regions are urgently required. CA practices may be integrated into major ongoing development programs such as watershed program, drought prone area program (DPAP), Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), *Rashtriya Krishi Vikas Yojana* (RKVY), National Mission for Sustainable Agriculture (NMSA), and National Food Security Mission. Context-specific CA practices and technologies should be developed which are suitable to soils, climate and cropping conditions, and socioeconomic features. There is an increasing opportunity to the long untapped potential of rainfed areas, home to smallholder farmers through saving of inputs and increasing resource productivity and efficiency.

1.9 Expected Benefits from Adoption of CA Practices

CA practices helps in narrowing gap between current and potential yield crops. These approaches are equally valid and suited to both irrigated and rainfed production systems and bring the following benefits:

Short term: Adoption of CA practices reduces the cost of cultivation through components such as reduction in machinery costs. Zero or minimum tillage involves uses of few passes of tillage implements over the field that results in comparatively lower fuel and repair costs than that of intensive tillage practices. However, this concept might mask some of the complexities in fair comparison of CA and conventional tillage practices. Some farmers complement their existing tillage practices with CA (partially switching to CA on some part of the fields or some years).This might increase their machinery costs as they need to invest for two cultivation systems. Another attention is the reduction of labor costs in CA than conventional counterparts. This follows from the decreased demand of labor in land preparation at the beginning of the growing season. As the CA practices involve minimum disturbance to soil and incorporation of crop residue that enhance the soil aggregation, the rate of soil erosion is highly reduced in CA than conventional ones. In other way, it reflects higher nutrient use efficiencies of fertilizers applied, as soil erosion also removes considerable amount of nutrients from soil. Indirectly, it is saving the cost of fertilizer input in CA practices.

Medium term: The retention of crop residues and limited disturbance to soil aggregates favor the retention of soil moisture, moderation in hydrothermal regimes, and increased infiltration, which is one of the most prioritized parameter to be considered in semiarid regions where water availability and retention are the challenges in crop cultivation. CA practices also encompass increased levels of soil organic C as it incorporates crop residues and protect the soil organic matter from oxidation and decomposition by soil microbes through locking up in soil aggregates. Proper aeration and availability of substrates for soil microbes influence the buildup of beneficial soil microbes that play crucial role in improving soil quality through production of enzymes, exopolysaccharides, and glomalin-like proteins. Therefore, the mutual relationship between the enhancement of soil C and biological properties could be more conspicuous in CA practices.

Long term: CA practices help in the buildup of SOM and thus can contribute to C-sequestration. In fact, since soil has been regarded as a large terrestrial sink for atmospheric CO_2, CA can ultimately contribute in mitigation of increasing emissions of GHGs through various ways.

Switching from conventional tillage to either no-tillage or to CA would increase the net C-sequestration potential of agricultural lands. Carbon sequestration through CA is important in climate change adaptation efforts since it contributes to so many soil functions and properties that are related to productivity. For example, C-sequestration helps to improve soil properties, such as soil structure and aggregate formation, which contribute to increase in available water holding capacity. From a soil fertility point of view, C-sequestration increases the cation exchange capacity (CEC), especially those of coarse-textured (sandy, sandy loam) soils, and is a vital for storage of essential crop nutrients such as N, P, S, and other macronutrients and micronutrients (Delgado et al. 2011).

1.10 Preessential for Adoption of CA

Some conditions are essential for practicing CA in the field including every components of its adoption. Planting or drilling in soil is accomplished in a narrow seedbed by the use of no-till seed drill/strip-till seed drill. Further, it should ensure that the tillage operations should not invert the soils; rather a minimal disturbance of the soil is sufficient enough to sow the seeds or planting. Full-width/optimum tillage involving one or more tillage trips should be followed retaining crop residue (at least 30%) in the field. Special machines such as duck foot cultivator, no-till seed drill, strip-drill seed drill, and Happy Seeder (with different variants) may be used for tillage and sowing operations. Weed management in CA is accomplished through use of cover crops, knife rollers, and appropriate herbicides to kill the weeds. CA does not encourage use of intensive tillage implements such as disk harrow, rotavator, mold board (MB) plough, and chisel plow. To promote soil fertility and protect the soil from erosion and degradation, use of cover crops, incorporation of crop residues, and reduced use of herbicides (spot application) are recommended.

1.11 CA Interventions for Untapped Rainfed Regions

Experience from several experiments in India showed that minimum or reduced tillage does not offer much advantage over conventional tillage in terms of grain yield without maintenance of adequate amount of residue on the soil surface (Bhale and Wanjari 2009; Sharma et al. 2009; Somasundaram et al. 2020). However, due to the shortage/nonavailability of crop residues in rainfed areas in arid and semiarid regions, several alternative strategies have emerged for generation of residues either through in situ cultivation and incorporation as a cover crop or harvesting from perennial plants grown on bunds and adding the green leaves as manure cum mulch (Kumar et al. 2011). On the other hand, it also accompanies difficulties in sowing and application of fertilizers and pesticides and problems of pest infestation amid crop residues (IARI 2012).

In general, the rainfed soils are very low in organic carbon (OC) and other essential nutrients. In majority of the rainfed lands, OC is in the range of 0.3–0.6% on weight basis (Srinivasarao et al. 2009; IARI 2012). Reduced tillage (RT) coupled with residue retention in rainfed region has shown favorable effect on soil organic carbon (SOC) and other soil properties after 3 years of crop cycle than conventional tillage (CT) (Somasundaram et al. 2019). It is evident from the perusal of data that to bring significant changes in SOC under rainfed regions requires a long-term continuous residue addition coupled with minimum disturbances in soil. Therefore, untapped area of rainfed regions (90 Mha) needs to be explored and utilized for CA interventions for carbon sequestration and enhancing the productivity of those areas. Appropriate location-specific CA should be developed for the following dominant cropping systems in the rainfed regions (Yadav and Subbarao 2001) such as shown in Fig. 1.9. Other location-specific CA practices that can be developed are *kharif*-allow-*rabi* cropped areas followed in semiarid alluvial soil regions of India in which vast areas of low to medium rainfall semiarid regions *kharif* cropping is skipped for growing a less risk prone *rabi* crop (gram, mustard, or wheat) by adopting precision farming/agriculture consisting of weather forecasting, field operations, seeding, variable rate of fertilizer, water, and herbicide applications through sensor system further enhancing input use efficiencies (Basso 2003). This helps in early sowing of the monsoon season crop that allows early harvesting to save enough soil moisture for the *rabi* crop. Similarly, digital technologies can be potentially utilized for farm advisories via farmer-KVK communication through mobile alerts (fertilizer dose and crop management) and have greater potential in enhancing farm productivity and socioeconomic condition. Crop yields and stability much depend on *kharif* rains and capacity of soils to store and supply water. CA practices coupled with residue retention help in conserving soil moisture and nutrient in the region. Cotton fallow and cotton followed by pigeon pea constitute a major production system in the shallow and medium black soil region receiving medium rainfall. In this region high amount of runoff and soil erosion are the major factors limiting yield and stability of crops. Adopting CA practices may help in reverting these trends.

1.12 Conclusions

Conservation agriculture (CA) is definitely a sustainable production approach which not only conserves natural resources but also enhances productivity and soil quality. Location-specific CA technology/machinery generation–dissemination–adoption of CA practices has to be looked into for broader perspective, and it has to go hand in hand, that is, close partnership, with farmers for maximum benefits. The main advantages of CA practices are realized in rainfed agro-ecoregions if those practices are adopted simultaneously over a long-term basis. Interdisciplinary research efforts are required to develop appropriate implements for seeding with minimal disturbances, residue incorporation, and intercultural operations under conservation agriculture. A lack of awareness/knowledge among the farming community about

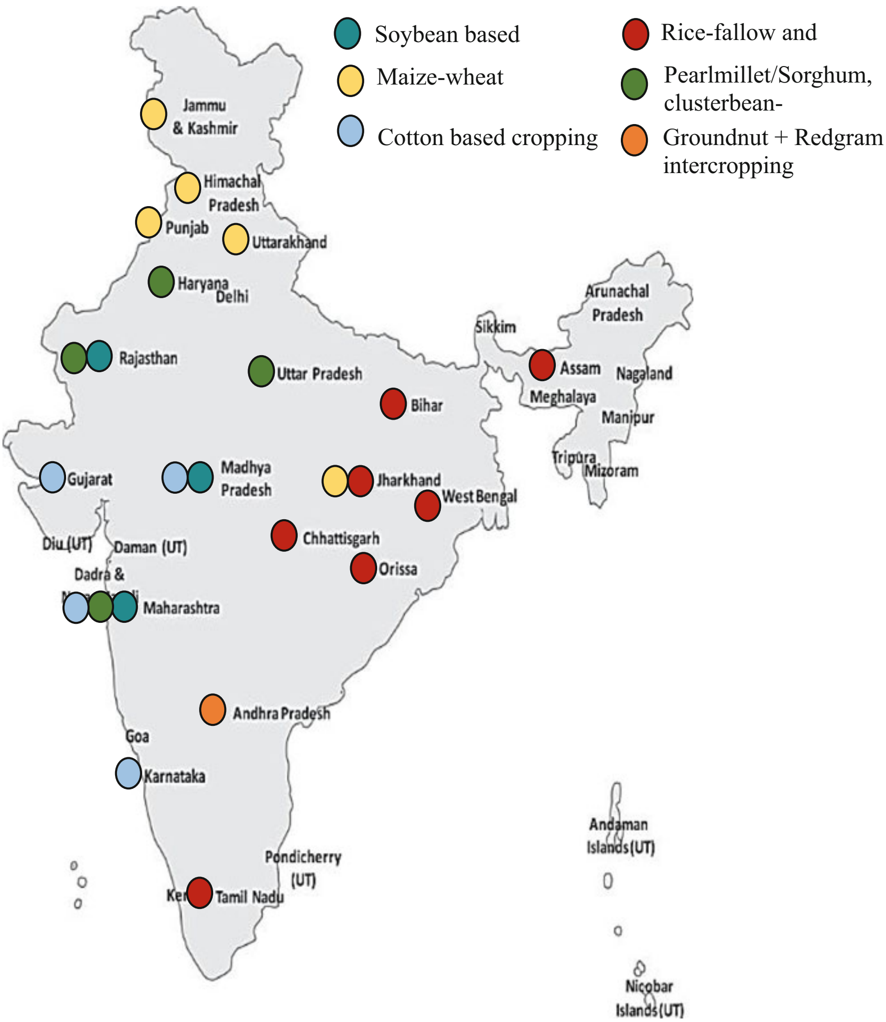

Fig. 1.9 Location-specific cropping systems that can be developed with CA practices. Each colored bubble represents the state in which the cropping systems are intensively followed. The names of the states on the immediate right side of the bubbles (Map constructed from the list of cropping systems given by Yadav and Subbarao 2001)

the CA technology is another reason for non-acceptance. CA component should be included in soil health card/smart card for proper monitoring of crop residue retention/burning. Familiarization of CA technologies at each KVK and state agricultural departments help in changing the mindset of farmers and spreading awareness and dissemination of these technologies at block level through attractive CA demonstrations. CA can serve as an alternative management practice that can minimize the crop residue burning and make use of it to improve the soil quality and reduce environmental pollution. The need to modify the harvesting equipment in CA is another call to be addressed. Creation of incentives and policies for adoption of CA will benefit farmers and also to expedite the adoption process.

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Strategic or Occasional Tillage: A Promising Option to Manage Limitations of no-Tillage Farming

2

K. L. Page, Ram C. Dalal, and Y. P. Dang

Abstract

No-till (NT) farming has several advantages over traditional tillage due to its ability to control erosion, lower fuel costs, conserve soil moisture, and promote greater soil health. However, long-term NT systems can also suffer from several management challenges, largely centred around controlling weed, pest, and disease populations, the stratification of nutrients at the soil surface, and the development of soil structural issues, such as soil compaction. Occasional strategic tillage (ST), whereby otherwise NT soils receive infrequent tillage events, may be a management option that can help farmers deal with some of the negative effects of long-term NT practice. We have reviewed the information around the drivers prompting farmers to introduce ST into NT systems; the likely effects of ST on crop agronomy and soil physical, chemical, and biological properties; and the current evidence for how best to implement ST. Overall, there are likely to be both advantages and disadvantages associated with ST, and it is important that full consideration be given to the timing and type of tillage used to minimise any negative effects of tillage and maximise its positive impact. In addition, further research is required to better understand and guide growers on how to best use ST to their advantage on a range of soil types and cropping systems.

Keywords

Strategic tillage · Soil properties · Nutrient stratification · Herbicide-resistant weeds · Crop productivity · Environmental effects

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2.1 Introduction

In traditional agricultural systems, the soil is usually tilled several times during the fallow period to control weeds and prepare a seedbed suitable for sowing. In addition, residues from the previous crop are typically removed, either by burning, baling, or grazing, to make tillage and sowing easier and assist establishment of the next crop. The exact nature of tillage operations can vary from region to region, but worldwide one of the most common techniques involves ploughing with a mouldboard plough, which inverts the soil and helps burry weeds, followed by several passes with a disc harrow, which helps to further break up the soil, bury weed seeds, and prepare the seedbed for sowing (Zarea 2010). In regions with lighter or more fragile soil, many farmers also use non-inversion tillage based on tine and disc implements (Dang et al. 2015b). In these situations, tines lift and shatter the soil, removing any shallow compacted layers, and discs cut and mix the stubble and any soil clods to leave a fine tilth.

However, since the 1960s and 1970s, concerns regarding the fuel costs and soil degradation associated with tillage operations have prompted many farmers worldwide to begin switching from traditional forms of tillage to no-tillage (NT). No-tillage is a system that avoids tillage of the soil and aims to retain crop residues at the soil surface so that at least 30% of the soil surface is covered by residue (Kassam et al. 2015). Herbicides are used to control weeds, and specialised equipment is used to sow the seed directly into untilled soil (Kassam et al. 2015; Lyon et al. 2004). Since the 1990s the adoption of no-till has increased exponentially around the world, and a recent analysis estimated that conservation agriculture, which combines the practice of no-till with the diversification of crop rotations, including legumes, is practised on around 157 Mha of cropping land worldwide, with the USA, Brazil, Argentina, Canada, and Australia being the top five adopters (Kassam et al. 2015).

No-till has a number of advantages over traditional tillage. In particular, its ability to help control erosion, lower fuel costs, conserve soil moisture, and promote greater soil health is highly valued (Lyon et al. 2004; Verhulst et al. 2010; Zarea 2010). The increased soil cover, structural stability, and macroporosity associated with NT systems help to increase soil water infiltration, slow runoff, and consequently decrease rates of erosion and increase moisture storage in the soil profile (Lyon et al. 1998; Page et al. 2013b). Such improvements are particularly valued in rainfed semi-arid areas where soil moisture is typically the major limitation on crop yield. Greater soil organic carbon concentrations (Chan et al. 1992; Page et al. 2013b; Thomas et al. 2007), soil nutrient stores (Chan et al. 1992; González-Chávez et al. 2010; Redel et al. 2007), and biological diversity (González-Chávez et al. 2010; Wang et al. 2010) are also commonly observed in NT systems (relative to traditional tillage).

However, while NT can offer significant advantages for many cropping systems, a number of problems associated with its use have emerged. These largely centre around controlling weed and pest populations, the persistence of soil and stubble-borne diseases, the stratification of nutrients near the surface of the profile, and the development of soil structural issues, such as soil compaction (Dang et al. 2015b). Strategic tillage (ST), which is the practice of periodically cultivating no-till soils, has been proposed as a mechanism to deal with some of the disadvantages associated with the long-term absence of tillage. However, research into whether occasional ST will undo some or all of the benefits of long-term NT is in its infancy and our understanding of the pros and cons of this type of approach is incomplete. This chapter will review current information regarding the problems associated with NT that may benefit from using occasional ST and the impact of using ST within an otherwise NT system.

2.2 Drivers for Occasional Strategic Tillage

2.2.1 Soil- and Stubble-Borne Pathogens

The increased retention of residues in NT systems can provide some pathogens with a refuge in which to survive between harvest and planting while host plants are absent (Bockus and Shroyer 1998; Roper and Gupta 1995). In traditional tillage systems, the burial and subsequent decomposition of this residue tends to lead to the death of residue-borne pathogens (Bockus and Shroyer 1998). The reduced soil disturbance, increased soil moisture, and lowering of soil temperatures in NT systems can also create a more favourable soil environment for many plant pathogens and encourage disease persistence (Bockus and Shroyer 1998; Cook and Haglund 1991; Wildermuth et al. 1997a). Pathogens commonly observed to increase under conservation tillage management include *Gaeumannomyces graminis* var. *tritici* (take all) (Pankhurst et al. 1995a; Roget et al. 1996), *Fusarium pseudograminearum* (head blight, scab or crown rot) (Wildermuth et al. 1997a; Wildermuth et al. 1997b), *Pyrenophora tritici-repentis* (tan or yellow spot) (Bockus and Shroyer 1998; Marley and Littler 1989), *Pythium* spp. (pythium seed and root rot) (Pankhurst et al. 1995a), *Rhizoctonia solani* (rhizoctonia root rot, bare patch, purple patch) (Cook and Haglund 1991; Pankhurst et al. 1995a), and *Pratylenchus* spp. (root lesion nematode) (Pankhurst et al. 1995b; Pankhurst et al. 1995c; Rahman et al. 2007; Thompson et al. 2008).

2.2.2 Insect Pests

Soil-associated insect pests, particularly those with below ground pupal stages, can also be favoured by NT management. For example, the larval stages of species such as *Helicoverpa armigera* can cause crop losses in most crops, while others such as *Helicoverpa punctigera* can attack species such as cotton, chickpea, and most summer legumes (Wildermuth et al. 1997b; Wilson et al. 2013). The pupae of *Helicoverpa* carry over in soil during the fallow period and continuous NT favours a build-up in its population. *Helicoverpa* has become a major constraint to cotton production globally, especially in NT systems (Mensah et al. 2013; Wilson et al. 2013). The key to successfully managing pests in NT cropping systems involves integrated pest management, in which chemical, cultural, and genetic methods of pest control are deployed strategically while encouraging biological control agents that occur naturally in the agro-ecosystem. The use of tillage is currently recommended as one of the control measures for pests that have a soil-inhabiting stage, particularly *Helicoverpa*, and this can be a clear impediment to the adoption of NT in some industries (Downes et al. 2012).

2.2.3 Herbicide-Resistant Weeds

Tillage helps to control weed populations by physically destroying weed plants and burying seeds to prevent them from germinating (Chauhan et al. 2012; Heenan et al. 1990; Zarea 2010). Practices such as residue burning are also known to destroy weed seeds and decrease weed infestations (Heenan et al. 1990). Under NT, the absence of these practices can increase the population of some weed species (Buhler et al. 1994; Chauhan et al. 2012; Lyon et al. 1998). To counter this, a combination of herbicides, crop rotations, cover crops, and alterations to crop management practices (e.g. row spacings, seeding rates, crop planting times) can all be used to help the crop outcompete weed species (Page et al. 2013b) although the use of herbicides is generally the dominant strategy employed by growers in western agricultural systems.

The herbicide glyphosate [N-(phosphonomethyl) glycine] has played a particularly dominant role in controlling weeds during fallow periods and prior to crop sowing in NT systems. However, its extensive use over a number of decades and the reduction in use of other weed control measures had led to glyphosate resistance in some weed populations (Powles 2008; Powles and Preston 2006). Some common species known to be affected include annual rye grass (*Lolium rigidum*), barnyard grass (*Echinochloa colona*), liver seed grass (*Urochloa panicoides*), windmill grass (*Chloris truncata*), and fleabane (*Conyza bonariensis*) (Dang et al. 2015b). A range of other weed species have also developed resistance to several selective postemergent herbicides such as chlorsulfuron ((2-chloro-N [(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino] carbonyl benzenesulfonamide)), atrazine [6-chloro-N-ethyl-N0-(1- methylethyl)-1,3,5-triazine-2,4-diamine], and clodinafop-propargyl (Dang et al. 2015b).

The increasing emergence of herbicide resistance represents a serious threat to NT management that requires integrated weed management in order to address this threat to crop production. This is an approach that incorporates as wide a range of weed control measures as possible to reduce weed populations by managing the weed seed bank (Powles and Preston 2006). This involves maximising the control of emerged weeds and minimising seed production from survivors to gradually reduce the prevalence of weeds over time (Chauhan et al. 2012). As tillage is an effective strategy for the control of weeds, occasional ST integrated into NT systems may be part of the group of strategies available to growers to help control weeds. For example, one study showed a 61–80% reduction in the emergence of small seeded species such as fleabane when using ST strategies (McLean et al. 2012).

2.2.4 Stratification of Nutrients and Carbon

In NT systems, the plant uptake of nutrients from the subsoil followed by the return of plant residues to the soil surface can lead to the stratification at the soil surface of immobile nutrients, such as P and K (Deubel et al. 2011; Vu et al. 2009), and soil organic carbon (Dalal et al. 2011; Jones et al. 1994; Page et al. 2013a). The shallow application of nutrients via fertiliser also accentuates this stratification (Costa et al. 2010; Lupwayi et al. 2006). This stratification can be a problem, particularly in regions with high temperatures and high evaporative demand, as plant nutrient extraction will be reduced from surface soil when it dries. This then drives the extraction of nutrients from the subsoil, leading to further depletion of nutrients from these deeper soil layers (Bell et al. 2012; Singh et al. 2005). To address nutrient stratification, the only practical solution is to use ST to place fertiliser nutrients deeper in the profile although the depth to which fertilisers can be placed using current technology is generally limited to the top 0.3 m of the soil profile (Bell et al. 2012; Ma et al. 2009).

2.2.5 Soil Structural Issues

No-till systems can lead to increases in bulk density in the plough layer when compared with conventionally tilled sites, especially in sandy and silty loam soils (Gregorich et al. 1993; Li et al. 2007; Mielke et al. 1986; Moreno et al. 1997). This is generally attributed to reduced soil disturbance, subsequent soil settling, and the repeated trafficking of the soil by agricultural machinery (Gregorich et al. 1993; Larney and Kladivko 1989). In some instances, the increase in bulk density can be sufficient to affect root growth due to increases in soil strength (Braim et al. 1992), and it can also decrease total porosity, air permeability, and air-filled pores (Linn and Doran 1984; Mielke et al. 1986). Where high bulk density is limiting crop growth and yield, tillage can be an effective strategy to alleviate surface and subsoil compaction (Batey 2009; Hamza and Anderson 2005; Tullberg 2010), particularly when vehicle traffic has not been confined to defined traffic areas (i.e. controlled traffic).

In hard-setting sodic soil, the development of surface crusting can also be an issue where NT management is practised due to its ability to reduce infiltration rates from rainfall events (Silburn and Connolly 1995). Many NT systems can reduce the impact of sodicity due to the increases in soil organic carbon and increases in soil aggregate stability observed at the surface of the profile (Chan et al. 2002; Chan and Mead 1988; Hajabbasi and Hemmat 2000; Li et al. 2007). However, in environments where the quantities of crop residue produced are low and it is difficult to accumulate sufficient organic carbon to significantly impact on aggregate stability, no improvements in aggregate stability may be observed (Carter and Mele 1992; Frey et al. 1999). In such soils, occasional ST to increase surface roughness and break apart the soil crust may be required (Hatfield et al. 2001).

2.3 Effects of Occasional Strategic Tillage on Soil Properties, the Environment, and Crop Agronomy

Due to the increasing management issues surrounding the use of long-term NT, there is an increasing perception among some growers that strict NT is unsustainable in the long term (Argent et al. 2013), and many are shifting towards a more flexible approach to tillage that includes some soil disturbance (Kirkegaard et al. 2014). However, growers who practise strict NT systems are concerned that even one-time tillage operation may undo much of the positive effect of NT farming systems on soil conditions, and those promoting ideas of strictly no soil disturbance predict irreparable damage to soil from occasional ST (Grandy et al. 2006). Clearly, the use of any tillage operations in NT farming systems must consider the balance between erosion and soil degradation impacts from tillage against the potential benefits associated with improvements in weed, pest, and disease control and the remediation of soil compaction and nutrient stratification.

2.3.1 Soil Hydraulic Properties and Processes

The impact of tillage on soil water infiltration and storage can have important implications for crop production and the broader environment. Water storage and water supply is one of the major factors limiting dryland crop production, particularly in semi-arid regions, and thus any practice that changes the soil hydrology could potentially influence crop yield. The introduction of tillage in a NT farming system could potentially influence evaporation of water from the soil surface, infiltration rates, and hydraulic conductivity because of the changes in physical properties of the soil. The impact of tillage on soil runoff and erosion can also have significant impacts, both on the soil locally and on surrounding waterways.

Evaporation is a major component of the water loss from soil, and losses can increase when soil structure is modified by tillage. Tillage has been shown to increase short-term evaporation by as much as 20–30 mm as it moves moist soil to the surface where it is exposed to greater drying (Hatfield et al. 2001). Evaporation mainly occurs from the top 0.1–0.15 m of the disturbed layer, with the overall amount dependent on climatic conditions, the depth of the tilled layer, the time and nature of tillage, the nature of tillage-induced surface structure, and the pore geometry of tilled layer (Jalota and Prihar 1990). No-till systems generally experience reduced evaporation compared to CT, with one study reporting that total soil water fluxes were 10–12 mm for a 3-day period following each cultivation operation, while the total evaporation fluxes from NT fields were <2 mm over the same period (Hatfield et al. 2001). During the use of occasional ST especially closer to the sowing period, this increase in evaporation could have significant impacts on sowing opportunities and/or the germination and establishment of crops.

Soil physical characteristics, such as bulk density, macroporosity, hydraulic conductivity, and soil aggregation, all have an important impact on the infiltration of water into the soil profile, and modifications to these by tillage also have the potential to impact soil hydrological processes. The effects reported of occasional ST on soil bulk density have been variable (Table 2.1). For example, one study reported increased soil bulk density 5 years after a one-time tillage had been conducted on a fine silty soil that had been under continuous NT for more than 20 years (Kettler et al. 2000). Other studies have reported reduced soil bulk density and increased total porosity 1 year after mouldboard tillage on a fine loamy soil, with no effects detected after 4 years (Pierce et al. 1994). Dang et al. (2018) also reported that soil bulk density in the top 0.1 m soil depth was quite variable and not significantly affected by tillage 3 months after a one-time tillage on a range of Vertisols, Solonetz, and Calcisol although it was trending lower after 24 months.

Occasional ST also has the potential to alter soil aggregation, which is important for maintaining good soil structure and water infiltration. Tillage is known to cause a breakdown of soil aggregates (Six et al. 2004) and fragment roots and mycorrhizal hyphae, which are major binding agents for macroaggregates (Bronick and Lal 2005). Tillage also exposes a greater portion of the soil to the freeze–thaw and wet–dry cycles which promote the breakdown of macroaggregates (Six et al. 2004). However, studies conducted to date indicate that although in some cases reduced aggregation and loss of particulate organic carbon (>53 μm) have been reported following occasional ST (Dang et al. 2018; Grandy et al. 2006), the majority of studies have observed either little or no impact (Dang et al. 2014; Dang et al. 2018; Kettler et al. 2000; Pierce et al. 1994; Quincke et al. 2007b; Wortmann et al. 2010) (Table 2.1).

Disturbance of soil in continuous NT systems by ST would be expected to result in a loosening of soil and potentially an increase in macroporosity and hydraulic conductivity of the tilled zone. However, again studies have reported variable effects following ST, and due to high spatial and temporal variability, hydraulic properties are often poor indicators of response to management systems (Vogeler et al. 2009). For example, Pierce et al. (1994) reported increased macroporosity in the surface soil (>24 mm pore radii) in the year after mouldboard tillage of NT fine-loamy soil compared to non-tilled NT, whereas Kettler et al. (2000) reported no difference in the pore-size distribution between continuous NT soil and one receiving a one-time mouldboard tillage operation (Table 2.1). On the other hand, Díaz-Zorita et al. (2004) reported a reduced number of mesopores in one-time tilled NT soil compared to NT soil. Similarly, Quincke et al. (2007b) reported that one-time tillage on silty clay loam increased the water infiltration rate and reduced soil water sorptivity, whereas on a fine silty soil, both infiltration rate and sorptivity were reduced. Dang et al. (2018) reported that in 2 Solonetz and 2 Calcisol, soil infiltration rates decreased following ST but remained unchanged on 10 Vertisols (Dang et al. 2018). The impact of ST on deep drainage has not been documented and may not be apparent in the short term (Kay and VandenBygaart 2002). Tillage may

Table 2.1 Impacts of implementing occasional strategic tillage on productivity and soil quality attributes in long-term NT systems

Soil type and soil texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
Vertisol (v) (10) Solonetz (s) (2) Calcisol (d) (2)	Chisel, narrow chisel, disc, offset disc, prickle chain, Kelly chain, tyne, scarifier	Various over 14 properties	Grain yield, profitability, CO_2, CH_4 (v/s), runoff (d), erosion (s), weeds (s) BD, SOC, POC, P, TMA (d/s), runoff (v), erosion (v/d), N_2O BD (s), SW, POC, TMA (v), infiltration (s/d), weeds (v,d)	↑ NS ↓	Monitored over 3 years	Dang et al. (2018)
Solonetz	Chisel	Weed control	MBC/N, TMA, CLPP	NS	1 year after tillage	Liu et al. (2016b)
Calcisol	Chisel Offset disc	Weed control	MBC, TMA, catabolic activity	↑	13 months after tillage. Greater effects in chisel compared to offset disc	Liu et al. (2016c)
Vertisol	Chisel, disc	Weed control	Grain yield, SW, pH, BD, EC, P, SOC, MBC, metabolic activity	NS	4–7 weeks after tillage	Liu et al. (2016a)
Vertisol, Solonetz, Calcisol	Cultivator, Kelly prickle harrow	Weed control, pests	Runoff (s/d), erosion (s), CO_2 (s) Runoff (v), erosion (v/d), N_2O, CO_2 (v) CH_4 oxidation (s)	↑ NS ↓	Several months after 3 ST operations	Melland et al. (2017)
Vertisol	Chisel plough, offset disc	Weed control	MBC, enzyme activity, CLPP	NS	2–17 weeks after tillage	Rincon-Florez et al. (2016)

Vertisol	Chisel	Unspecified	Enzymatic activity, metabolic diversity, CLPP	NS	15 weeks after tillage	Rincon-Florez et al. (2016)
Vertisols Aridisol	Chisel and blade (every year)	Weeds control	Grain yield SOC (0–0.2 m), weed population	NS ↓	22 crops average After 9 years	Radford and Thornton (2011)
Vertisols (3) Solonetz Calcisol	Chisel or offset disc or chain harrows	Weed control	Grain yield SOC, P, BD, POC, SW, FDA (0–0.1 m) Weed population	NS NS ↓	1st and 2nd crop After 3 months In-crop	Crawford et al. (2014)
Silt loam	MT or sweep (three occasions)	Weed control	Grain yield SOC, TN (0–0.075 m) pH, BD (0–0.075 m) Macroporosity	↑ ↓ ↑ NS	1st and 3rd crop After 5 years After 5 years	Kettler et al. (2000)
Silt loam	Chisel and disc	Soil compaction	Grain yield Grain yield SOC, TN, P (0–0.1 m) SW, SA, SHC (0–0.1 m) Macroporosity	↑ ↓ NS ↓ ↓	1st crop 2nd and 3rd crop After 8 or 20 months	Díaz-Zorita et al. (2004)
Silty clay loam (2)	Chisel or Disc or MT	Nutrient stratification	Grain yield Grain yield P runoff (0–0.025 m) SOC, POC (0–0.025 m) SOC, POC (0.05–0.1 m) Yield, SA, SOC, P, VAM	NS ↑ ↓ (MT) ↓ ↑ NS	1st crop 2nd crop After 2 years After 2 years After 2 years After 5 years	Quincke et al. (2007b) Quincke et al. (2007a) Wortmann et al. (2010)

(continued)

Table 2.1 (continued)

Soil type and soil texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
Chernozem fine-loam (3)	Cultivator once or Cultivator twice or Cultivator twice, disc	Weed control Nutrient stratification	Grain yield SOC, POC, pH, SA (0–0.1 m BD (0.05–0.1 m)	NS NS ↓	1st, 2nd, 3rd crops After 2 months	Baan et al. (2009)
Eutric leptosol (silty loam)	MT and disc	Soil compaction	Grain yield Grain yield SOC, AC, β-glu (0–0.05 m)	NS ↓ ↓	1st and 2nd crop 3rd crop After 1 year	López-Garrido et al. (2011)
Silt clay loam (2)	Chisel or disc or MT	Nutrient stratification	P, K, VAM (0–0.025 m) P, K, VAM (0.025–0.1 m)	↓ (MT) ↑ (MT)	After 1 year After 1 year	Garcia et al. (2007)

Numbers in parenthesis are the number of sites; *MT* mouldboard tillage, *SOC* soil organic carbon stocks, *POC* particulate organic carbon (53–250 μm), *P* extractable phosphorus, *K* extractable potassium, *TN* total nitrogen, *SW* soil water, *SHC* saturated hydraulic conductivity, *BD* bulk density, *AC* active carbon by $KMnO_4$ oxidation, *VAM* vesicular-arbuscular mycorrhizae, *SA* soil aggregates, *β-glu* β-glucosidase activity, *v* Vertisol, *s* Solonetz, *d* Calcisol, ↓ or ↑ indicates significant decrease or increase, respectively, at $p < 0.05$; *NS* nonsignificant temporally contribute to increased hydraulic conductivity (Warnemuende et al. 2007), but this may only lead to increased deep drainage if that same tillage operation and any loss of surface cover do not result in increased surface crusting and runoff.

2.3.2 Soil Chemical Properties and Processes

2.3.2.1 Soil Organic Carbon and Nitrogen

One of the major concerns regarding the introduction of ST into long-term NT systems is the effect that it will have on SOC. Long-term tillage is known to result in a decline of SOC due to its ability to fragment macroaggregates, thereby improving microbial access to aggregate-protected soil C (Six et al. 2004) and/or stimulating decomposition of soil C (Fontaine et al. 2007). Thus, occasional ST has the potential to lead to SOC loses, particularly of more labile fractions, such as particulate organic matter (POM) (Gajda 2010). However, a review of the studies that have examined the effect of one-time ST on SOC does not find any consistent effects, and while some studies report significant loss of SOC (Stockfisch et al. 1999; VandenBygaart and Kay 2004), others find there is no change (Dang et al. 2018; Quincke et al. 2007a; VandenBygaart and Kay 2004) (Table 2.1). In addition, it should be noted that the study by Stockfisch et al. (1999) used a fixed soil depth and bulk densities collected before tillage to calculate SOC stocks in different treatments. This approach may have resulted in lower estimates of SOC stocks following tillage (and increased estimates of C loss) than if an equivalent mass method had been used. Overall, it is likely that any net changes in SOC at a site will be determined by the organic matter input of the land use and the degree of organic carbon protection by soil clay minerals.

While differences in the effect of total SOC stocks following occasional ST may be observed, there is more consistency regarding its effect on the distribution of soil C throughout the profile. Stratification of SOC stocks in the surface of the profile is often observed under long-term NT, and studies that have examined the effect of ST generally report a redistribution of SOC from the topsoil layers to throughout the tillage zone (Kettler et al. 2000; Pierce et al. 1994; Quincke et al. 2007a) (Table 2.1).

The effects of tillage on total N generally mirror those reported for total SOC. Tillage increases aggregate disruption, making SOM more accessible to soil microorganisms (Six et al. 2004), and increases mineral N release from soil N pools (Kristensen et al. 2000). However, the effect of tillage on N mineralisation has been found to be moderately short-lived with differences only noticeable for a few weeks (Silgram and Shepherd 1999). Following ST, while some studies have reported lower total N stocks in the surface of the profile (<0.1 m) (Kettler et al. 2000; Pierce et al. 1994), generally no differences are reported below this depth (Kettler et al. 2000, Pierce et al. 1994) or over the entire tillage zone (Díaz-Zorita et al. 2004; Kettler et al. 2000) (Table 2.1).

2.3.2.2 Nutrient Stratification

The effect of occasional ST on nutrient stratification has largely been found to depend on the type of tillage conducted. For example, Garcia et al. (2007) reported greater redistribution of nutrients and incorporation of compost P following mouldboard tillage compared to less aggressive tillage treatments, such as one-time chisel or disc tillage (Table 2.1). Pierce et al. (1994) reported one-time mouldboard tillage redistributed P in the 0–0.1 m layer through the top 0.2 m, but tillage did not eliminate stratification of P in the top 0.05 m soil.

Where NT has resulted in lowered pH at the surface of the profile, occasional ST has the potential to raise pH at the surface by redistributing hydrogen ions more evenly throughout the tillage zone. This has been observed, with one study reporting significant redistribution of soil acidity in NT soil following a one-time mouldboard tillage, and tillage was most effective if followed by chisel and disc ploughing (Garcia et al. 2007). However, it should be noted that Baan et al. (2009) and Díaz-Zorita et al. (2004) did not find significant differences in soil pH between NT soil and one-time tillage soil (Table 2.1).

2.3.3 Soil Fauna and Flora

The introduction of occasional ST into NT systems has the potential to affect soil fauna and flora populations due to the changes that tillage has on the soil physical and chemical environment. Tillage influences different microbial species in different ways, depending upon species' survival strategies and life cycles. The compilation of results from 106 studies that examined the impact of tillage on soil organisms found that although there was a wide range of responses between different species, most organism groups had greater abundance or higher soil microbial biomass (SMB, defined as mass of living microbial tissues) in NT soil than in CT soil (Wardle 1995). In a similar review of 45 studies, it was observed that as tillage was reduced, populations of 28% of microbial species increased, 29% showed no significant change, and 43% reduced (Stinner and House 1990).

While the effect of NT compared to CT on soil flora and fauna populations is relatively well researched, the impact of occasional ST within an overall NT system is less well understood. Wortmann et al. (2008) reported that one-time tillage in an NT system reduced the depth stratification of SMB without reducing the total biomass in the top 0–0.3 m soil depth (Table 2.1). The effects were greatest with mouldboard tillage, followed by less disruptive tillage operations. Mycorrhizae were found to be more sensitive to tillage events, and the quantity of arbuscular mycorrhizal (AM) biomarkers in the second year after tillage was 22% less for tilled treatments compared to NT. Similar reduction in AM caused by one-time mouldboard tillage in western Nebraska, USA, were found to persist for 5 years (Drijber et al. 2000). The reduced AM density with tillage may be partly due to disruption of the hyphal network and root channels that developed under NT (Garcia et al. 2007). Other studies have reported no differences in SMB, total microbial activity, and microbial community structure 1–3 months (Rincon-Florez et al. 2016) and 12 months (Liu et al. 2016b) after a one-time chisel tillage operation on a Vertisol and Solonetz soil that had been under long-term NT although total microbial activity did decrease after 12 months in the Vertisol (Dang et al. 2018). Similarly, slight increases in MBC and microbial diversity were observed 13 months after tillage in a Calcisol (Liu et al. 2016c).

There have been very few studies to examine the effect of occasional ST on soil fauna populations. However, in general, it is known that changes to mesofauna (0.2–2 mm) populations (which consist mainly of springtails and mites) are caused by physical disturbance of soil. Springtails are usually inhibited by tillage disturbance; however, mites exhibit a wider range and more extreme response to tillage, with extreme increases or decreases having been found (Wardle 1995). The other main group within the mesofauna are the enchytraeids, which may also be both inhibited or stimulated by tillage (Cochran et al. 1994; Wardle 1995).

Large organisms are generally more sensitive to tillage than smaller organisms due to their longer life cycles and greater sensitivity to the habitat disruption that comes with the physical disruption of the soil during tillage (Wardle 1995). Obvious examples would include earthworms and termites, which are the most significant components in many soils, affecting soil properties and processes through their feeding, casting, and burrowing/tunnelling activities (Kladivko 2001). Earthworm populations are adversely affected by cultivation and can increase markedly under NT (Robertson et al. 1994). However, the specific impact that occasional ST will have on soil fauna populations is currently under-researched.

2.3.4 Crop Productivity and Reliability

While there is some variability in the results reported, studies conducted in the USA, Europe, and Australia generally suggest that occasional ST tends to either have no effect on or improve productivity and profitability in the short term, while in the long term, the impact is either negligible or negative (Baan et al. 2009; Crawford et al. 2014; Dang et al. 2018; Díaz-Zorita et al. 2004; Kettler et al. 2000; Liu et al. 2016a; López-Garrido et al. 2011; Quincke et al. 2007a; Quincke et al. 2007b; Radford and Thornton 2011) (Table 2.1). Instances where it has been effective in increasing productivity include those where it has overcome nutrient and C stratification (Ma et al. 2009; Quincke et al. 2007a), assisted in managing herbicide-resistant weeds (Kettler et al. 2000), and helped alleviate compaction (Díaz-Zorita et al. 2004).

2.3.5 Crop Reliability in Variable Seasons

No-till systems usually have a much wider window of opportunity for sowing than CT systems because the soil is usually trafficable a few days earlier as well as retaining enough water to sow a crop for a longer period, especially on Vertisols (shrink-swell clay soils) of semi-arid tropical and subtropical environments

(Freebairn et al. 1997). If the introduction of occasional ST in NT results in loss of water from the tilled layer, it will decrease sowing opportunities, particularly in variable seasons. The climatic conditions throughout the season will influence soil water, aeration, and temperature and thus will have a marked influence on crop responses and yields in different seasons to ST; however, no specific studies have been done to specifically assess the pros and cons of ST from a crop reliability perspective.

2.3.6 Environmental Effects

2.3.6.1 Erosion and Runoff

One of the main reasons for the adoption of NT farming system has been to combat erosion and runoff, and introducing ST has the potential to undo some of the benefits around erosion and runoff control. However, studies examining the effect of ST on erosion and runoff have reported variable results (Table 2.1).

For example, in the first year after tilling a long-term NT silty loam soil, Smith et al. (2007) reported significantly higher runoff volumes and rates from tilled plots as compared to long-term NT plots. However, there were only small differences in saturated conductivity (Ksat) values for both the 0–0.15 and 0–0.60 m depths, with Ksat values being slightly higher for the NT field than tilled field. Warnemuende et al. (2007) also reported a significant impact of tillage on the rate of runoff in the first year post-tillage on a long-term NT clay loam, with NT treatments having approximately 50% lower runoff. This was due to differences in mean Ksat, which ranged from 0.07 to 1.61 cm/h for NT and from 0.52 to 2.30 cm/h for tilled soil. However, Quincke et al. (2007b) did not observe significant differences in runoff volume between NT and one-time tillage of NT soils after the second and third crops of sorghum. Melland et al. (2017) reported that in 2 Solonetz and 2 Calcisol soils, infiltration rates decreased following ST and that in the Solonetz this leads to an increase in runoff and erosion. However, in 10 Vertisols, ST had no effect on either infiltration or runoff and erosion.

2.3.6.2 Greenhouse Gas Fluxes

Fluxes of nitrous oxide (N2O), carbon dioxide (CO2) and methane (CH4) between agricultural soils and the atmosphere substantially affect the global GHG inventory, and tillage can influence this GHG production in several ways. For N_2O, the effect of tillage systems depends on climatic conditions, soil properties, and fallow management (Dalal et al. 2003; Stehfest and Bouwman 2006). On poorly drained soils, higher water content and reduced aeration under NT soil generally leads to greater denitrification and emission of N2O than under CT (Regina and Alakukku 2010). For generally well-aerated soils, the impact of NT on N2O emission is often small (Dang et al. 2018; Rochette 2008) although one study did report lower N2O emissions from NT than CT (Wang et al. 2011). In this study higher N2O emission for CT was attributed to mechanical disruption of soil structure, reduced percolation, and poor aeration, thus resulting in enhanced denitrification and N2O production.

While there are no reports concerning the impact of one-time tillage on N2O emissions, any effect is likely to be site-specific and vary with climatic conditions.

Differences in CO2 emissions following tillage are likely to result from both short-term and long-term effects. Short-term effects occur due to the physical soil disturbance and aggregate disruption occurring during tillage, while long-term effects occur due to the changes in physical, chemical, and biological soil properties after several years of tillage (Oorts et al. 2007). Immediately following tillage, large amounts of CO_2 are lost from the soil (Reicosky et al. 2005), with some of this initial flush generally attributed to emission of CO2 from the soil atmosphere and the remainder to increased microbial respiration due to the greater microbial access to labile SOC and increased aeration following the disruption of aggregates during tillage. In accordance with this, studies examining ST events have reported an immediate increase in CO2 flux from soil following tillage (Dang et al. 2018; López-Garrido et al. 2011; Quincke et al. 2007a). However, one study observed that this flux was found to be small if tillage was undertaken when the soil temperature was low for several weeks following the tillage (Quincke et al. 2007a). Most studies have only measured short-term CO2 emissions following one-time tillage in NT, and the longer-term effects are currently unknown.

Emissions of CH_4 from aerobic soils are generally very small and are not affected by tillage regime (Regina and Alakukku 2010; Wang et al. 2011). Bacteria and archaea responsible for oxidising CH_4 in the aerobic surface layer of soils are sensitive to disturbance, and NT may thus be beneficial to the capacity of soils to oxidise CH_4 (Hütsch 2001). However, there is an inconsistent effect of tillage on CH_4 emissions depending on soil conditions (Regina and Alakukku 2010), with emissions either unchanged (Wang et al. 2011), increased (Ball et al. 1999), or reduced (Alluvione et al. 2009) under NT compared to under CT. There have been very few studies to examine the effect of ST on CH_4 emission although Dang et al. (2018) did observe that in a Vertisol and Solonetz soil the capacity of NT treatments to absorb CH_4 was three to four times greater than soils where ST had been conducted.

2.3.6.3 Pollution of Water Courses

Eutrophication of water courses is a serious environmental problem and largely attributed to elevated concentrations of dissolved reactive P. Phosphorus transport in runoff and erosion of P-bearing sediment to surface water is related to surface soil extractable P concentration (Wortmann and Walters 2006). Although NT can greatly reduce runoff and erosion, a stratified P-enriched surface layer developed under NT soils can increase risk of loss of P in runoff (Ulén et al. 2010), and some studies have reported the loss of dissolved reactive P from NT soil to be 348% higher than from tilled soil (Puustinen et al. 2005). Occasional ST tillage can reduce the risk of P loss to waterways. For example, the concentration of P in runoff has been reported to reduce by a factor of 6 in tilled soil compared to long-term NT (Smith et al. 2007), with Quincke et al. (2007b) reporting that the concentration of dissolved reactive P in runoff was more effectively reduced by mouldboard tillage compared to disc tillage. The benefit of tillage has been attributed a dilution of high P surface soil and increased P sorption by subsoil (Sharpley 2003).

Nitrogen can be transported from soil to water courses as N attached to soil particles in runoff, or via leaching, primarily as nitrate (NO3) but also as ammonium (NH4) and organically bound N. However, currently there is a lack of consensus in the literature on the effect of tillage regime on both NO3 leaching and N in runoff. Leaching of NO3 has been shown to be greater from NT than CT soil (Turpin et al. 1998); however, these results are not consistent in all studies (Stoddard et al. 2005). Fertilizer N has also been shown to be lost at greater rates in runoff from NT than CT (Kleinman et al. 2011; Smith et al. 2007) although again results are not consistent, with some studies reporting that NT can reduce N losses in runoff (Torbert et al. 1996). The variability in results observed is due to differences between soil types, agronomic management, and climatic conditions (Power et al. 2001), and the effect of ST on N loss is thus also likely to be dependent on these factors.

2.4 Strategic Tillage within the NT Management System: Where, When, and How?

Clearly the reintroduction of some tillage could potentially be used to help alleviate some of the problems associated with the lack of soil disturbance in NT systems. However, determining when some form of tillage is the most effective management option, the appropriate timing for tillage operations (e.g. following harvest or preceding sowing), the type of tillage that should be used (shallow or deep, inverted or not), and the frequency of tillage operations are all key factors that need to be considered.

2.4.1 Timing of Tillage Operations

In many regions, when ST is conducted will have a critical impact on its effectiveness. For example, in regions where cropping is reliant on stored soil water accumulated over a fallow period, the impact that tillage has on soil water can significantly affect the subsequent crop. If tillage is conducted at the end of the fallow, close to sowing, the loss of soil water in the seeding zone may result in a loss of planting opportunities or poor crop establishment (Dang et al. 2015b). However, if tillage is conducted immediately after harvest, it may lead to a loss of soil cover due to the incorporation and accelerated decomposition of crop residue, which can decrease soil profile recharge and increase the risk of soil erosion (Freebairn et al. 1991).

The decisions around timing are thus complex and will require consideration of factors such as soil water content, the purpose for which tillage is occurring (e.g. to accelerate stubble decomposition for the purposes of disease control or to deal with late emerging weeds), and expected climatic conditions (Dang et al. 2015b). The use of historical records and/or rainfall forecasts can be particularly helpful in making decisions around the timing of tillage operations. For example, one study demonstrated that there was a 40–55% chance that soil water lost from the seed zone of a clay soil following ST would be replenished before sowing if tillage was conducted between March and May (Dang et al. 2014). However, this increased to 90–95% if tillage was conducted between January and May, indicating that tillage earlier in the fallow period was more likely to lead to successful crop establishment (Dang et al. 2014).

2.4.2 Soil Water Content

From a tillage perspective, optimum soil water can be defined as the water content at which tillage produces the best aggregate distribution. Tillage performed at higher than the optimum soil water contents produces large clods resulting in soil structural damage, while tillage performed at lower than the optimum soil water contents requires excessive energy and can also produce large clods (Dexter and Bird 2001). In the case of subsoil tillage to remove compacted layers or nutrient stratification, water content will affect the ability of tillage to fracture compacted layers or inject nutrients at an appropriate depth. To loosen compacted layers, the water content should be such that the soil is sufficiently fragile to shatter as the loosening tine passes through, or just below, the compact layer (Batey 2009).

2.4.3 Purpose of Tillage

One of the main drivers determining how and when tillage should be conducted will be the purpose for which the tillage is being used. For disease and pest management, the aim of tillage is to reduce the contact of the following crop with carry-over inoculum or pest populations. In the case of stubble-borne diseases, this means that the aim of tillage should be to either incorporate or bury stubble relatively soon after harvest to allow improved access to, and faster decomposition of, stubble-harbouring pathogens by soil biota. Removing the inoculum from the soil surface by burial can also eliminate the possibility of it reaching new crops via raindrop splash or wind dispersal (Summerell and Burgess 1988; Wildermuth et al. 1997a). Tillage early in the fallow may also reduce nematode populations through exposure of the topsoil to heating and drying out (Thomas et al. 1997), with more frequent tillage shown to reduce parasitic nematodes down the profile to at least 0.45 m (Haak et al. 1993). Similarly, postharvest tillage to reduce the overwintering stage of insect pests, such as *Helicoverpa* spp., is also an extremely effective control measure, with tillage to a depth of at least 0.1 m capable of damaging or disturbing pupae, sealing their entrance tunnels and trapping emerging adults. Tillage also exposes survivors to attack by birds, mice, earwigs, and wasp parasites (Mensah et al. 2013; Wilson et al. 2013).

When conducting tillage for weed management, the exact timing and nature of the tillage will depend on the desired outcomes. For a salvage situation where tillage is being used to control emerged weeds, it is important to implement the tillage prior to flowering and under conditions to achieve maximum weed mortality. However, when using tillage strategically to reduce the weed seed bank, the window for implementation can be any time after weed seed fall and before the following seed-germinating rainfall (Medd 1999).

Where tillage combined with the deep placement of nutrients is being used to address nutrient stratification issues, timing is primarily influenced by the residual value of those nutrients in the soil after fertiliser application. In high P-fixing soils, for example, deep placement of P fertilizer early in the fallow may be less effective due to sorption reactions rendering increasing proportions of that P unavailable for crop uptake although the significance of these reactions can be minimised by band application of P fertiliser. As a general principle, in soils where nutrient fixation or unavailability is an issue, deep fertiliser applications will be more effective close to the time of sowing to reduce time for fixation. However, such strategies are risky as tillage undertaken near the end of the fallow can result in excessive loss of soil water (Dang et al. 2014) or a poorly structured seedbed with suboptimal crop establishment (Deubel et al. 2011; Ma et al. 2009).

2.4.4 Tillage Implement and Frequency

A range of different tillage implements are available to farmers when conducting ST, and the type used and the frequency of its operation will be largely determined by the objective of the tillage operation (Table 2.2). In the case of weed control, for example, different tillage implements can alter the position of weed seeds in the soil profile, which may favour or impede seed germination and seedling emergence depending on the weed species involved. For example, inversion tillage buries surface weed seeds, which can impede their emergence, but can also bring buried seed to the soil surface, thus providing a more favourable environment for germination (Chauhan et al. 2012; McGillion and Storrie 2006).

The one-off implementation of a tillage operation that results in weed seed burial below emergence depths is potentially a very useful management tactic for herbicide-resistant weeds (McGillion and Storrie 2006) (Table 2.2) and has been effective in controlling species such as herbicide-resistant ryegrass (Newman 2011) and downy brome (*Bromus tectorum*) (Kettler et al. 2000). However, such aggressive tillage may excessively disturb soil in other situations, and in many regions with more fragile soils, the use of inversion tillage is uncommon. In contrast, implements that produce minimal soil inversion result in weed seeds remaining on or near the soil surface (Pratley 2000). A shallow tillage in the preceding fallow using such implements can be used to encourage weed seed germination so that the seedlings can be controlled shortly after with another shallow tillage or a nonselective herbicide prior to crop sowing (Pratley 2000). Studies have also observed significant reductions in weed species including turnip weed (*Rapistrum rugosum*), wild radish (*Raphanus raphanistrum*), wild oats (*Avena fatua*), fleabane (*Conyza bonariensis*), feathertop Rhodes grass (*Chloris virgata*), and windmill grass (*Chloris truncata*)

Table 2.2 Examples of the type of tillage implement and the timing of tillage used during occasional strategic tillage for the management of problems in long-term NT systems. (Reproduced from Dang et al. (2015b))

Purpose of tillage	Optimum tillage time	Tillage implement	References
Disease management Fungal disease Root-lesion nematode	Postharvest, early in fallow Postharvest, early in fallow	Disc or blade Disc for surface soil (0–0.1 m) Frequent tillage for subsoil (0.45 m)	Wildermuth et al. (1997a) Wildermuth et al. (1997b) Obanor et al. (2013) Thompson et al. (2010) Haak et al. (1993)
Pest management Winter crops Summer crops	Postharvest Postharvest, early in fallow	Light tillage, scarifier Chisel, disc to 0.1 m	Mensah et al. (2013)
Weed management In-crop Fallow	Prior to weed flowering Post seed fall, before germinating rains	Shallow tine Disc	Pratley (2000) McGillion and Storrie (2006)
Nutrient stratification Sodic soil Non-sodic soil	Postharvest, early in fallow Postharvest, early in fallow	Para plough Deep ripper tine	Dang et al. (2010) Bell et al. (2012)
Stubble management	Previous crop harvest Fallow for partial removal	Prickle chain, trash cutter Offset disc	Scott et al. (2010)
Soil physical constraints Surface soil Subsoil	Early in fallow Early in fallow	Cross tine Deep ripper tine	Spoor (2006) Hamza and Anderson (2005)

using tillage equipment such as harrow, gyral, chisel, and offset discs (Crawford et al. 2014; McLean et al. 2012).

When using tillage implements to address nutrient stratification issues by applying nutrients at depth, the deep placement of nutrients as much as 0.3 m below the seed has been achieved with tines at sowing (Jarvis and Bolland 1990) and to 0.15–0.2 m below the soil surface with a vertical coulter knife before sowing (Fernández and Schaefer 2012) although most examples have not been achieved in heavy clay soils. Para-tillage implements, straight-shanked deep ripper tines and knife openers have also been successfully used to apply fluid fertilizers throughout the profile to 0.4 m (Doudle and Wilhelm 2003). Use of para-tillage implements with non-inverting tines can also be effective and would be advantageous in the soils with subsoil sodicity (Dang et al. 2010) (Table 2.2).

When tillage or ripping is used to ameliorate soil structural issues, such as soil compaction, hard pans, and hard-setting soils, the type of tillage implement used will depend upon whether soil compaction is on or below the surface and its thickness, depth, and severity. A wide variety of soil-loosening implements with differences in tine shapes and arrangement have been successfully used and discussed in detail (Spoor 2006). Surface soil compaction can generally be ameliorated using cross tine tillage producing brittle-type loosening disturbance (Table 2.2). However, where compaction occurs below the surface, deep ripping is a common management technique to shatter dense subsurface soil horizons that limit percolation of water and penetration of roots (Spoor 2006).

2.5 Conclusions

It is clear that the introduction of occasional ST operations into NT farming systems could impact on agronomy, soil, and the environment (Fig. 2.1); however, the exact nature of this impact is likely to vary with soil type, climate, and soil and crop management. Overall, the introduction of occasional ST is likely to result in short-term decreases in soil water, which may result in unreliability of crop sowing in variable seasons. It is also likely to lead to short-term losses of SOC and may increase the possibility of erosion and runoff events. Soil fauna and flora, especially macrofauna, could also potentially be negatively affected in the short term.

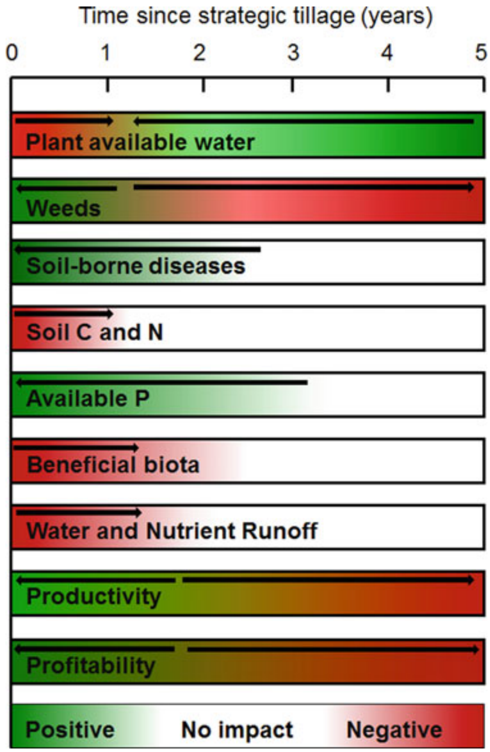

Fig. 2.1 Implications of occasional strategic tillage in otherwise no-till farming systems on agronomy, soil, and environment. Direction of arrows indicates positive (←) or negative impact (→). Length of arrow indicates time since introduction of strategic tillage. Red colour indicates negative impact; green colour indicates positive impact; and white colour indicates no impact. (Reproduced from Dang et al. (2015a))

However, if done appropriately, ST is likely to be able to alleviate problems associated with the stratification of SOC and plant nutrients; assist with the management of certain crop diseases, pests, and weeds; and help alleviate soil structural issues, such as compaction and surface crusting. However, it is important when making a decision to implement ST that full consideration is given to the most appropriate time to conduct tillage operations and the most appropriate tillage implements to use in order to minimise any negative effects of tillage and maximise its positive impact.

Further research is needed to help better understand and guide farmers on how to best use ST to their advantage on a range of soil types and cropping systems. In particular, it is currently difficult to determine how long a one-time ST operation would be effective in keeping otherwise NT fields below the economic thresholds of weed, disease, and insect populations. The challenge for ST operation in the NT systems is to maintain economic levels of production and at the same time reduce environmental damage such as soil erosion and water pollution. Future research needs revolve around the trade-offs between the effectiveness of tillage in overcoming specific constraints of the NT systems and the impacts of that tillage on crop frequency, soil quality, and the wider environment. It is likely that ST will provide farmers with an important tool for managing some of the constraints of long-term NT; however, it is a tool that needs to be used with caution to minimise its potential negative effects.

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No-till Farming: Agronomic Intervention through Cover Cropping for Enhancing Crop Productivity

3

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Abstract

Tillage disturbs the soil and causes soil erosion. Various conservation tillage mechanisms are undertaken to reduce erosion, and one such is no-till. No-till (NT) is the method by which crops are raised every year without disturbing the soil. The advent of machinery that helps drilling in either through crop residues or cover crop mulch has helped reduce soil erosion and increased the spread of NT farming. The impact of NT on increasing crop yields has been researched upon with varying results. The adoption incentive is always increased yield for the producer, and cover cropping is one major recommendation for yield improvements through NT. Cover crops can be grown as sole crop or a mixture to enable exploiting different layers of the soil, help fixing atmospheric nitrogen, improve soil nutrient status, improve soil porosity, and, above all, produce maximum biomass to help build the soil and prevent erosion. Cover crops as a feature in organic or conventional rotations must be thought as to why and where they fit into the rotation. Planting and termination dates have to be coordinated between the cover crop and chosen cash crop so that they do no overlap but have a wide enough growth window. It is important for the cover crop to produce maximum biomass, but the cash crop must also be planted at the right time for the critical yield to be maintained or improved. Research that is innovative and balances

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conservation of soil with increased crop yields should be the best serving option that needs to be developed, and it is fairly obvious to turn to cover cropping.

Keywords

No-till · Cover crops · Soil properties · Crop productivity

3.1 Introduction

Tillage, in simple terms, is the process of opening up the soil for planting of the crop, the first or in sequence, and is practiced on most agricultural lands around the world. However, tillage is a leading cause for erosion of farm soil as it destroys soil aggregates making soils more prone to erosion. There are many different tillage methods: conventional, conservation, ridge, strip, and vertical, with another option of no tillage at all. No till? What would that be, and why would that option be interesting to producers?

"No-till" is the method by which crops are raised each year without disturbing the soil at all. In other words, it can be described as a method whereby crops are cultivated without carrying out the plowing or tillage operations "considered necessary" for establishing a good crop stand and environment. The crop is sown by drilling either in to crop residues or in a cover crop mulch without opening the soil. It minimizes or reduces the soil disturbance, thereby drastically reducing soil erosion. It also reduces the release of carbon dioxide, a greenhouse gas into the atmosphere, which happens due to intensive tillage practices. Not breaking the soil leads to buildup of soil organic matter, improved water holding capacity, higher nutrient availability, and the release of nutrients for crop growth (Blanco-Canqui et al. 2015; Vincent-Caboud et al. 2017).

3.2 "No-till" as a Concept

How did this concept come to be? Since turning to agriculture, human history points to the plowing of the land for sowing and crop cultivation. The advent of machinery made it much easier to continue tilling the land (Margulies 2012). However, the loss of fertile soil from farm lands due to erosion, caused in part from the breaking of soil particles, and the eventual problems it created made people begin to take notice of the effects of tillage. Also, the arrival of herbicides for the control of weeds, which previously needed a turn of the soil for control, and the invention of seed drills which could plant the seeds without opening up the soil set the move towards no-till farming. With more machinery and advancement of technology to carry out specific farm practices, no-till seemed like a good option to harvest the abovementioned benefits and achieve environmental rehabilitation, provided there was no compromise on the crop yields recorded. Though the benefits of NT are many, producers farm for profit, and they must see an economic incentive to follow any practice that allows for environmental rehabilitation. Adoption of NT also brings about financial saving, along with saving in labor and fuel costs. A UNEP report (Neufeldt 2013) cited Lorenzatti (2006) in Argentina that while a liter of fuel could produce 50 kg of grain under conventional tillage, it would be 123 kg under no-till farming (from UNEP 2013). The benefits of no-till farming can build over years.

No-till (NT) farming is spreading around the world across diverse ecosystems and production systems. Adoption has been faster in the USA compared to other countries, and it has led to a drastic reduction in farmland erosion over decades. In 1962, Harry Young Jr. was recorded as the first farmer to grow corn without tillage in the USA (Coughenour and Chamala 2000). Between 1982 and 1997, overall cropland erosion dropped by more than a third in the USA, where policy interventions to promote NT practices on highly erodible land contributed up to 62% of the overall reductions, from 3.1 billion tonnes of soil in 1982 to 1.9 billion tonnes in 1997 (Claassen 2012). The share of total conservation tillage that is NT also varied from 67% (45% of total acreage) for wheat in 2017, 56% (40% of total acreage) for soybeans in 2012, 44% (18% of total acreage) for cotton in 2015, and 42% (27% of total acreage) for corn in 2016 (Claassen et al. 2018). Continuous NT has been adopted across 21% of all cultivated cropland acres in the USA (Creech 2017).

Neufeldt (2013) also reported that NT agriculture increased in Australia from 9% of cropland in 1990 to 74% in 2010. In the countries of Argentina, Brazil, Paraguay, and Uruguay, the highest rates of NT cultivation cover 70% of total cultivated area, two-thirds of which are under permanent NT schemes, resulting in significantly increased soil carbon storage (Derpsch et al. 2010). Conservation agriculture (CA) that comprises of no or minimum mechanical soil disturbance, biomass mulch soil cover, and crop species diversification was reported in 78 countries in 2015–2016, an increase in adoption by 42 more countries since 2008–2009, respectively (Kassam et al. 2018). Many other countries opt for no-till, but not under a permanent system which reduces the effectiveness and accrued benefits under no-till.

3.3 No-till and Adoption Incentives

No-till practices reverse the occurrences under tillage by minimizing mechanical soil disturbance, providing permanent soil cover, and diversifying crop species grown in sequence and/or association (FAO 2013). Keeping a residue on the soil surface breaks the impact of the raindrops and helps soil to stay in place and prevent erosion. To transition from conventional farming to NT, many a times, there is need for government intervention and support through policy changes. This transition is a costly process as there is a need to invest in heavy machinery/ equipment and also can create an overdependence on plant protection chemicals and herbicides. In the USA, many farmers are “partial” adopters, adopting these conservation practices in some but not all of their acres. Roughly 40% of combined acreage of corn, soybean, wheat, and cotton were in no-till/strip till in 2010–2011, with adoption rates higher for some crops (e.g., soybean) and some regions (USDA ERS 2017). Federal government subsidies toward adoption of such conservation practices give incentives for farmers to switch to these practices (Plumer 2013). Cropping system, rainfall intensity and frequency, slope, and the soil of the locality all decide the success of NT farming in minimizing soil loss by erosion. Montgomery (2007) (as reviewed by Margulies 2012) reviewed 39 studies comparing NT and conventional tillage (CT) practices on soil erosion, and found no-till practices to reduce soil erosion rates by up to 98%, including long-term experiments with NT corn plantings. Overall cropland erosion dropped in the USA by adoption of NT practices (Claassen 2012).

Other incentives towards adoption of no-till conservation practice would be enhanced crop yields (increased benefits realized above the cost savings), increased soil organic matter (SOM) and water retention. Production increases are not expected from area increases but from yield increases (Friedrich and Kassam 2016), and so it is important to achieve that from NT if we want to see greater adoption of NT.

Reduction in the short-term crop yield is one major barrier for farmers considering adoption of NT system. However, considering the ecosystem services of NT, maintaining crop yields at or above optimum production levels could also serve as an incentive. What are the interventions that could be carried out in a NT that would result in such production? Increasing the availability of nutrients that enable crop growth and improving the SOM could be a sure path to enhancing crop productivity through diversification of crops, adoption of crop rotations, and cover cropping. The other environmental benefits that accrue add up over time to increase crop yields in the future.

3.4 Crop Yields in Relation to no-till

Profit is probably the most important factor influencing the adoption behavior of farmers with respect to conservation agriculture practices such as NT, reduced tillage coupled with stubble retention (Cary and Wilkinson 1997). Farmers show greater interest in alternative production practices that show yield response. Many researchers have shown increase in crop yields with no-tillage, while few others have shown the converse to be true. Studies have shown that different crops respond differently to climatic and soil parameters in NT systems. Vyn and Raimbault (1993) indicated a yield decline of corn in NT after initial 8 years, while Beyaert et al. (2002) have reported a no effect on yield.

Pittelkow et al. (2014) observed that conservation agriculture (CA), in its approach to manage agro-ecosystems for improved and sustained productivity, represents a set of three crop management principles: (1) direct planting of crops with minimum soil disturbance (i.e., NT/minimum/reduced tillage), (2) permanent soil cover by crop residues or cover crops, and (3) diversified crop system/rotation. However, the perception that exists among producers is that NT generally reduces crop yields and lower economic returns except on well-drained soils and highly sloped and erodible lands (Triplett and Dick 2008; Pittelkow et al. 2015). Grandy et al. (2006) reported that there were no crop yield trade-offs due to the differences in tillage conditions in soybean and corn in a long-term tillage study in Michigan. They reported that although agronomic challenges exist in NT, over a longer period of time, the yield in these systems can equal or exceed tilled systems. Similarly, in a study over 9 years in Maryland, Cavigelli et al. (2008) reported similar average corn yield between NT and CT (7.88 and 8.03 Mg ha^{-1}, respectively). Cook and Trlica (2016) and Karlen et al. (2013) have also reported similar results in their studies.

From their meta-analysis comparing various tillage practices along with their yield, Pittelkow et al. (2014) found that NT negatively impacted crop yields by 5.7%, although under certain conditions it produced yields equivalent to or greater than CT systems. But certainly, yield is only one component of agricultural systems, and there is an urgent need to optimize farming practices across other environmental and socioeconomic indicators. Importantly, the negative impacts of NT are minimized when all the other CA principles are also applied simultaneously (22.5%). The largest yield declines occur when NT is implemented alone (29.9%) or with only one other CA principle (25.2% and 26.2% for residue retention and crop rotation, respectively). To help close the yield gap with CT, these findings suggest that instead of implementing NT as the first step toward CA in cropping systems where residue retention and crop rotation are absent (and anticipating that these two principles will follow in time), the primary focus should be on implementing NT systems that already include the other two principles.

Cook and Trlica (2016) reported from their study that NT yielded less than tilled soil (corn and soybean) when the soil test values were lower than recommended level and that NT with NPK management may allow farmers to maintain high yields while reducing soil and nutrient losses. In a more recent publication, Trlica et al. (2017) concluded from a long-term experiment since 1991 that NT and CT have carried the same potential for profit as other tillage systems under full fertility management.

In Iowa, Al Kaisi and Yin (2004) found that NT yielded as much or more than other tillage methods under corn-soybean rotation, while a survey of Illinois farmers found that most conservation tillage systems (NT, reduced till, ridge till, or mulch till) had higher profits than CT due to reduced costs involved (Liu and Duffy 1996). DeFelice et al. (2014) made an extensive study of corn and soybean research that compared yields of NT and CT systems in the USA, and they found that NT tended to have greater yields (about 12% more) than CT in the south and west regions. The two tillage systems had similar yields in the central USA, and NT typically produced lower yields than CT in the northern USA and Canada. No-tillage had greater corn and soybean yields than CT on moderate to well-drained soils, and the yields tended to benefit from crop rotation in NT. Similarly, Toliver et al. (2012) evaluated yields from 442 paired tillage experiments across the USA along with the environmental factors and revealed that mean yields for sorghum and wheat with NT were greater than with CT. They also recorded that soybean and wheat grown on sandy soils using NT had larger downside yield risks associated with NT than with NT on loamy soils, supporting the hypothesis that soil and climate factors significantly impact NT yields.

3.5 Agronomic Interventions for Increasing Crop Productivity in no-till

3.5.1 Sowing into Crop Residues

Maintaining crop residues on the soil reduces the exposure of the surface soil to natural elements and soil erosion is reduced drastically. However, sowing into crop residues can cause planting challenges related to seed placement. Challenges of NT include either retrofitting planting equipment or buying new specialized ones. However, the advent of seed drills that can help plant in the residue drilling at specified intervals makes adoption of NT a greater possibility. DeHate (2017) opines that the planter has to do more work to get the seed where it needs to be, and therefore NT planters need to have more down pressure and be a better equipment to clean the row right in front of where the seed needs to be dropped in the soil.

3.5.2 Cover Cropping Practices

No-till farming is implemented to a greater extent by organic farmers. In a continuous NT farming, weeds are controlled by herbicides rather than by tillage. However, this may lead to the development of herbicide-resistant weeds, as well as pesticide residue runoff into water as infiltration is improved under NT. However, in organic NT, the use of herbicides is not an option, and cover cropping is one major recommendation for weed control and yield improvements through NT; cover crop mulch-based NT production is emerging as an innovative alternative production practice (Vincent-Caboud et al. 2017). The main crop here is seeded into the residues of the terminated cover crops (CCs). The different methods by which cover crops are integrated into the organic NT systems can be studied from Fig. 3.1 incorporated here. However, in the USA, CCs were in use on less than 2% of total cropland (for all crops) during 2010–2011 (608 million acres) (USDA ERS 2017). Wade et al. (2015) noted that during 2010–2011, in the USA, approximately 4% of farmers adopted CCs on some portion of their fields, and only 1.7% did so, on cropland. In organic NT systems, NT planting is not continuously used for each crop but only for some of the main crops in the rotation like corn, soybeans, or vegetables (Rodale Institute 2011). No-tillage systems have also not been widely adopted in Europe despite the potential benefits of integrating NT into organic systems (Peigne et al. 2015).

Hepperly et al. (2008) reported that when the use of CCs intensified, they can effectively substitute for chemical inputs by providing effective weed control and even adding nutrients to soil reducing the cost and energy of fertilization substantially. Figure 3.2 shows the effect of CCs in increasing crop yields from a Rodale Farming Systems Trial.

Cover crops fall under different groups: cereals like oats, barley, triticale, and winter rye that produce very high biomass; legumes like sunn hemp, winterpea, cowpea, berseem clover, phacelia that are able to fix atmospheric nitrogen and improve the soil nutrient status; and brassica like the radish that has deep taproot

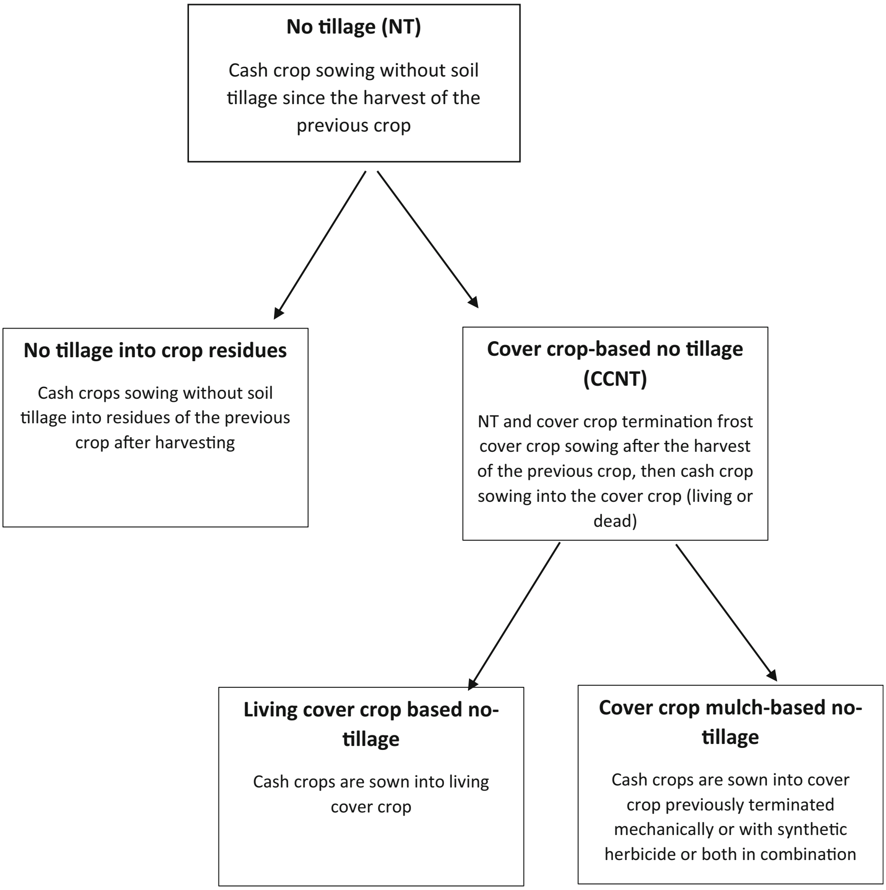

Fig. 3.1 Diagram of different techniques of no-tillage and cover crop management (Adapted from Vincent-Caboud et al. 2017)

system and helps improve soil porosity. The CCs can be grown as sole crop, in mixtures, or in sequence to build the soil and prevent erosion. Synergistic and antagonistic reactions have also been reported on growing CCs in sequence (Shekinah and Stute 2019).

3.6 Cover Crop and its Influence on Crop Yield

The success of cover cropping for NT depends on achieving a dense weed-free stand that will produce high amounts of biomass to provide subsequent nutrients and also keep away weeds in the main crop because of the biomass residue on the ground. Towards this end, it is very important to keep the date of planting CCs early as planting dates have an impact on the quantity of biomass produced, which in

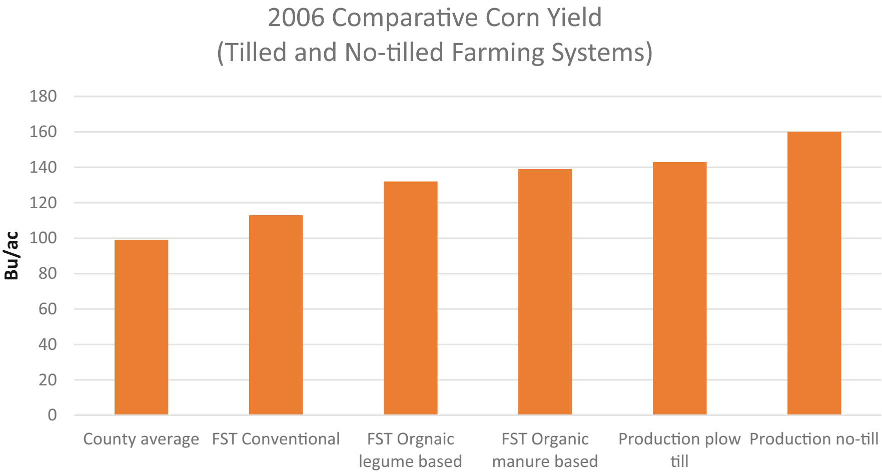

Fig. 3.2 2006 comparative corn yield (tilled and no-tilled farming systems). Rodale Institute Farming Systems Trial; yield in Bu per acre (Adapted from Hepperly et al. 2008)

turn also affects the nutrient addition and weed management. In date of planting studies in Wisconsin with sunn hemp, Stute and Shekinah (2019) reported that yield declined linearly from the initial date of planting (July 2), with a biomass decline of 1.3% per day and 8.9% per week. Care should be taken to ensure that the cover crop achieves maximum biomass as to form a mat of residue on termination. There are different ways to keep the CC residue on the soil forming a layer of mulch which conserves soil moisture and suppresses weeds. Mowing, undercutting, and rolling are methods that are used to terminate CCs. But it is imperative that the termination operations are done at the right time by adopting appropriate methods. Problems arise if the CC is in vegetative stage as it will continue to grow and interfere with the growing main crop. If it is far into the reproductive stage where it produces seed, then the CC will become a weed in the next cropping season. Maximizing agronomic benefits associated with CCs will depend on appropriate species choice and residue management (Ashford and Reeves 2003; Wortman et al. 2012a).

No-till cover crops greatly influence the yield of the main crop due to nutrient release, moisture conservation, and weed suppression, along with other tangible benefits like erosion control, improved soil structure, and infiltration. Reimer et al. (2012) stated that "potential yield increases associated with increased soil fertility were an economic motivation of CC adoption." No-till soybeans grown after rye termination with a roller crimper achieved similar yields as those in a chemically terminated CC while reducing residual weed biomass in Illinois (Davis 2010). Cover crops can help alleviate drought stress by potentially increasing infiltration rates and soil moisture content (Bergtold et al. 2017).

Economic considerations regarding the adoption of CCs are multifaceted. Inconsistent findings on the profitability of CCs and NT greatly influence adoption rates (Boyer et al. 2017). The producer has to consider direct benefits (yield and revenue increase), direct production costs, indirect benefits (i.e., possible savings), indirect opportunity costs, risks, and agricultural policy considerations (Bergtold et al. 2017). Clark et al. (2017) experimented with production systems which included tillage with no CCs, tillage with a mowed and incorporated CC (cereal rye, Secale cereale L.; and hairy vetch, Vicia villosa L.), and NT with a crimped CC in a wheat-corn-soybean rotation. Corn yield was reduced by 30% in NT plots with equal population which indicated that N immobilization may be significant in crimped CCs. Soybean and wheat were competitive under organic NT when soil moisture and weed control were adequate, which the authors suggested meant that adequate biomass of CC was crucial for competitive crop yields (Clark et al. 2017). Veenstra et al. (2007) have reported from various studies that apart from providing nitrogen, leguminous CC improve soil physical characteristics, reduce soil erosion, increase water infiltration, and increase crop yield potential and soil productivity.

Table 3.1 adapted from Blanco-Canqui et al. (2015) shows that the effect of CCs on crop yield in the USA has been variable. Their impacts on crop yields depend on annual precipitation, CC species (legume vs. nonlegume CCs), growing season (summer vs. winter CCs), tillage system (NT vs. CT), and number of years of CC management.

In Garden City, Kansas, Holman et al. (2012) concluded that CCs could be introduced during the fallow period with no reduction in the yield. Experiments found that winter and spring CCs and forage crops grown in place of fallow in a NT winter wheat-fallow system did not reduce the wheat yield but a winter triticale CC did reduce yields compared with fallow plots without CCs under NT management. Similarly, in Bozeman, Montana, Burgess et al. (2014) found that early termination of spring-planted annual legume CCs, such as pea and lentil used as green manure, did not reduce wheat yields. In semiarid regions, it has been observed that while CCs do not always reduce crop yields, at the same time, they do not necessarily increase crop yields. Under favorable climatic conditions, high biomass-producing and high N-fixing summer or tropical legume CCs such as cowpea, pigeon pea, and sunn hemp may have more rapid and greater effects on increasing crop yields and soil properties than winter CCs with low biomass input (Blanco-Canqui et al. 2012). Mahama et al. (2016) reported from a NT study in Kansas that the mean increase in grain yield as a result of including cowpea, pigeon pea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation over fallow with 0 kg N/ha was 78%, 91%, 66%, 72% and 12%, respectively.

Studies have indicated that crop yields increased as a result of adopting CCs in areas of high rainfall (Andraski and Bundy 2005; Balkcom and Reeves 2005; Blanco-Canqui et al. 2012). In south central Kansas, sunn hemp and late-maturing soybean as summer legume CCs increased crop yield when managed under a NT winter wheat–grain sorghum rotation under low N application (Blanco-Canqui et al. 2012). Sunn hemp increased the grain sorghum yield by 1.43 Mg ha^{-1} at 0 kg N ha^{-1}, by 0.67 Mg ha^{-1} at 33 kg N ha^{-1}, and by 0.58 Mg ha^{-1} at 100 kg N ha^{-1}, while it increased the wheat yield by 0.27 Mg ha^{-1} at 66 kg N ha^{-1} relative to plots without CCs.

Table 3.1 Cover crop effects on grain yield across different precipitation zones, soil types, tillage systems, and cover crop species

Study site	Precipitation (mm)	Soil structure	Tillage system	Cropping system	Cover crop planting time	Time after experiment start	Cover crops	Grain yield (kg ha^{-1})	References
Beltsville, MD	1192	Gravelly loam	No-till	Corn	Winter	1	No CC	7.7^{bc}	Decker et al. (1994)
							Hairy vetch	8.7^{a}	
							Winterpea	8.9^{a}	
							Crimson clover	8.1^{ab}	
							Wheat	7.2^{c}	
South Charleston, OH	1033	Silt loam	No-till	Corn	Winter	2	No CC	11.1 ns	Henry et al. (2010)
							Red clover	11.7	
						3	No CC	9.2 ns	
							Red clover	9.3	
Poplar Hill, MD	1009	Silt loam	No-till	Corn	Winter	Across 3 years	No cc	6.3^{b}	Decker et al. (1994)
							Hairy vetch	8.9^{a}	
							Winterpea	8.4^{a}	
							Crimson clover	8.7^{a}	
							Wheat	6.9^{b}	
Rock Springs, PA	1006	Silt loam	No-till	Corn	Winter	3	No CC	9.70 ns	Duiker and Curran (2005)
							Rye	10.02	
Columbia, MO	992	Silt loam	No-till	Corn	Winter	Across 3 years	No CC	$4.83^{a\text{-}d}$	Reinbott et al. (2004)

							Oat	4.56^{cd}	
							Hairy vetch	5.06^{ab}	
							Austrian winterpea	5.19^{a}	
							Hairy vetch + oat	$4.88^{a\text{-}d}$	
							Winterpea + oat	4.47^{d}	
				Sorghum			No CC	6.59^{b}	
							Oat	6.57^{b}	
							Hairy vetch	7.33^{a}	
							Austrian winterpea	7.06^{ab}	
							Hairy vetch + oat	6.94^{ab}	
							Winterpea + oat	6.64^{b}	
Hoytville, OH	859	Clay loam	No-till	Corn	Winter	2	No CC	6.2^{b}	Henry et al. (2010)
							Red clover	7.3^{a}	
						3	No CC	7.3 ns	
							Red clover	7.9	
Andover, SD	602	Loam	No-till	Corn	Fall	1	No CC	13.39 ns	Reese et al. (2014)
							CC mix	13.02	
						2	No CC	11.83^{a}	
							CC mix	10.07^{b}	

(continued)

Table 3.1 (continued)

Study site	Precipitation (mm)	Soil structure	Tillage system	Cropping system	Cover crop planting time	Time after experiment start	Cover crops	Grain yield (kg ha^{-1})	References
Akron, CO	428	Silt loam	No-till	Wheat	Summer	Across 6 years	No CC	3.92^{a}	Nielsen and Vigil (2005)
							Winterpea or field pea	2.64^{b}	
Trail City, SD	414	Loam	No-till	Corn	Fall	1	No CC	6.90 ns	Reese et al. (2014)
							CC mix	7.66	

Table adapted from Blanco-Canqui et al. (2015)
CC cover crop; *ns* non-significant; values followed by a similar letter are not significantly different while followed by different letters are

Table 3.2 Average cotton lint yields (kg ha^{-1}) by winter cover crop, tillage system, and N application rate from 1984 to 2012

N rate (kg ha^{-1})	No cover	Winter wheat	Hairy vetch
	Conventional till		
0	827 (276)*	745 (219	969 (299)
34	943 (295)	931 (266)	1084 (361)
67	1031 (345)	1034 (351)	1058 (369)
101	1106 (351)	998 (331)	1010 (365)
	No-till		
0	683 (267)	695 (222)	974 (321)
30	912 (274)	942 (248)	1074 (355)
60	1053 (344)	1055 (328)	1042 (370)
90	992 (363)	1038 (319)	947 (403)

Adapted from Boyer et al. (2018)
*Standard deviation in parentheses

When combined with improved management systems such as NT, CCs can enhance benefits of current NT compared to NT without CCs (Blanco-Canqui et al. 2011). Cover crop mixtures are considered more beneficial as different CCs can be expected to perform different functions at different layers of soil than a single species could. For example, mixing radish with rye can alleviate both soil compaction and soil erosion risks due to the bio-drilling potential of radish and abundant aboveground biomass cover produced by rye (Chen and Weil 2010).

The ecosystem services provided by CCs are also strongly interrelated. The figure adapted from Blanco-Canqui et al. (2012) shows interactions among soil physical, chemical, and biological properties and how it directly affects soil and water conservation, soil fertility, agricultural production, and environmental quality.

Increases in crop yields drive the profitability of NT planting because production costs of the two tillage systems (conventional and NT) are often similar due to investment costs on machinery in NT (Triplett and Dick 2008). Similarly for CCs, differences in net returns to NT and till planting have varied across studies (Hanks and Martin 2007; Triplett and Dick 2008; Zhou et al. 2017). Cotton lint yields in Tennessee over a period of 28 years have been compared with tillage systems and cover crops. The results (Table 3.2) showed that the cotton yield did not decrease due to cover cropping in NT (Boyer et al. 2018). However, there are other producer risks such as weed management and termination time that come into play when adopting NT or CCs. Cochran et al. (2007) made a significant finding, stating that tillage method made a difference in affecting cotton lint yields for all four cover alternatives (no cover, winter wheat, hairy vetch, and crimson clover). The interaction suggested that no-tillage significantly increased lint yields over time compared with conventional tillage and that the CC alternatives did not provide a great influence on the lint yield. Research in cotton indicates that any yield benefit derived from conservation tillage may not be seen until after multiple years of using the system (Triplett et al. 1996). Though NT with CC does not bring positive benefits every time, there are significant studies to suggest that NT does not decrease crop yields greatly and, over time, even builds up soil carbon and crop yield.

3.7 Cover Crop Management

What does a CC do that increases or at least helps maintain crop yield along with other ecosystem services under NT? The positive correlation of SOC with crop yields indicates that increase in SOC concentration with the addition of CCs is a determinant for the increase in crop yields (Blanco-Canqui et al. 2012). The addition of nutrients, especially N, when the chosen CCs are legumes, helps improve the soil nutrient base for increased crop yields. Senaratne and Ratnasinghe (1995) found that the growth and N yield of the commercial crop was positively correlated with the quantity of nitrogen fixed by the preceding legume crop. For organic farmers, alternating this practice (NT with CCs) with crops that are established with tillage avoids selection for perennial weeds (Rasmussen et al. 2014; Smith et al. 2011). CCs need to produce a biomass in the range of 5–8 t ha^{-1} in order to form an effective layer of mulch to prevent weeds from establishing (Mohler and Teasdale 1993).

When CCs are not harvested for a crop, the biomass they produce and the benefits gained by leaving it as a residue on the soil are many. But, CCs need to be terminated efficiently in a way that they do not present competition to the following cash crop. Termination method and residue management can influence N mineralization, soil availability, crop N uptake, weed communities, and soil moisture availability (Mirsky et al. 2009; Parr et al. 2011; Wortman et al. 2012b). Effective ways of termination of CCs can include use of herbicide sprays known as “burn-down” (Lu et al. 2000). A burn-down pass to terminate CC is unlikely to be an additional pass for a “NT” operator, as it is common to spray a nonselective herbicide prior to planting to terminate winter weeds (Bergtold et al. 2007). However, newer methodologies have been evolving to accomplish the same task without the introduction of harmful chemicals in the environment, especially in organic NT systems.

In the Midwest, if planted in August or September, following an early summer cash crop, it was best to simply let freezing temperatures terminate a sunn hemp crop. Many farmers have reported good success using crimping or mowing of sunn hemp as nonchemical methods of termination. Compared to mowing CCs, termination with a roller crimper reduces fuel and labor inputs, improves weed suppression by uniformly distributing residues, and prolongs residue decomposition (Creamer and Dabney 2002). The blades of the roller cause injury to the CCs accelerating the process of termination (Kornecki et al. 2006). This method does not disturb the soil and can be used alone or in conjunction with reduced rates of non-selective herbicide (Ashford and Reeves 2003). Moving toward the use of roller crimping for the termination of cover crops instead of herbicide applications can help to produce grain crops year after year without compromising on yields or soil erosion. Triplett and Dick (2008) argue that this form of roller crimping NT still requires surface disking of the soil during some seasons which reduces the NT’s ability to reduce soil erosion.

Growing of sunn hemp would therefore lead to NT corn if roller-crimped, with additional benefits of improved N status of the soil. Roller crimping may require multiple passes to sufficiently kill the CC. This system can greatly benefit organic NT corn while conventional farmers can also be benefitted by sunn hemp (Shekinah and Stute 2019). Clark et al. (2017) also reported that optimum time of CC crimping is important for acceptable weed control and was able to produce competitive yields in organic NT soybean and wheat. In Pennsylvania, Keene et al. (2017) found that minimizing CC seed production with strategic termination is critical in a rotational NT system of hairy vetch plus triticale-corn-cereal rye-soybean-winter wheat rotation. Slower decomposition of rolled residue also results in a longer period of weed suppression (Lu et al. 2000). Winter kill may be possible for less hardy CCs but result in lower level of biomass and less weed control (Mannering et al. 2000).

Yield results in organic NT are also dependent on past production history and CC stands. In an experiment at Rodale Institute, yields of 7–10 Mg ha^{-1} were achieved under favorable conditions with CCs (hairy vetch), while a yield as low as 1.1–-3.4 Mg ha^{-1} was realized in other sites (Mischeler et al. 2010). Although rye mulch effectively suppressed weed growth in Wisconsin, rye regrowth competed with soybean (*Glycine max* L.) to reduce crop yield by 24% in organic NT treatments compared to tilled system (Bernstein et al. 2011).

Precedence must always be given to planting the cash crop. Bergtold et al. (2017) stated that giving additional 2 weeks for spring termination of hairy vetch could produce significant increases in the N accumulation and delaying winterpea termination by 18 days nearly doubles N contribution from 6.4 to 12.2 kg; however, if cash crop planting is done soon after termination, dying but not dead CCs will compete for soil nutrients and water.

3.8 Crop Rotation

Although organic production systems have been found to increase SOC pools over conventional tilled systems (Liebig and Doran 1999), a conventional NT system can also accumulate surface C compared to organic tilled systems with CC (Jokela et al. 2011). Cropping systems can influence SOC by the quality and quantity of residue returned to the soil (Sainju et al. 2007). Longer and more complex crop rotations can bring greater benefits including crop yield increases in a conventional system (Katsvairo and Cox 2000; Meyer-Aurich et al. 2006), increased soil quality (Karlen et al. 2006), and greater profits (Meyer-Aurich et al. 2006) although benefits are not consistently realized. However, in an organic system, where weed competitiveness and management is the major source of yield reduction, many studies found that increased rotation length and complexity can reduce weed population (Teasdale et al. 2004). Not much documentation is found on the benefits of crop rotation in organic agriculture of crop yields. Organic cropping systems that depend on cover cropping for weed management through soil coverage and nutrient supply through N fixation by use of leguminous CCs help improve or sustain crop yields in NT. Positive effects on soil physical, chemical, and biological properties have been found through the adoption of crop rotation involving cover cropping in NT farming. Selection of CC with strong and vigorous root systems is essential for the system to succeed (Garcia et al. 2013), and the CCs contribute to crop rotation diversification (Calonego and Rosolem 2010). The variable root systems of CCs (brachiaria and sorghum-sudan have large root systems, while sunn hemp and radish have fewer roots) break the compacted soil layers, while biomass increases the soil organic matter (SOM) and plays greater role in soil aggregation. Thus, the inclusion of CCs in a crop rotation, especially in a NT, plays an important role in improving soil properties that can enhance the commercial crop yields. Garcia et al. (2013) reported enhanced SOM and improved physical properties by growing crop rotations that included ruzigrass (*Urochloa ruziziensis*) grown in fall/winter, sunn hemp, sorghum-sudan grown in spring, and soybean as the summer crop under NT in a 3-year rotation. Increasing crop diversity and rotation length may have contributed to higher soybean yields in the 3- and 4-year systems compared with the 2-year system (Liebman et al. 2008). Mallarino and Ortiz-Torres (2006) noted that over a 21-year period in Iowa, no yield difference occurred for corn when the crop was grown at high N fertilizer levels in a 2-year rotation with soybean vs. when it was grown in a 4-year rotation sequence of corn-oat-alfalfa-alfalfa. In contrast, soybean yield was higher when that crop was grown in a 4-year rotation (soybean-corn-oat-corn) than in a 2-year rotation with corn.

Previous evaluations of organic rotational NT have demonstrated the weed suppression and reduced labor inputs compared to tillage-based organic management (Teasdale et al. 2012; Bernstein et al. 2011). Research at the Harvey County Experiment Field in Kansas over a 5-year period explored late-maturing soybean and sunn hemp and evaluated their effect on wheat-sorghum rotation in a NT condition. Averaged over N rate, wheat yields were 3.4 bu. ac^{-1} greater with CCs than with no CC in rotation, with notably increased yields under 60 kg N than 90 kg N when soybean was in the rotation. Similarly, sorghum produced 7.0 and 19.7 bu. ac^{-1} more in the rotations with soybean and sunn hemp, respectively, than in the rotation with no CC (Claassen 2008).

Practices such as organic no-till agriculture and perennial grain agriculture systems should be developed and prioritized for research (Margulies 2012). It is necessary to develop NT farming for any future role it will play in the development of sustainable agriculture. Problems associated with NT are those of pesticide and nutrient runoff and transport into water bodies. Working this out as an organic no-till system with cover crop or crop rotational practices for NT could help improve the system reducing the payload of the runoff along with greater control of soil erosion. In his paper, Margulies (2012) argues that while the earliest proponents of NT farming suggested that farmers would be best served in mimicking natural ecosystem processes to retain soil and suppress weeds, the result today is an agriculture that traded in the plow for pesticides and soil erosion for water contamination, the full consequences of which we may not know for some time.

3.9 Conclusions

Adoption of NT as a conservation strategy to prevent soil erosion can gain further traction if there are increased crop yields. Favoring that is the use of CCs in rotation with a clear indication of when and where they fit in the rotation. Adoption of CCs under NT influences the yield of the main crop due to moisture conservation and weed suppression, nutrient addition, and release along with other tangible benefits like erosion control, improved SOC, soil structure, and infiltration. Cover crops, when combined with improved management systems such as NT, can enhance benefits of NT compared to NT without CCs. A leguminous CC also fixes atmospheric nitrogen and improves the nutrient status of the soil. In fact, CC mixtures are considered more beneficial as different CCs can be expected to perform different functions at different layers of soil than a single species. Combination of CCs also help to alleviate both soil compaction and soil erosion risks due to biological tillage and also abundant aboveground biomass that enriches organic carbon in soil. Moreover, the ecosystem services provided by CCs are also strongly interrelated. CCs strongly influence the interactions among soil physical, chemical, and biological properties, and it directly affects soil and water conservation, soil fertility, agricultural production, and environmental quality. Research that is innovative and balances conservation of soil with increased crop yields and reduction in the exposure to potentially harmful herbicides and pesticides in water sources should be one of the best serving options that need to be developed on a larger consistent scale. Under such compulsions, it is fairly obvious and influential to turn to biological systems like the use of cover cropping, small grain cropping, and crop rotations to make no-till farming successful and sustainable.

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Inbuilt Mechanisms for Managing Weeds in Conservation Agriculture Systems: A Revisit

4

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Abstract

Conservation agriculture (CA) is a cultivation practice encompassing nil disturbances to the land and soil cover to protect soil biota with efficient nutrient cycling through diversified crop rotation. The primary aim is to protect the production resources from the current soil-degrading practices. The present-day practices no longer act as soil biome vitalizers, but rather pose irreparable damage to soil health agricultural biodiversity. Jethro Tull, the father of tillage, believed and advocated that tilling the soil has great powers to support vegetation, and tillage is practiced since ages not only to nourish the plants but also to make the soil free from weeds. However, soil erosion is an inevitable bonus to it. The CA pillars have inherent mechanisms for weed management too. Non-inversion tillage minimizes the turnover of deep layer weed seeds to the surface, surface remaining weed seeds becoming prey to predators, and, to some extent, the chemicals released from crop/cover crop residue inhibit weed seed germination although these systems are too complex to explain. In this chapter, we have attempted to throw some lights on the agronomy aspects of CA and weed management in these systems.

Keywords

No-till · Weed dynamics · Cover crops · Crop diversification

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4.1 Introduction

Conservation agriculture (CA) is the modern chant (*mantra*) in agriculture encouraging researchers to debate and discuss the practices, bottlenecks, and management interventions through world CA congresses. This method of farming is against the known convention of tillage practices (Jethro Tull, the father of tillage). A change in traditional tillage principle is the basis of CA (Lumpkin and Sayre 2009) plausibly to arrest the soil organic matter (SOM) decomposition. Realizing its potential at the global level, recently, the 7th World Congress on Conservation Agriculture was held in Argentina during 2017, and region-wise CA prospects have also been reviewed widely. CA is defined as an agricultural management system that aims to minimize soil disturbance, permanent residue for soil cover, and rotation of crops (FAO 2012). Although, these principles underpin the SOM content as a storehouse of nutrients to support and nourish the crops in this system, of late, nutrient management is also considered as a principle (Vanlauwe et al. 2014) particularly in the African drylands.

Weeds, the plants "out of place", are as old as agriculture, and in the unploughed soil ecology, weeds manage to germinate, flourish, and survive better than the crop plants. Conversion to CA systems in the past decades has resulted in the dominance of grassy perennial weeds under modern concepts of tillage, viz. reduced tillage (Froud-Williams et al. 1984) and no-tillage, few among the two forms of no-disturbance soil systems; their management is a serious concern although the weed species varies from crops and cropping systems and soil types. For example, the USA has witnessed the menace of field bindweed (*Convolvulus arvensis* L.) in corn-soybean rotation (Buhler et al. 1994) under conservation tillage systems. It is pertinent to state that agricultural management systems can have both immediate and long-term effects on weed species density, abundance, and diversity (Ramesh 2015; Ramesh et al. 2017) and short-term effects too.

Conservation tillage systems may result in equal crop yields to that of conventional systems if weeds are efficiently managed and uniform crop stands are established (Mahajan et al. 2002; Ramesh 2015). A plethora of modern tillage practices viz., no-till, reduced tillage etc., results in a reduction of soil tillage modifies soil microenvironment (Chauhan et al. 2006) and weed seed burial and replenishment is also altered drastically. However, the weed problems may pose a threat only in the initial couple of years (Mashingaidze 2013), since thereafter in a well-managed CA system, the weed seeds either become redundant or become prey to predators (Barberi and Lo Cascio 2001). Adoption of CA influences weed populations differently from conventional agriculture (Chauhan et al. 2012; Ramesh 2015).

4.2 Weed and Weed Seed Ecology Under CA Systems

Analysing the weed seed ecology which comprises seed dormancy, germination, and weed seed recruitment will aid in devising strategies to manage weeds in CA systems (Barberi and Lo Cascio 2001, Ramesh 2015). It is obvious that frequent tilling of the soil oxidises soil organic matter. This brings weed seeds to upper layer from lower layers and also stimulates the dormant seeds to germinate. Spatial weed dynamics (Lutmen and Rew 1997) is equally significant in CA, as the physical movement of seeds/propagules (Marshall and Brain 1999) decides their dominance. In addition, seed heterogeneity in the vertical distribution in the soil profile (Traba et al. 2004) and their viability (Torresen et al. 2003; Carter and Ivany 2006) due to NT also decide their survival and proliferation.

Depth of seed burial (Ballare et al. 2008) is also related to weed menace since at 10 cm depth, only Johnson grass and velvetleaf emerged, albeit only in limited numbers, whereas in buckhorn plantain, large crabgrass, common purslane, chickweed, and corn spurry, none of which emerged from beyond 6 cm. Even though raising of cover crops could hinder weed seed emergence through resource competition, weeds like *Senecio vulgaris* could adjust its morphology to low-light conditions through phenotypic plasticity (Baumann et al. 2001) and flourish.

More than half of the weed seedbank was concentrated in the surface layer at 5 cm depth in a NT system, and half of which was only common lambsquarters in a NT corn-soybean rotation (Clements et al. 1996). A 6-year study in soybean-corn rotation and continuous corn rotation has found foxtails (*Setaria* spp.) near the soil surface (Hoffman et al. 1998), and Konstantinovic et al. (2010) have noticed the weed seeds in the top few inches of soil under NT. Weed shifts under NT (Hinkle 1983; Koskinen and McWhorter 1986; Buhler 1995; Malik et al. 1998; Thomas et al. 2004) and RT (Gill and Arshad 1995; Torresen and Skuterud 2002) have been noticed due to minimized soil disturbance (Buhler et al. 1997). For example, horseweed has shifted to goldenrod in soybean within a couple of years of NT (Kapusta and Krausz 1993), and plausibly tillage type led to a shift in weed flora (Conn 2006; Montanya et al. 2006). In Central India, Blaise et al. (2015) reported that the least number of grassy weeds was observed in the no-tillage (NT), reduced till (RT), and mouldboard plough (MB) treatments than conventional till (CT) treatment. However, more dicot weeds were observed under RT and NT plots than the CT. They also observed from the average season data that CT and MB treatments recorded 17–30% more weed species than RT and NT treatments. NT, RT, and CT treatments had more weed seeds in 0–5 cm soil depth than the MB. The trend in 5–15 cm soil depth was MB $>$ CT $>$ RT $=$ NT. Another study in India, a long-term site under NT, didn’t encounter any shift in weed flora at all in rice-wheat cropping system (Singh et al. 2010). In contrast, in a dryland cropping system, NT witnessed more competition from *Vicia sativa* and less from *Chenopodium album* in Vertisols (Sharma et al. 2013). There is substantial information available concerning the relevance of use of each CA pillar for weed management also which is discussed hereunder.

4.3 CA Components in Weed Management

4.3.1 Principle 1: Tillage Systems

4.3.1.1 No-Till

Weed community diversity is as important as that of any other criterion for weed management. Derksen et al. (1995) couldn't notice any evidence for a change in community diversity towards conservation tillage practices. In contrast, Zelaya et al. (1997) and Zanin et al. (1997) could observe the change in diversity due to tillage. Later, Legere et al. (2005) noticed the tillage mediated weed community composition. It was established beyond doubt that soil disturbance is related to persistence; *Datura ferox* weed seedling emergence was negatively related with depth of burial in soybean fields (Ballare et al. 2008), and hence tillage was recognized as one of the primary factors that changes weed communities (Owen 2008). Notwithstanding to this fact, Menalled et al. (2001) have noticed a significant increase in the number of weed seeds of *Digitaria sanguinalis* and *Panicum dichotomiflorum*, both of which are annual grasses, in conventional as well as NT, indicating that tillage is immaterial for the proliferation of grassy species. Of course, positive relationship was found for annual grassy weeds (Froud-Williams et al. 1983a, b; 1984), viz. foxtail (yellow and giant) and fall panicum in NT (Webster et al. 2003). Weed species strata in NT and conventional tillage had varied weed species, confirming the ability of seedbanks to buffer disturbances across a variety of cropping systems (Legere et al. 2005).

NT facilitated the weed seed deposition on the surface (Hoffman et al. 1998), and the effective distribution in the soil is a function of soil texture and seed characteristics. NT generally favoured the development of younger seedbanks, irrespective of the soil texture (Benvenuti 2007) and those remaining after predation. If weed seed production is suppressed in the initial couple of years of NT, the active weed seedbank is expected to decline. Without inversion of the soil, weed seeds positioned deeper in the soil become immobile and germinate to replenish the seedbank if the plants could produce seed (Shaw et al. 2012). Non-inversion tillage might be helpful in the long run as it creates unfavourable conditions and the absence of bringing old and dormant weed seeds to favourable germinating conditions at the surface (Baral 2012).

4.3.1.2 Weed Seed Predation

Weed seed predator's (Baraibar et al. 2009) activity and density would be higher in NT-based cropping systems due to the abundant availability of food. If the natural predation is just 25–50%, weed population could very well be curtailed (Firbank and Watkinson 1985), and under normal circumstances, this may exceed 50% (Bohan et al. 2011). Hence Ichihara et al. (2011) considered weed seed predation as the ecosystem service in CA to nurture and maintain agricultural biodiversity. This is achieved through the maintenance of a minimum of 30% crop residues, which not only protects the soil from the exposure to erosive forces but also helps diverse weed seed predators to thrive in the crop ecosystem, viz. rodents, birds, ants, ground beetles, and crickets, and weed communities are restructured (Ghersa and

Martinez-Ghersa 2000). An optimistic estimate by Cardina and Norquay (1997) has indicated that more than three-fourths of weed seeds annually produced in cereals may not emerge as seedlings, due to weed seed predation (Westerman et al. 2003). Predator fire ants were noticed by Pullaro et al. (2006) under mulched cover of *Mucuna pruriens* (L.) DC. var. utilis, *Vicia sativa* cv. cahaba and *Secale cereale* L. in *Capsicum annuum* L., and *Brassica oleracea* L., acephala group fields in the south-eastern United States. The predation under NT (Mwale 2009) may be either pre- or post-dispersal to keep weeds under check (Ward et al. 2011). Carabid beetles are important predators in conservation biology. For example, large ground beetles (Brust and House 1988; Titi 2003; Shearin et al. 2007), *Harpalus rufipes* DeGeer (Westerman et al. 2003), fire ants on seeds of *A. retroflexus*, *Poa annua*, *C. album*, *Solidago altissima* (Seaman and Marino 2003), etc. were noticed under conservation tillage systems. *Rumex dentatus* seeds were concentrated in upper soil layer under NT rice-wheat cropping system (Chhokar et al. 2007) aiding for predation. Reduction in tillage coupled with cover crops could reduce soil disturbance and may improve the quality of habitat for weed seed foraging (Quinn et al. 2016).

4.3.1.3 Reduced Tillage

Weed species requiring light for germination were likely to become more dominant under RT. Similarly, species that require burial for germination may become less prevalent (Chauhan et al. 2006). Since a reduction in tillage enhanced seedbank density (Legere et al. 2011), floristic composition and diversity of weed infestation depend (at least in part) on the soil seedbank in agro-ecosystems (Gulshan et al. 2013). Weed seed population persistence was an increasing function of disturbance frequency in soils and shallow disturbances; for example, RT was more advantageous for weed seeds because they allow them to stay close to the surface and not miss any germination opportunity (Eager et al. 2013); however, the chances of predation was also enhanced.

4.3.1.4 Tillage Systems in Cropping Systems

Crops and cropping systems had a prodigious influence on the weed seed recruitment (Barberi and Lo Cascio 2001). NT corn field had maximum weed seeds on the soil surface (Kellman 1978). Further, wheat-dominated rotation had more weed seedbank than barley-dominated rotation (Salonen 1992). Notwithstanding to this fact, continuous corn-based NT systems over 6 years have resulted in just one-fifth of the first year weed seeds, i.e. 41,000–8000 seeds m^{-3} (Murphy et al. 2006). Although tillage has an overriding effect on weed seedbank than cropping system per se as evidenced from winter wheat systems (Wojciechowski and Sowiński 2005), predators may help better to minimize weed seed recruitment to the weed seedbank if a range of phenologically dissimilar crop species (Heggenstaller et al. 2006) are included in the cropping system.

4.3.1.5 Zero Disturbance Systems

If soil is undisturbed, the weed seeds could remain exposed to the topsoil layer (Hoffman et al. 1998). Higher population of grassy weed green foxtail (*Setaria* *viridis*) was noticed (Wrucke and Arnold 1985) under NT corn-soybean rotation. Domination of annual grasses such as *D. sanguinalis* and *P. dichotomiflorum* was noted in NT corn-soybean-wheat at Michigan (Menalled et al. 2001). Only perennial weeds (*Epilobium* spp. L. and *Sonchus arvensis* L.) were related to NT in a winter wheat (*Triticum aestivum* L.)–oil-seed rape (*Brassica napus* L.)–winter wheat-maize (*Zea mays* L.) rotation (Streit et al. 2002). The weed seed count was inversely proportional to depth of soil profile in a pearl millet-wheat cropping sequence in India (Yadav et al. 2005) under NT. Perennial weeds were found to dominate in wheat-corn cropping system after several years of ZT (Xiangju et al. 2006).

4.3.1.6 Reduced/Minimum Disturbance Systems

A change in soil microenvironment and lesser possibility for turning soil upside down under RT have several ramifications. Diverse population of perennial weeds under RT in corn-soybean rotations was noticed (Buhler et al. 1994). Later, Buhler (1995) found a reduction in the densities of large-seeded dicot species under RT in corn-soybean rotation; for example small-seeded weeds, such as pigweeds, emerged only from shallow burial depths (0.5–2.5 cm) (Ghorbani et al. 1999; Oryokot et al. 1997).

4.3.2 Principle 2: Cover Crops and Its Residues

It was noticed by Putnam et al. (1983) that the residues of certain cereal and grass cover crops significantly reduced weed population in the next season crop. In general, broadleaved weeds were more susceptible to cover crop mulch than grassy weeds (Einhellig and Leather 1988). By virtue of soil coverage as a physical barrier (Chhokar et al. 2007; Altieri et al. 2011), the cover crop residues manage weeds successfully; in addition to the possible allelopathic chemicals released by them, the latter is often inconsistent (Moore et al. 1994). While subterranean clover, a legume cover crop, decreased weed seedbank density (Moonen and Bàrberi 2004), rye cover crop did not (Bellinder et al. 2004) do so. Cover cropping strategies should be tailored in such a way that late-season weeds are managed through desirable ecosystem for invertebrate predators (Gallandt et al. 2005).

The allelopathic reaction with rye residues under simulated no-till conditions was demonstrated by Barnes and Putnam (1983). In contrast, Teasdale and Mohler (2000) have proven that rye and hairy vetch could act only as mulch to manage weeds rather than allelopathy. This suggests that the composition of the residue has a specific role in suppressing weeds; for example, neither maize nor sorghum residue was effective in weed suppression (Mashingaidze et al. 2009) on clay loam and sandy soils at Zimbabwe.

Clover species are recognized as good cover crops. However, the selection of clover species is an important criterion for weed suppression. For example, Persian clover (*Trifolium resupinatum*), red clover (*T. pratense*), alsike clover (*T. hybridum*), berseem clover (*T. alexandrinum*), and crimson clover (*T. incarnatum*) are very good weed suppressors but gave strongest negative effect on dry matter accumulation of leek (up to 90%). White clover (*T. repens*) could balance weed suppression and yield reduction in leek plant. Hence den Hollander et al. (2007) have concluded that clover species selection is an important element for optimization of cover crop-based systems. Although subterranean clover (*T. subterraneum*) is the shortest species, it gave inadequate weed suppression.

Inclusion of a cover crop as a catch crop between two main crops helps to reduce weed density in CA cropping system. For example, mung bean can be grown as a cover crop in rice-wheat cropping system (Rao and Chauhan 2015). Although research has shown that cover crops could play an important role in weed management in CA systems, at present, residue retention on farmer fields is low due to multivarious reasons. Greater awareness with strong extension support is the need of the day to harness the twin benefits on soil health and weed suppression. In addition to rice-wheat systems, non-rice-wheat cropping systems also need attention in India (Bhullar et al. 2016).

4.3.3 Principle 3: Crop Rotation and Diversification

Crop rotation for weed management (Froud-Williams 1988) through temporal diversification and intercropping (spatial diversification) (Liebman and Dyck 1993) and cropping system diversity for weed resistance management (Beckie 2009) are the common strategies due to (1) diverse weed flora especially in CT on continuous corn (Ball and Miller 1993) and (2) prevention of the domination of problem weeds as the effectiveness of rotations in reducing weed density was dependent upon the crop (Doucet et al. 1999) since maize-based cropping systems accounted for just 5.5% variation in weed density, while crop rotation accounted for nearly 40% variation. In spite of the complexity in cropping systems due to numerous interactions between cultural techniques, climate, and soil characteristics, the effects of cropping systems are cumulated over long term and the weed seeds persist over time and constitute seedbanks (Jones and Medd 2000). Diverse rotations that exploit multiple stress-encouraging weed seed predation could contribute to the effective weed suppression (Westerman et al. 2005). A decade-old study on a loamy sand soil comprising tillage systems with or without cover crop on winter wheat-rye-pulse rotation did not curtail weed density (Shrestha et al. 2002). Crop rotation with reduced tillage might reduce weed density (Murphy et al. 2006) but is dependent on the components of the crops in the rotation; for example, variability of species richness in maize across tillage practices was insignificant (Demjanová et al. 2009). In sequel to the above, studies on barley-red clover rotation with different tillage practices have shown that only species density was regulated by weed management, while the relative frequency was influenced by rotation (Legere et al. 2005). Soybean-corn rotation consistently lowered horseweed densities under NT only from third year (Davis et al. 2009) as compared to the continuous soybean rotation, but not in the initial years (Davis et al. 2007). Crop rotation improves soil health but reduces buildup of weeds (Chauhan and Mahajan 2012).

4.4 Conclusions

The basic principles of CA, viz. non-inversion tillage, crop residue maintenance, and crop rotation and diversification, if implemented together in toto, have the in-built capability of weed management in a CA. Although in the initial period of conversion to CA systems, managing weeds may prove to be challenging but in the long run will prove efficient. Crop residue retention on farmer fields need to be strengthened. Further, utilizing herbicides is to be looked from the environmental protection angle; the age-old traditional practices, viz. mulching, cover crops, crop rotation/diversification, and other agro-techniques, as pillars of CA, should be given due emphasis in managing weeds under CA. The major principle of maintaining the ground cover with dead or live organic mulch, which leaves less time for weeds to establish during fallow or a turn-around period, should be followed without second thought. Benefits of these practices need wider awareness for weed management coupled with improved soil health need to be propagated in India. Research effort needs to be enhanced to develop CA and promote its adoption in non-rice-wheat cropping systems in India. In addition to these principles, selection of appropriate crop cultivar, efficient crop rotation, and appropriate cover crop will determine the successful crops under CA with least dependence on other forms of weed management.

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Conservation Agriculture in Cotton-Based System: Impact on Soil Properties

5

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Abstract

In recent years, sustainability of agricultural systems has become an important issue all over the world. Maintaining soil health under intensive land use is a major challenge for the sustainable use of resources in the developing world. Assessing land use-induced changes in soil properties is essential for addressing the issue of agro-ecosystem transformation and sustainable land productivity. Soil health is declining and has become an environmental and economic issue of increasing global concern as degraded soils are becoming more widespread, owing to intensive use and poor management. Several developments in agriculture including mechanization have brought considerable changes in soil physical, chemical, and biological attributes as compared to the conventional tillage practices. In recent years, the principles of conservation agriculture such as minimal soil disturbance, crop residue retention, and crop rotations are viewed as a key to maintain soil health and sustainable production system in the long term. Worldwide cotton is grown on varied soil types ranging from the deep black Vertisols to the shallow Inceptisols and Alfisols, which were known for their physical constraints including soil crusting, compaction, and poor trafficability, which overall affect cotton growth and development. Conservation agriculture and its components such as minimal tillage, residue recycling, and crop rotations have brought considerable changes in soil structure and improved aggregate stability, infiltration rate, aeration, root penetrance, carbon storage, availability of nutrients, soil biological activities, and crop growth. The present review brings together fundamental aspects of conservation agriculture, in relation to soil physical, chemical, and biological properties, and their impact on soil health and cotton productivity.

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Keywords

Asiatic cotton · Gossypium spp. · Microbial activity · Semi-arid tropics · Upland cotton

5.1 Introduction

Tillage is defined as the mechanical manipulation of the soil for the purpose of crop production (Hillel 1998; Busari et al. 2015). Tillage is practiced for two major reasons: firstly, preparing a fine seedbed prior to sowing and, secondly, obtaining an effective weed control. Besides these two major functions, tillage also aided in destroying the hibernating insects, turning over crop residues, and incorporating manure and fertilizer into the soil. When tillage is done to perform so many multiple functions, what is the harm arising from it? Basically the problems arise because tillage disrupts the soil structure, thereby affecting many soil physical, biological, and chemical properties. When excessive tillage operations are performed or when tillage is done when the soil moisture is high, it leads to a structural breakdown. This resulted in deterioration of the soil quality. For instance, in the rainfed regions of central India where cotton is grown on the deep black Vertisols, excessive tillage operations are frequently done to control the weeds (Blaise and Ravindran 2003). Developments of modern farm machinery with improved implements lead to greater mechanization. Furthermore, it led to a replacement of traditional implements, animal and manual labour. Several studies across the world indicated an adverse effect of the modern plough tillage systems followed. The “dust bowl” in the USA was the best example for greater soil erosion due to excessive tillage operations (Baumhardt 2007).

Cotton (*Gossypium* spp.) is a commercial crop that sustains the livelihoods of millions of farmers, especially the poor and marginal farmers in the African continent and those of Asia. It is also a major commodity crop in the developed countries such as the USA, Australia, and some European nations such as Turkey, Greece, and Spain. It is grown on nearly 33 million hectares globally with India, China, and the USA being the top three producing nations in the world. Cotton is grown on varied soil types ranging from the deep black Vertisols to the shallow Inceptisols and Alfisols.

In the major field crops such as rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), and soybean (*Glycine max*), there has been a shift from intensive tillage practices to a more conservative approach the world over. These crops generate substantial amount of crop residue, and their retention on the soil surface is much easy. On the contrary, crops such as cotton produce very little biomass (Blaise and Ravindran 2003) and the challenge to retain crop residue in the field is high because of competing uses or disposal through burning to ward off insect pests (Prasad and Power 1991). Enhancement and safeguarding soil productivity is an essential element for sustainable crop production to meet the basic needs of an ever-growing population (Lambin and Meyfroidt 2011; Bhattacharyya et al. 2013). Thus,

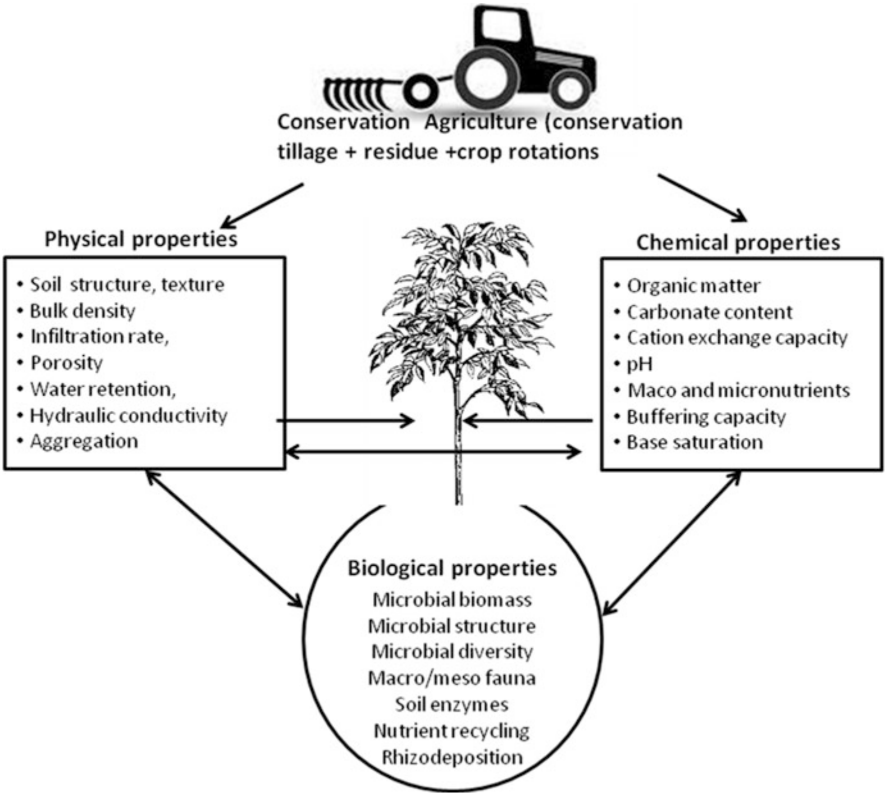

Fig. 5.1 Effect of conservation agriculture on soil properties

conservation agriculture is viewed as a solution to maintain soil quality and influences the physical, chemical, and biological properties (Fig. 5.1).

Conservation agriculture (CA) includes three basic principles: (1) minimal soil disturbance, (2) retaining crop residue cover on the soil surface, and (3) crop rotation. Minimal soil disturbance can be achieved by conservation tillage practices ranging from zero tillage (no-till), reduced (minimum) tillage, mulch tillage, ridge tillage, and contour tillage. The different types of tillage are discussed in this book in Chap. 1. Because cotton crop produces very little biomass, growing high residue-producing crops in rotation is an option achieving the twin benefit of rotation as well as residue cover improving soil health and quality. This approach would hold the key to the future sustainable cotton production. Soil health and quality can be maintained by several methods, mainly by alleviating the soil physical and chemical constraints (Fig. 5.2). In this chapter, we focus on the impact of conservation agriculture systems on the soil physical, chemical, and biological properties in the cotton-based systems.

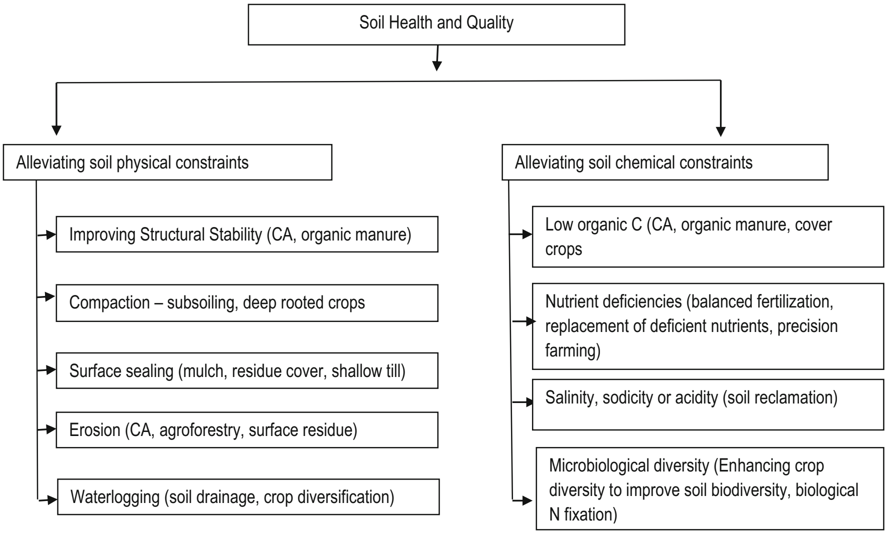

Fig. 5.2 Components to enhance soil health and quality

5.1.1 Soil Physical Properties

Worldwide, poor soil physical properties are associated with the three major soil groups, namely, Alfisols, Ultisols, and Vertisols (Lal and Stewart 1995). Incidentally, these are the soil groups that support cotton production in the major cotton-growing countries of the world. Soil physical constraints include sealing and crusting, compaction, and poor trafficability. Tillage disrupts soil physical properties by causing fracture to develop within the soil aggregates. In the process, it also affects a number of soil physical properties accelerating surface runoff and soil erosion. Furthermore, tillage operations reduce retention of surface crop residue that acts as a cushion against the pounding raindrops (Rasnake 1983). Effects of conservation tillage on soil properties vary, and these variations depend on the particular system chosen (Busari et al. 2015). The major soil physical properties that get influenced due to a change in the tillage system are discussed subsequently.

5.1.2 Soil Structure

Soil structure or spatial heterogeneity dominates the physical properties of soil and its functioning (Dexter 1997). Soil structure can be defined in terms of form and stability (Kay et al. 1988). It is the spatial arrangement of the primary particles (solids) and the pore system (void) in the soil. A stable soil structure is one that has the ability to retain a balanced arrangement when exposed to different stresses (Angers and Carter 1996). Soil structure and stability change with biotic and abiotic factors (Fig. 5.3). Biotic forces include invertebrate (macro- and microfauna, root

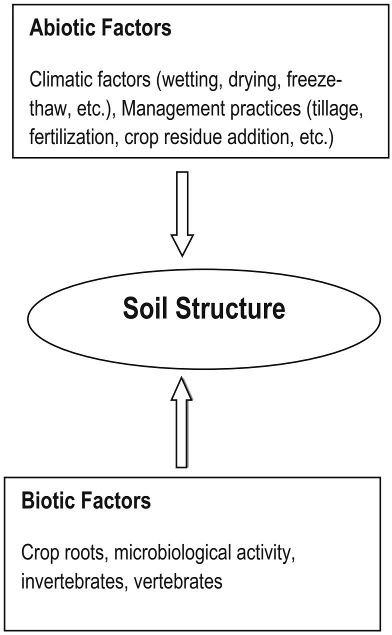

Fig. 5.3 Factors influencing soil structure

growth, and microbiological) and vertebrate (human and animal traffic) activities. Among the abiotic factors that influence soil structure are climatic and management practices such as tillage, fertilization, crop residue addition, etc. In turn, soil structure influences a number of soil physical properties. The stability of the aggregates and the pores between them affects the movement and storage of water, aeration, erosion, biological activity, and crop growth. Maintaining high soil aggregate stability is essential for preserving soil productivity, minimizing soil erosion and degradation, and minimizing environmental pollution derived from soil degradation as well (Amézketa 1999). Among the management practices, tillage has a considerable influence on the soil structure at the soil surface and in the subsoil – the rooting zone. On the Vertisols of New South Wales, Australia, Hulugalle et al. (2004) reported that soil structural damage could be minimized by avoiding tillage and traffic under wet conditions. Gwenzi et al. (2009) reported significant improvement in the mean weight diameter (MWD) and water stable aggregates (WSA) by minimizing tillage operations on the Alfisols of Zimbabwe (Table 5.1).

Crop rotation through the return of crop residues modifies the soil environment through the development and distribution of bio-pores and the dynamics of microbial communities and contributes to the development of soil structure (Ball et al. 2005). Compared with sowing cotton every year, including wheat in cotton-based cropping systems, improved cotton yield and reduced soil quality decline (Hulugalle et al. 2012). Minimum tillage when combined with a cotton-wheat rotation had a better surface structure (Hulugalle et al. 2004); however, it leads to an increase in sub-surface compaction. In a separate study, Rochester et al. (2001) too reported

Table 5.1 Effect of tillage on the mean weighted diameter and water stable aggregates in the 0–15 and 15–30 cm soil depth of the Typic Haplustalf

	MWD (mm)		WSA (%)	
	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Conventional till	0.10a[a]	0.12a	1.0a	1.1a
Minimum till	0.20b	0.23b	2.7b	3.0b
No-till	0.22b	0.19b	3.5b	2.3b

Source: Gwenzi et al. (2009)
[a]Values followed by the same letter in a column are not significantly different

improved soil structure with cotton followed by a legume, such as vetches (*Vicia* spp.) as a rotation crop. In Vertisols, soil structure is better quantified by assessing the shrinkage indices (Daniells 1989). Hulugalle et al. (2017a, b) reported that structure is not necessarily improved by including a cover crop such as vetches, though it improved the soil fertility because of frequent machine traffic on the field for sowing and termination of the crop. Shrinkage indices were determined by plotting soil-specific volume against soil water content, and linear functions were fitted to the zones of structural, normal, and residual shrinkage. Hulugalle et al. (2017a, b) reported the highest average soil-specific volume of oven-dried soil (0.65 m^3 Mg^{-1}) with cotton-cotton followed by cotton-wheat rotation (0.62 m^3 Mg^{-1}). Cropping systems that had no fallow period between the rotation crop caused a significant reduction in the specific volume when oven-dried ($P < 0.01$) and at normal swelling limit ($P < 0.05$) (Table 5.2). Average specific volume declined when the fallow period was shortened by including vetches in the system, and the differences were significant (SEM = 0.005, $P < 0.001$). Furthermore, Hulugalle et al. (2017a, b) observed a greater value of the slope of the structural shrinkage line, s, in cotton-wheat-vetch cropping system than that prior to imposition of the cropping systems suggesting that eliminating the fallow in the crop rotation (CV, CWV) may have increased soil compaction. On the other hand, inclusion of a wheat crop followed by a fallow improved porosity. Soil porosity in the cotton-wheat cropping system after post-cotton-picking followed by a wheat crop has been documented previously by other researchers on the Vertisols (Daniells 1989; Constable et al. 1992; Antille et al. 2016).

From the studies conducted thus far, it is evident that effects of weather play an important role in the structural resilience in the fine-textured soils that undergo shrinking and swelling. This is not true for the soils that do not respond to the wet-dry cycles or the freeze-thaw cycles such as the medium-textured soils and the sandy soils. In these soil types, the pores and cementing processes by mucilage and organic matter play a bigger role in soil structure development.

Table 5.2 Effect of crop rotation on soil-specific volume and air-filled porosity

Rotation	Specific volume ($m^3\ Mg^{-1}$)			Air-filled porosity ($m^3\ m^{-3}$)		Slope of residual Shrinkage (r) line	Slope of structural Shrinkage (s) lines
	Oven-dried	End of normal shrinkage zone	Normal swelling limit	End of normal shrinkage zone	Normal swelling limit		
Cotton-cotton	0.65	0.66	0.86	0.26	0.23	0.25	0.21
Cotton-wheat	0.62	0.65	0.91	0.25	0.18	0.16	0.37
Cotton-vetch	0.58	0.61	0.84	0.23	0.16	0.26	0.27
Cotton-wheat-vetch	0.58	0.62	0.79	0.18	0.14	0.21	0.54
SEM	0.013	0.016	0.029	0.022	0.0019	0.071	0.049

Source: Hulugalle et al. (2017b)

5.1.3 Bulk Density

Bulk density (BD) is a measure of soil's weight or mass per unit volume. Thus, a porous soil will have a lower BD and will permit more water infiltration. It will also facilitate roots to grow better than the soil having a higher BD. Bulk density is also one of the indicators for soil compaction. In general, soil BD increases with soil depth. Since the conservation tillage systems maintain high amounts of crop residue on the soil surface, it results in a significant change in soil properties, especially in the upper few centimetres (Anikwe and Ubochi 2007). Siri-Prieto et al. (2007a, b) reported greater BD with no-tillage treatments (1.65 Mg m^{-3}) than the paratilled treatments, at the end of the cotton-peanut (*Arachis hypogea*) rotation on the Coastal Plain soils of Alabama, USA. Paratilling with no-till leads to a significant decline in the BD in the untrafficked and trafficked interrow positions in the surface (0–5 cm) as well as at the lower soil depths (5–15 cm and 15–25 cm). On the grey Vertisols of Auscott, Warren, Australia, Bennett et al. (2017) reported an increase in BD where wheel traffic occurred, irrespective of row spacing or traffic system. The greatest increase was restricted to the topsoil. On the other hand, Veenstra et al. (2006) found BD decreased in the cotton-tomato rotation at the end of 4 years with conservation tillage systems (Table 5.3). These differences were closely related to the number of tractor passes. Inclusion of a cover crop resulted in more number of tractor passes than those without a cover crop. On the Alfisols of Zimbabwe, Gwenzi et al. (2009) found no differences between the conservation and conventional tillage systems with regard to BD.

5.1.4 Soil Compaction and Penetration Resistance

Soil strength is one of the indicators of soil compaction (Batey 2009). Penetration resistance is a common measure of soil strength. Soil compaction increases penetration resistance and restricts root growth. In the field, mechanical restrictions to root growth can be effectively diagnosed by measuring the soil strength. A cone penetrometer will provide a measure of resistance offered by soil in terms of cone index (CI) values. Based on the CI values, the need for tillage operations can be assessed/optimized in order to maintain effective plant rooting and facilitate good water and nutrient uptake. With heavy machine load and shear forces applied in the plough

Table 5.3 Effect of conservation tillage systems on the soil bulk density (Mg m^{-3}) at the end of 4 years of cotton-tomato rotation cycle

	Tillage treatments			
Soil depth	CTCC[a]	CTNO	STCC	STNO
0–15 cm	1.20b	1.05a	1.28c	1.24bc
15–30 cm	1.42e	1.36e	1.37e	1.35d

Source: Veenstra et al. (2006)

[a]*CTCC* conservation tillage with cover crop, *CTNO* conservation tillage without cover crop, *STCC* standard tillage with cover crop, *STNO* standard tillage without cover crop

Table 5.4 Effect of tillage treatments on soil penetration resistance in different soil depths

Tillage treatments	Soil depth		
	0–10 cm	10–20 cm	20–30 cm
Ridge tillage formed in autumn	1.404a	2.054a	2.903a
Ridge tillage formed a month before planting	1.189a	1.808a	2.500b
Conventional mouldboard ploughing	1.814b	2.433b	3.185a

Source: Gürsoy et al. (2011)

zone, the soil structural stability is affected and leads to compaction in the subsoil layers (Wiermann et al. 2000). In the cotton-growing countries of Africa and central India where bulk of the plough operations are done by animal traction, the impact on subsoil compaction would be less than that of the tractor and machine-based farming. Nevertheless, compaction would arise due to animal and human traffic as well. Presently, there are no data to indicate the extent of compaction forces applied in the cotton-based systems.

With regard to the different tillage systems, Gürsoy et al. (2011) in a short-term 2-year study on the irrigated clay loam soils of Diyarbakir, Turkey, reported lower soil penetration resistance with the ridge tillage treatments compared to the conventional tillage systems at all depths (Table 5.4). In general, irrespective of tillage methods, penetration resistance increases with an increase in soil depth (Somasundaram et al. 2019). High CI values in the soil layers >20 cm reaching CI values greater than 2.0 MPa offers considerable resistance to the root growth (Taylor et al. 1966). At soil strength >2 MPa, cotton taproot penetration was about 40% compared with that on where root penetration was not impeded (Taylor and Gardner 1963). The critical threshold for cotton root growth and exploration is 1490 kPa (Bennett et al. 2017, McKenzie and McBratney 2001). Furthermore, soil compaction hinders water flow into the soil and consequently a negative impact on crop growth (Lowery and Schuler 1994). The CI values decreased with increase in soil moisture content (Kumar et al. 2012). A power model of CI on soil moisture content was able to explain 60% of the variability in CI (Eq. 5.1).

$$y = 61.252x^{-1.376} \tag{5.1}$$

Subsoiling is an option to break the hard pans present in the lower soil depths since it helps facilitate root growth and better water entry into the soil. One such example is the use of an in-row subsoiler. It is a form of conservation tillage system that breaks the hard pans without any soil inversion. It also retains substantial amount of crop residues on the soil surface. Raper et al. (2007) on the Coastal Plain Ultisols (coarse-loamy, siliceous, subactive, thermic Plintic Paleudults) of Alabama, USA, reported reduced CI with in-row subsoiling prior to planting. However, the effects of subsoiling are short-lived. Therefore, subsoiling is needed every year especially in soils that are susceptible to compaction. Similarly, results were also reported by Siri-Prieto et al. (2007a, b). Controlled traffic farming was proposed as an alternate option to reduce penetration resistance caused by heavy machinery. Bennett et al. (2017) reported significantly greater percentage of soil depth with penetration resistance less than the critical threshold of 1490 kPa with the controlled traffic farming system than the existing system.

An alternative to subsoiling every year is an option of growing deep-rooted crops in rotation with cotton. Cone index values were greater when cotton was either grown continuously as a mono-crop (cotton-cotton) or cotton was rotated with wheat as compared to lablab (*Lablab purpureus*), field pea (*Pisum sativum*), and faba bean (*Vicia faba*) as a cover rotation crop (Rochester et al. 2001). It is speculated that reduced soil strength contributed to improvement in lint yields of the following cotton crops by facilitating the development of better root systems (Rochester et al. 2001).

5.1.5 Infiltration Rate

Infiltration is the downward entry of water into the soil and is a sensitive indicator of soil quality (Thierfelder and Wall 2010). The velocity at which water enters the soil is infiltration rate and is expressed in mm per hour (Morgan 1995). This soil property depends on the soil texture (percentage of sand, silt, and clay) and clay mineralogy. Movement of water moves is rapid in the sandy soil since water moves through the large pore spaces, whereas it moves slowly in a clayey soil that has a high proportion of small pores. Crop and soil management practices also influence infiltration by modifying soil structure, surface sealing or crusting, and soil organic matter. Management practices that leave very little crop residue leads to a reduction in the soil organic matter content and a poor soil structure. Such soils have a poor infiltration rate than those soils with a good soil structure. Fine texture when combined with good soil structure is known to improve water retention in Vertisols (Vervoort and Cattle 2003; Vervoort et al. 2006; Somasundaram et al. 2018). Generally, conservation agriculture (CA) practices have been found to help maintain or improve water infiltration into soil (Morgan 1995). Tillage practices alter the soil structure and disturb the surface pore continuity. In studies conducted in Zambia, Thierfelder and Wall (2010) observed significantly higher infiltration rate in the CA plots than the conventionally ploughed plots in the cotton-maize rotation. Studies done in Burkina Faso indicated that minimum tillage had a great effect on the infiltration potential of the sandy soil (Lixisol), while compost did not have a big effect on this soil. A reverse trend was seen on the loamy soil (Luvisol) (Ouattara et al. 2006). On the loamy soils, influence of compost on the infiltration was greater than the tillage practices. Siri-Prieto et al. (2007a, b) reported the least infiltration (36% of water applied) with the conventional practices while paratilling increased infiltration in no-tillage to 83%. While on the clay loams (Paleustoll) and loamy sand (Aridic Paleustalf) of Texas, USA, Baumhardt et al. (1993) reported that infiltration rate was not affected by the tillage systems at mid-growing season.

Leaving a residue (standing stubble) leads to lower cumulative evaporation than those with stubble incorporation on Vertisols of New South Wales, Australia. At the

Table 5.5 Effect of wheat stubble management on cumulative evaporation (mm) during drying cycle 4 (sampled February 2010), Australian Cotton Research Institute, Narrabri, NSW (Source: Hulugalle et al. 2007)

Time (h)	Stubble incorporated	Standing stubble
12	4.9	4.1
24	6.8	5.6
48	9.2	7.6
96	12.6	10.4
120	13.9	11.4
180	16.7	13.7
240	19.0	15.6

Source: Adapted from Hulugalle et al. (2007)

end of 240 h, the former treatments had 3.4 mm less cumulative evaporation than the stubble-incorporated cores (Table 5.5). However, the differences in evaporation between stubble incorporation and standing stubble systems were small indicating a more effective storage of water under rainfall in the latter (Hulugalle et al. 2013) was probably due to increase in infiltration rather than a reduction in evaporation. Similarly, Thierfelder and Wall (2010) observed greater soil water storage in maize due to better infiltration rate following cotton with CA practices. Furthermore, a self-mulching layer creates a zone of low water transmissivity between the wetter layers below and atmosphere evaporation dynamics, thus reducing liquid water evaporation. Jalota and Prihar (1990) suggested that in non-self-mulching fine-textured soils, shallow tillage has a similar effect by creating a loose, dry layer of low water transmissivity that reduced evaporation.

Naudin et al. (2010) reported a better water balance with conservation tillage combined with a residue mulch treatment than those without any mulch in Cameroon. Soil hydraulic conductivity and water retention were changed measurably by growing winter cover crops (Keisling et al. 1994). These changes occurred due to an improvement in the soil structural properties such as greater porosity, and proportion of large pores were found to be measurable changed by having winter cover crops.

5.1.6 Soil Erosion

Erosion refers to the process whereby the topsoil is lost and moved from one place to another either by wind or water. Water erosion takes place through (1) detachment of soil particles, (2) movement, and (3) deposition. Detachment of soil particles is subjected to the direct impact and erosive forces of raindrops that dislodge soil particles. It takes place more readily in a bare soil than a soil that has a protective vegetative cover. A tillage system which maintains surface residue, such as the no-till or mulch till, is effective in reducing surface crusting and sealing and thereby increases infiltration capacity and reduced surface runoff and hence reduced erosion risks (Morgan 1995). Furthermore, vegetative cover also significantly reduces the risk of wind erosion. Any form of tillage that induces surface roughness reduces the risk of wind erosion. However, it is dependent on the direction of the wind. When the wind is perpendicular to the ridge tillage, wind erosive forces are substantially low. On the contrary when the ridges are in the direction of the wind, the surface roughness has very little effect. Ridge and mulch tillage are very effective in reducing wind erosion as they trapped the soil particles (Armbrust et al. 1964). However, increasing the height of the ridges >10 cm leads to an increase in erosion because of the wind erosive forces inflicting on the ridge crest. Montgomery (2007) reported that the conservation tillage practices significantly reduce soil erosion and keep it in balance with the rate of production as compared to the conventional tillage practices. Very little crop residue remains from a dryland cotton (Yule and Rohde 1996), with hardly 10% ground cover. Thus, the amount of erosion and sediment load is greater than with a cereal crop having >40% ground cover (Hulugalle et al. 2002). Interestingly, Hulugalle et al. (2002) reported that the length of fallow period also affected suspended soil in the runoff and the soil loss. The greater the length of the fallow, the greater was the soil erosion because the soils were wetter and consequently caused more runoff than those with a shorter fallow length. Wherever length of the fallow period was shorter, it led to greater water infiltration.

Soil erosion by erosive water forces increases with increase in the water runoff from the field. Although CA practices have been identified as erosion-mitigating technology, it may not be suitable for all types of soils. For instance, in the floodplains of the Zambezi, Africa, Baudron et al. (2012) reported no differences in the amount of runoff between the conservation and conventional systems in the fine-textured soils. On the other hand, where the soils were coarse and prone to sealing and surface crusting, more runoff was observed with CA practices than the present farming practices of tillage.

5.2 Soil Chemical Properties

Apart from the soil physical constraints, soil chemical constraints are common and occur in most of the soils, thus, limiting crop productivity. Among the chemical constraints commonly noticed is the poor soil quality and health due to soil infertility. Infertile soils can be due to a deficiency or toxicity of an essential nutrient and/or low organic carbon (C) which is the most researched of the chemical properties.

5.2.1 Soil Organic Carbon

Soil organic carbon (SOC) is a function of the quantum of residue added. Under the semi-arid tropics, where the rate of decomposition is high, the amount of residue needed to bring about a change in the SOC would be greater. This is evident from the large amount of high-quality manure, and green manure application over time brought about a significant improvement in the SOC (Blaise 2006). On the other hand, in spite of the conservation tillage practices over a period of 5 years, very little improvement in SOC was observed (Blaise and Ravindran 2003). Areas cropped with low residue-producing plants (e.g. cotton or peanut) are especially susceptible to soil erosion and reduced SOC due to small amounts of residue returned to the soil. In a recent study of 5 years, Gabhane et al. (2014) reported no significant differences in the SOC between the conservation systems and the conventional tillage systems in the deep black soils (Typic Haplustert) of Akola, Maharashtra, India.

Loss of SOC in the cotton-based systems is common across the cotton-growing regions of the world. In a study on the Australian Vertisols, Senapati et al. (2014) reported substantial loss of SOC at the end of 19 years. Measured SOC storage at the end of 19 years with the cotton-cotton under conventional till was 35.5 Mg C ha^{-1}, whereas with the minimum tillage system, it was 42.6 Mg C ha^{-1} and 40.1 Mg C ha^{-1} under cotton-wheat system, indicating a loss of SOC under cotton-based cropping systems by 0.69–0.96 Mg C ha^{-1} $year^{-1}$. Similarly, in the cotton belt of the USA, Franzluebbers et al. (2012) estimated a loss of SOC by 0.31–0.19 Mg C ha^{-1} $year^{-1}$ in the 0–0.20 m soil depth under conventionally tilled cotton. Kintché et al. (2010) observed a loss of SOC by 2.9–3.2 Mg C ha^{-1} in the top 0.20 m soil layer within 30 years in cotton-based cropping systems under conventional tillage and fertilizer application in Togo, semi-arid Western Africa. Insufficient return of crop residue to the soil, intensive tillage, burning of crop stubble, long bare fallow, excessive water and nitrogen inputs, hot summers, and extreme climatic events such as floods and droughts are probable reasons for the loss of SOC under cotton cropping systems.

On the other hand, some researchers reported an increase in the SOC content. Cultivated sandy Coastal Plain soils have very low SOC (<10 g kg^{-1}), due to highly weathered soils, and climatic conditions tillage causes rapid residue decomposition of SOC (Hunt et al. 1997, Motta et al. 2007). Intensifying soil C input by integrating a winter annual forage crop into the cotton-peanut rotation, coupled with minimal surface soil disturbance (no-tillage or paratill + no-till), increased SOC in this soil after only 3 years (Siri-Prieto et al. 2007a, b). Gwenzi et al. (2009) on the Typic Haplustalfs reported an increase in the SOC content as well as the SOC stocks with minimum and no-tillage compared to the conventional tillage practices. The conservation tillage systems sequestered C (0.55–0.78 Mg C ha^{-1} $year^{-1}$), while there was a decline with the conventional systems (0.13 Mg C ha^{-1} $year^{-1}$). Studies that included sod-based rotations with row crops lead to increase in the SOC (Kintché et al. 2010). In comparison to the cotton-cotton system, lucerne strips had higher SOC in the subsoil of the on-farm Vertisol sites (Hulugalle et al. 1999). Rotations with sorghum increased C pool through residue biomass (Kintché et al. 2010).

In the cotton-based systems, where the amount of crop residue generated is small, it is essential that any small quantity of crop residue that is available be recycled. Because of the relatively high C/N ratios of the cotton stalks (40 ± 80) and root material (80 ± 180) compared to other crops, decomposition of cotton crop residues is slow (Hulugalle et al. 1998). Blaise and Bhaskar (2003), in a laboratory study, also reported the slow decomposition of cotton stalks as compared to the leaves due to the high lignin content. Therefore, the cotton stalks are considered as a waste material and destroyed by burning (Blaise and Ravindran 2003) in most of the tropical cotton-growing countries of Asia and Africa. The burning of cotton residues on the field did reduce the soil organic matter content compared to the control (Kintché et al. 2010).

Stalks can be made more efficient either by reducing the particle size or composting it. But the former requires energy.

Soil C stocks, originally of 15 t ha^{-1} after woodland clearance, decreased by around 3 t ha^{-1} at both sites and for virtually all treatments, reaching lower equilibrium levels after 5–10 years of cultivation (Kintché et al. 2010). Even when residues were incorporated and fertilizers used at high rates, crop C inputs were insufficient to compensate for C losses from these sandy soils under continuous cultivation. Decline in the SOC content of Ferralsol was more determined by a change in soil conditions due to woodland clearance and continuous tillage than by the quantities of C or N inputs added annually (Kintché et al. 2015).

In general studies suggest a decrease in the SOC with tillage. This decrease is primarily due to the physical destruction of the soil aggregates (Blaise 2011) which brings about an increase in soil aeration. As a result, the highly contrasting soil moistening and drying phases increase the vulnerability of SOC to decomposition and degradation (Balesdent et al. 2000). Another cause responsible for the decrease in SOC with the conventional systems could be due to loss of the enriched topsoil caused by various erosive forces.

5.2.2 Available Nutrients

Soil is a reservoir of nutrients that support plant growth. Nutrients are required in quantities that vary from crop to crop, whether the crop is irrigated or rain-dependent and the cultivar. Furthermore, nutrients such as nitrogen (N), potassium (K), and phosphorus (P) are removed in relatively larger or smaller quantities than the other nutrients such as calcium (Ca), magnesium (Mg), and sulphur (S), and the least amounts are those for the micronutrients. A deficiency or toxicity of any of these nutrients leads to a chemical constraint. Thus soil infertility commonly arises due to deficiencies of a single nutrient or multiple nutrients (Blaise and Prasad 2005). Single nutrient deficiencies are now uncommon because of continuous cropping that has resulted in the depletion of the soil fertility and negative nutrient balances. Unless the soil is replenished with what is removed by the crop, nutrient deficiencies are expected to exacerbate. Because of the importance of the macronutrients (N, P, and K) in soil fertility and the large amount of research done on these nutrients, the effects of conservation agriculture systems on these nutrients are discussed here.

Among the nutrients, N is tightly linked to the organic matter. Thus, changes brought about by the conservation tillage systems in the organic matter lead to increases in the available N content. Rochester et al. (1998, 2001) reported significant increase in the root zone available N content with legume cover crops that leads to a reduction in the fertilizer N requirement of the cotton crop. However, over a longer term, differences are small due to presumed recycling of N (Hulugalle et al. 2001). On the contrary, Gabhane et al. (2014) in the rainfed Vertisols of Akola, Maharashtra, India, reported no significant increase in the available N, P, and K content at the end of 5 years of minimum tillage vis-à-vis the conventional tillage. This was possibly because of the high temperature and small quantities of organic

Table 5.6 Effect of tillage on the N, P, and K content of the topsoil (10 cm)

Total N (%)	Total P (mg/kg)	Available K (mg/kg)	Total K (mg/kg)
0.87	118	96	1314
0.83	108	86	1171
0.86	111	77	1155

Source: Adapted from Koulibaly et al. (2016)

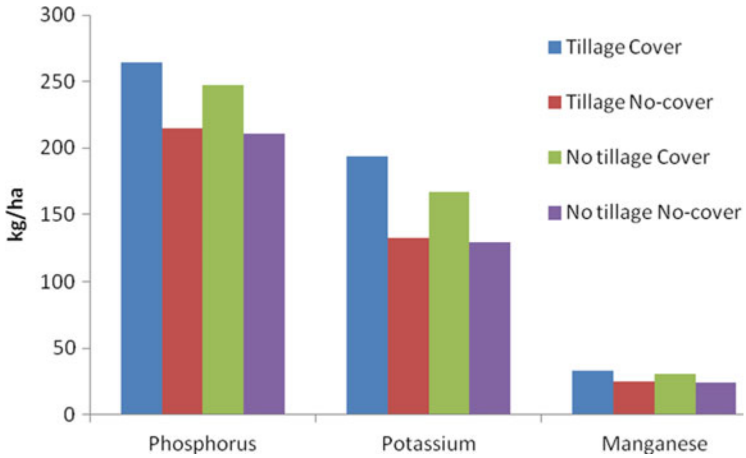

Fig. 5.4 Effect of cover crops on soil nutrient status (Adapted from Marshall et al. 2016)

residue getting recycled back into the soil (Blaise and Ravindran 2003). In the Lixisols of Burkina Faso, Koulibaly et al. (2016) reported an increase in total P, available K, and total K in the top 10 cm soil surface (Table 5.6). However, there were no changes in the organic C and the N content. However, when a cover crop is integrated into the conservation tillage systems, a significant increase in the soil available P by 17%, K by 26%, and Mn by 33% (Fig. 5.4) was observed in the Ultisols of Blackville, South Carolina, USA (Marshall et al. 2016). Studies clearly indicate that it is necessary to include a legume or biomass-producing cover crops.

5.2.3 Stratification of Organic C and Nutrients

Long-term conservation systems result in a vertical stratification of nutrients, i.e. the nutrients get concentrated in the top 30 cm soil layers, whereas in the conventional tillage systems, soil mixing occurs due to the mouldboard ploughing and soil inversion. These changes brought about by the conservation systems have a profound effect on the availability of nutrients to the crop. Studies in the cotton-based systems in the USA have suggested no-till systems to have greater SOC levels in the top 0–10 cm as compared to the conventional systems. Similarly, Gwenzi et al. (2009) reported greater SOC levels in the topsoil with the minimum and no-till

Table 5.7 Effect of the tillage systems on SOC content and the SOC stock with soil depth on the Typic Haplustalf of Zimbabwe

	SOC (g kg^{-1})			SOC stock (Mg C ha^{-1} y^{-1})		
Soil depth (cm)	CT[a]	MT	NT	CT	MT	NT
0–15	2.9a	5.6b	5.8b	7.3a	13.9b	13.5b
15–30	2.9a	4.7b	5.1b	6.9a	11.8b	12.8b
30–45	2.9	3.2	3.3	7.3	8.1	8.0
45–60	2.6	2.9	3.0	6.3	7.1	7.0

Source: Adapted from Gwenzi et al. (2009)
[a]*CT* conventional till, *MT* minimum till, *NT* no-till

systems than the conventional till systems while differences were not significant at lower depth (Table 5.7). On the Hapludox soil of Mato Grosso, Brazil, Souza et al. (2018), at the end of 9-year long-term study, reported that the differences in SOC were restricted to the top 5 cm of the soil with greater concentration in no-till cotton compared to the conventional tilled cotton. These differences arise due to the physical protection offered by the no-till systems as well as the diverse crop residues added into the system under no-till systems. On the silt loams of Memphis, USA, Howard et al. (1999) observed vertical stratification of extractable P and K. Conservation tillage usually improves the availability of surface P by converting it into organic forms of P. Crops take up P from below, "mining" and depositing it on the surface. In standard tillage systems, this P would be remixed into the soil profile, whereas in conservation tillage, it accumulates at the surface (Robbins and Voss 1991; Zibilske et al. 2002). Veenstra et al. (2006) reported increase in available concentrations of nitrate and P following conservation tillage systems in San Joaquin Valley, California, USA. In contrast, the conservation tillage system redistributed K to the surface of the soil. In the semi-arid tropics of central India, Blaise (2003) reported vertical and horizontal stratification of the mineral N, available P, and exchangeable K. Greater extractable P were observed in the plant row which was fertilized than the between cotton row samples (Fig. 5.5). Thus, if such conservation systems are practiced continuously, there will be a need for special sampling techniques (Blaise 2003) to address issues of soil fertility.

5.2.4 Salinity and Sodicity

Cotton is moderately tolerant to salinity. Most of the cotton is grown on nonsaline and non-sodic soils although the irrigated cotton is afflicted with the problems of soil salinity. In a field study in Syr Darya River Basin, Uzbekistan, Bezborodov et al. (2010) reported a 20% increase in salinity after cotton harvesting in 2007 without mulch, while in the corresponding treatment with mulch, it was negligible. Similar trend was observed with regard to sodicity. In the MSW treatment, sodium absorption ratio (SAR) of upper 0.15 m soil increased from 2.60 (pre-experiment level) to 5.26 after cotton harvesting in 2007. In the case of the same water quality irrigation

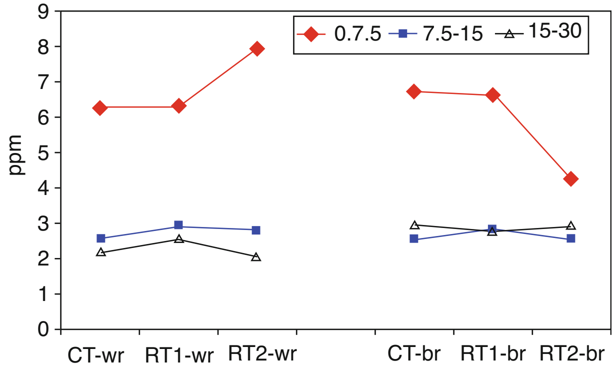

Fig. 5.5 Soil P stratification within row (wr) and between rows (br) as affected by tillage systems (CT, conventional tillage; RT, reduced tillage). Source: Adapted from the data in Blaise 2003

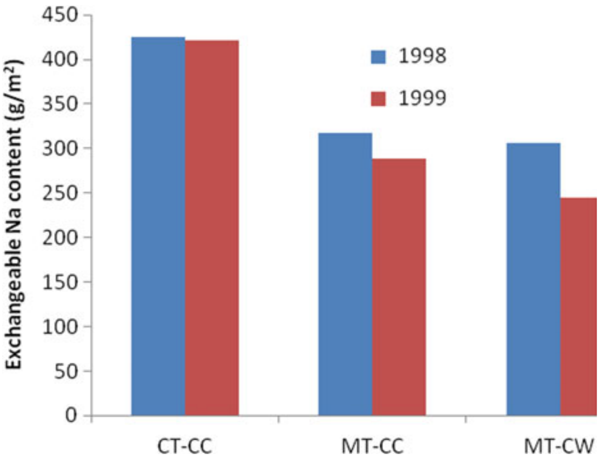

Fig. 5.6 Effect of tillage and crop rotation on soil sodicity in the 0–0.60 m soil depth. Adapted from Hulugalle et al. (2004)

with mulching (MSW + M) of alternate furrows, SAR of the same soil depth increased from 2.98 to 3.98; only one-third of the increase is observed in the MSW treatment. However, when the entire soil depth (90 cm) was taken into consideration, changes in the post-cotton samples for soil salinity and sodicity were not as large as in the case of the topsoil (15 cm). In Australia on the Vertisols, Hulugalle et al. (2004) found that the sodicity was lower with the minimum tilled cotton-wheat rotation than the conventional tilled continuous cotton systems (Fig. 5.6). Hulugalle et al. (1996) reported that the exchangeable sodium percentage at the bed surface was significantly reduced with incorporation of dolichos residue (1.2%) as compared to surface mulch retention (3.9%). Similar trends were observed for below bed samples. In general, the beneficial effects of conservation tillage and mulching could be due to reduced water loss through evaporation, either the shading of the soil (Huang et al. 2005) or as a vapour barrier by the surface crop residue against moisture loss from the soil (Mulumba and Lal 2008). In addition, with conservation tillage systems due to better soil structure, pore continuity is greater with the cotton-wheat than the cotton-cotton rotation system (Hulugalle et al. 1997). Due to greater pore continuity, the salt and nutrient leaching is facilitated (Jabro et al. 1991) under conservation tillage systems than the conventional tillage systems.

5.2.5 Soil Biological Properties

Giller (1996) reported that soil disturbance by tillage is one of the major factors which result in reductions in diversity of soil organisms due to desiccation, mechanical destruction, soil compaction, reduced pore volume, and disruption of access to food resources. Tillage disturbs soil structure heterogeneity, thereby affecting the relative population size and diversity of dominant soil microbial species that lead to changes in the relationships among the members of the soil biota within the soil ecosystem (Altieri 1999). In general, soil microbial communities respond to variations in tillage intensity in different ways, resulting in differences in soil ecology. This in turn contributes to variation in soil microbial stability when responding to abiotic disturbance and stress (Philippot et al. 2013).

5.2.6 Soil Enzyme Activities

Soil enzymes play a critical role in catalysing the reactions necessary for organic matter decomposition and nutrient cycling and were used as indicators of soil health by many researchers (Dick 1994; Velmourougane and Sahu 2013). Management practices such as tillage, crop rotation, and residue management may have varied effects on soil enzyme activities (Acosta-Martinez et al. 2003, 2004a, b). In the conservation tillage systems, Acosta-Martinez et al. (2004a) reported significant improvements in the enzyme activities in the surface soil layer. Increase in β-glucosidase, β-glucosaminidase, and alkaline phosphatase activities were observed in continuous cotton with conservation tillage on the fine sandy loam and loamy soils. However, differences were not significant on the sandy clay loam. Mankolo et al. (2012) on the Typic Paleudults reported all the enzyme activities were positively influenced by conservation tillage with cover crop rotation and use of poultry manure. On the rainfed Vertisols of central India, Blaise and Velmourougane (2014) reported higher enzyme activity in the surface than at lower soil depth. However, Green et al. (2007) did not observe significant differences among tillage practices for any of the enzyme activities on a soil profile basis (0–30 cm) in an Oxisol in the Cerrado region of Brazil. This shows that tillage mainly changes the vertical distribution of enzyme activity within the profile. Stratification of enzyme activities in the soil profile is mainly due to vertical distribution of organic residues and microbial activity and the strong correlation with the SOC and total N (Mankolo et al. 2012). Enzyme activity was better in the rotation systems than growing continuous cotton as a monoculture. Hota et al. (2014) noticed that incorporation of organic residues along with zero tillage showed greater acid phosphatase activities than the conventional tillage without residue.

5.2.7 Soil Microbial Biomass

Microbial biomass, the living component of SOM, is considered the most labile C pool in soils and a sensitive indicator of changes in soil processes/management practices, with links to soil nutrient and energy dynamics (Lupwayi et al. 2012; Wright et al. 2008). Soil tillage can influence the quantity and persistence of binding agents, which may lead to aggregate formation or breakdown (Six et al. 2000; Somasundaram et al. 2017). Intensive tillage disrupts the soil aggregates by fragmenting the roots and mycorrhizal hyphae, which act as a major binding agent for micro-aggregates leading to lower soil aggregation and structural stability in conventional tillage as compared to CA (Wang et al. 2015).

Researchers have studied the relationship between microbial biomass and soil properties like moisture (Herron et al. 2009), temperature (Li and Chen 2004), SOM content (Bardgett and Shine 1999), texture (Grandy et al. 2009), and depth (Hansel et al. 2008), which all are highly influenced by the tillage practices. In the cotton-based systems on the silty loam of Alabama, USA, Motta et al. (2007) reported significantly greater microbial biomass C in the surface layers with conservation tillage than the conventional tillage systems. In the same study, soil microbial biomass C was greater with rotation than continuous cotton monoculture (Fig. 5.7). On silty loams of Texas, USA, Wright et al. (2008) observed 11% increases in soil microbial biomass C with reduced tillage over the conventional

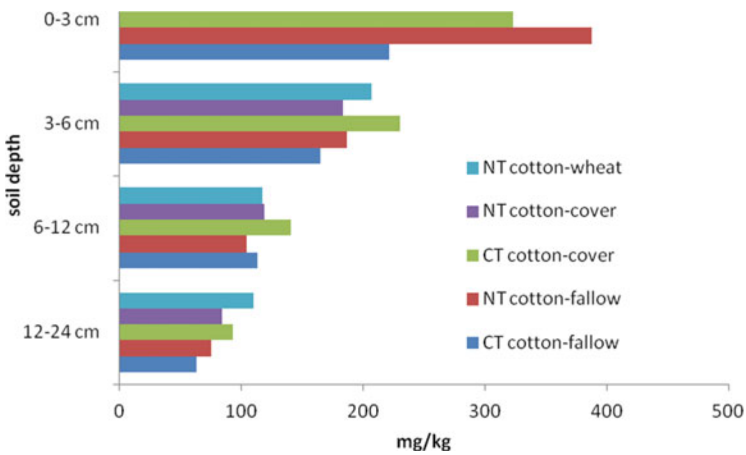

Fig. 5.7 Soil microbial biomass C as affected by tillage and crop rotation (Adapted from the data of Motta et al. 2007)

tilled cotton. Corresponding values for increase in the soil microbial biomass N was 62%. Furthermore, soil microbial biomass C was greater in the corn-cotton rotation than growing cotton alone. The favourable effects of zero tillage and residue retention on soil microbial populations are mainly attributed to increased soil aeration, cooler and wetter conditions, lower temperature and moisture fluctuations, and higher carbon content in surface soil (Doran 1980).

5.2.8 Microbial Population, Community Structure, and Diversity

Microorganisms play a vital role in ecologically important biogeochemical processes (Kennedy 1999). Microbiological properties are the most sensitive and rapid indicators of perturbations and land-use changes, as they develop in response to constraints and selection pressures in their environment (Lupwayi et al. 1998; Kuramae et al. 2012). Soil microbial diversity can directly influence plant productivity and diversity by influencing plant growth and development, plant competition, and nutrient and water uptake. The variations in microbial populations and their diversity are attributed to the differences in soil physical and chemical properties. In general, the microbial communities are reported to be affected by the following variables, in order of decreasing importance: soil type > time > specific farming operation > management system > spatial variation (Bossio et al. 1998). Acosta-Martinez et al. (2003) reported no differences among the management practices, but the fatty acid methyl ester profiles varied among the soil types mainly due to the differences in the enzyme activities found among the soils. In another study, Acosta-Martinez et al. (2004b) reported what when cotton was grown either in rotation or integrated with pasture and livestock, it had greater protozoa (20:4ω6c = 1.98%) and fungi (18:3ω9c = 1.30%) than under continuous cotton (20,4ω6c = 1.09%; 18:3ω9c = 0.76%). Sorghum-cotton and cotton-rye-sorghum crop rotations had lower ratio of fungi to bacteria than those under sorghum-rye. Soil under sorghum-rye showed higher population densities of *Bacteroidetes* and *Proteobacteria* while lower *Actinobacteria* compared to sorghum-cotton and cotton-rye-sorghum (Acosta-Martinez et al. 2010).

Conservation tillage that minimizes soil disturbance may promote root growth so as to select for favourable bacterial populations (Bulgarelli et al. 2013). Conservation tillage enhances abundance of plant growth-promoting rhizobacteria that perform multifunctional roles in rhizosphere (Yuan et al. 2015). Simmons and Coleman (2008) observed significant differences in the microbial communities on the Ultisols of Georgia, USA. Fungi, characterized by 18:2ω6, 18:1ω9, and 18:3ω6c fatty acids, were typically the lowest in the conventionally tilled soil, probably due to repeated disruption of the fungal hyphae associated with tillage. High amounts of dissolved organic carbon and invertase activity under zero tillage were shown to sustain the stability of proteobacteria (α-, β-, γ-) and bacteroidetes (Peiffer et al. 2013), which helps in possible role in nitrogen cycling (Chaparro et al. 2014). Conservation tillage systems, as seen in the previous sections, resulted in better soil structure, which enhances bacterial diversity, whereas plough tillage alters microbial interactions through reduced pore volume, soil compaction, erosion, and desiccation. Thus CA systems with tillage, cover crops, and crop rotations lead to an improvement in soil bacterial community resistance and resilience.

5.2.9 Transgenic Cotton Effects on Soil Biological Properties

Compared to the studies on CA in cotton-based systems on the soil biological properties, several studies have been conducted to assess the impact of the transgenic cotton cultivation on soil biological properties. Transgenic cotton developed for control of lepidopteran pests produces cry toxin in the plant. This cry protein is toxic to the cotton bollworm. However, when the fruiting parts, leaves, are shed, the toxin is added to the soil. Furthermore, the toxin could also be leached into the soil through the root exudates. A summary of the results of the various studies is presented in Table 5.8. In general, no adverse effects of the cry toxin was observed on the soil microflora or the fauna since the toxin is relatively short-lived and also gets adsorbed onto the clay-organ complex making it unavailable in the active form.

5.2.10 Macrofauna

Influence of soil macrofauna on soil physical properties such as soil aggregation are well known (Kooistra 1991). Among the macrofauna, earthworms and termites have strong impact on soil environment and are called as "ecosystem engineers" (Lavelle et al. 1999, Jones and Eggleton 2000). Limited data is available on the effects of CA systems on the macrofauna. Zida et al. (2011) reported no differences between the animal or hand tillage in the savannah zone of Saria, Burkina Faso. However, with recycling of crop residue and manure, significant improvement in the population of earthworms and termites was observed. Among the rotations, cotton-sorghum rotation had fewer numbers of termites than the sorghum alone due to the differences in food stock with soil depth and the quality.

5.3 Conclusions

Soil is a reservoir of nutrients and supports plant growth. For sustainable cotton production, it is essential to maintain soil health and quality. Various indicators are available to determine soil quality and health. Thus, the effects of conservation tillage/agriculture systems were assessed on the soil physical, chemical, and biological indicators. In general, adoption of conservation tillage systems in cotton-based systems indicated positive improvement in the soil physical, chemical, and biological properties. However, the conservation agriculture systems may not be suitable for all soil types and environments. Thus these parameters can be used to delineate management practices in the cotton-based systems.

Table 5.8 Effect of Bt cotton on soil microbial activity and functions

Experiments	Findings	References
Microbial population, composition and diversity		
Bt (Cry1Ac) and non-Bt cotton	A significant, but transient, increase in numbers of culturable bacteria and fungi in soil grown with Bt cotton	Donegan et al. (1995)
Bt (Cry1Ac) and herbicide tolerance (roundup ready) cotton	Significant difference in microbial composition in soil with Bt cotton residues than in soil with herbicide-tolerant cotton	Gupta and Watson (2004)
Bt (Cry1Ac) and non-Bt cotton	Extensive fungal colonization, higher ratios of fungi to bacteria, and different types of fungal spores in soil with Bt cotton than non-Bt cotton	Gupta and Watson (2004); Gupta et al. (2002)
Bt (Cry1Ac) and non-Bt cotton	Higher culturable bacteria (potassium and phosphate solubilizers and nitrogen fixers) in soil grown with non-Bt cotton in early and middle growth stages of cotton; no significant differences in numbers after the growing season	Rui et al. (2005)
Bt (Cry1Ac) and non-Bt cotton	No adverse effect on soil microbial populations	Valasubramanian (2001)
Bt (Cry1Ac) and non-Bt cotton	No adverse effects on microbial functional diversity and enzyme activities	Shen et al. (2006)
Bt (Cry1Ac) and non-Bt cotton	Higher microbial population/diversity in soil grown with Bt cotton than the non-Bt cotton	Velmourougane and Sahu (2013); Velmourougane et al. (2014)
Soil enzymes		
Bt (Cry1Ac) and non-Bt cotton	No differences in urease, alkaline phosphatase, dehydrogenase, phenol oxidase, and protease activities	Shen et al. (2006)
Soil amended with Bt (Cry1Ac) and non-Bt cotton biomass	The Bt cotton biomass addition stimulated the soil enzymes, viz. urease, acid phosphomonoesterases, invertases, cellulases, and inhibited the arylsulfatase	Sun et al. (2007)
Bt (Cry1Ac) and non-Bt cotton	Significant reduction in dehydrogenase activity in the rhizosphere of Bt-cotton	Sarkar et al. (2008)
Bt (Cry1Ac) and non-Bt cotton	Higher soil enzyme activity of urease, nitrate reductase, acid and alkaline phosphatase in Bt cotton	Mina et al. (2011)
Bt (Cry1Ac) and non-Bt cotton	Higher soil enzyme activity of urease and dehydrogenase in Bt cotton	Velmourougane and Sahu (2013); Velmourougane et al. (2014)
Nutrient recycling and other soil functions		
Bt (Cry1Ac) and non-Bt cotton	Lower soil respiration (CO_2 evolution) from soils amended with biomass of Bt cotton than with biomass of near-isogenic non-Bt counterparts	Flores et al. (2005)

(continued)

Table 5.8 (continued)

Experiments	Findings	References
Bt (Cry1Ac) and non-Bt cotton	Significant reduction in soil respiration in the rhizosphere of Bt-cotton over non-Bt	Sarkar et al. (2008)
Bt (Cry1Ac) and non-Bt cotton	Total mineral N was reduced in Bt cotton, whereas Olsen-P was increased	Sarkar et al. (2008)
Bt (Cry1Ac) and non-Bt cotton	Higher biological activities (soil respiration, fluorescein diacetate activity, microbial biomass carbon) in soil grown with Bt cotton than the non-Bt cotton	Velmourougane and Sahu (2013); Velmourougane et al. (2014)

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Impact of Conservation Agriculture and Residue Management on Soil Properties, Crop Productivity Under Pulse-Based Cropping Systems in Central India

6

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Abstract

Crop residue management is prime consideration in attempting fertility optimization in pulse-based cropping systems under soil-protective tillage technologies. Conservation tillage is a crucial element of conservation agriculture which has intended to support sustainable soil health and crop productivity. Conservation agriculture provides a new paradigm in agricultural research which primarily differs from conventional tillage and aimed to achieve specific production targets of food grains in India. Conservation tillage together with other supplementary practices such as soil cover with residue retention and crop diversity by including pulse crops was therefore emerged as a feasible way of ensuring sustainable production of food and helps in maintaining ecological integrity. Therefore, this book chapter reviewed how crop residue recycling is essential in achieving sustainable crop production in pulse-based cropping systems in Central India.

Keywords

Conservation agriculture · Pulses · Residue · Soil health · Tillage

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6.1 Introduction

Conservation agriculture (CA) technology is widespread and practiced for about six to seven decades globally (Lal 1976). Wherever CA was adopted, it seems to have benefits for both agriculture and environment. Yet, CA reflects a radical shift in thought on agricultural system production. This technology is perplexing and sometimes unrecognized factors supporting soil quality, productive potential, and services to the ecosystem (Kassam et al. 2009). The key requirement for effective CA systems is to have optimum root-zone ecosystem to the possible maximum depth. Beneficial biological activity and the plant roots are therefore carried on to the rhizosphere soil to maintain and reconstruct the soil structure and compete with plausible soil microbes, contributing to organic matter in soil and further to plant nutrient acquisition, retention, and chelation (Kassam et al. 2009).

CA has huge potential to convert mono-cropping areas to diversified cropping system and rotation involving double cropping through the introduction of low water-requiring pulses. In pulse-based cropping systems, pulse crop residues (foliar residue above soil surface and radical residues below the surface) are added as organic material which enhances soil biota and carbon accumulation in the soil (Somasundaram et al. 2018, 2019). Pulse cropping systems under CA can achieve increased levels of nitrogen in soil, increased root zone cation exchange capacity, increased rate of crop biomass, nutrient recycling, and speed recuperation of soil porosity (CropLife International 2005). In central India (Madhya Pradesh), around 11,173 (thousand ha) is under pulse crop cultivation which accounts for 51% of total cultivated area under different crops (Ministry of Agriculture and Farmers' Welfare 2016). Hence, there is an ample scope of utilizing pulse crop residues efficiently in CA system.

6.2 Crop Yield and System Productivity Under Pulse-Based Cropping Systems in CA

Pulse crops are crucial in relation to sustainable crop production, soil health, and nutritional security. Pulse residue is well known for its high C:N ratio in addition to availability of other plant nutrients. Data on nutrient composition of lentil residue and cereal residues is furnished in Table 6.1. There is a threefold increase in nitrogen content in residue of lentil when compared to residue of cereals. Other nutrients

Table 6.1 Nutrient contents of pulse residue in relation to cereal residues

Nutrient content	C (%)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	S (%)	Zn (mg/kg)	C:N ratio
Rice	47.7	0.54	0.11	1.68	0.8	0.48	0.09	119	88
Wheat	52.8	0.64	0.14	0.94	0.8	0.24	0.13	123	85
Lentil	48	1.64	0.12	1.68	4	0.24	0.47	148	29

Source: Modified from Lal 1998

Table 6.2 Quantity and nutrient contribution of leaf fall in different pulses

Parameter	Chickpea	Lentil	Pigeon pea
Leaf litter (t/ha)	1.1–1.7	1.3–1.6	1.3–2.8
N (kg/ha)	7.0–14.0	8.0–10.0	8.0–16.0
P (kg/ha)	3–5.5	3.5–4.5	2.5–5
K (kg/ha)	8.0–20.0	12.5–19	13.5–24

Source: Modified from Kumar and Yadav (2018)

like K, Ca, and S are found to have in higher contents in pulse crop residue, which are further released into the soil after incorporation.

From the years, pulses have been recognized as crops of “soil building”. These crops are widely recognized for restoring soil fertility in the cropping systems (Dhakal et al. 2016). This increase in soil fertility is mainly due to their inherent nitrogen-fixing ability, soil nutrient mobilization, and leaf shedding nature which is the most specific characteristics in pulses (Ofori and Stern 1987). Significant amount of leaf fall (leaf litters) is found in different pulse crops which add nutrients after decomposition to the soil (Table 6.2) (Kumar and Yadav 2018; Somasundaram et al. 2018). Inclusion of pulse crop in cropping systems has a positive impact on overall system productivity of the succeeding crops due to their residual effects on soil properties, and it will function as a part of integrated plant nutrient supply system. Pulses can arrest the declining trend in cereal-cereal system productivity by improving the physical, chemical, and biological environment in the soil (Savci 2012). Consequently, pulses are now a feasible alternative for enhancing sustainable soil health and natural resource conservation for sustainable farming.

Preceding pulse crop in sequential cropping contributes residual N in the range 18–70 kg/ha to the successive crop (Ali and Mishra 2000). Yield of cereal crops taken after legumes in crop rotation is increased, which is due to residual effect of N through biological nitrogen fixation (BNF) and additional root biomass by legumes to the successive wheat crop (Sinsinwar 1994). A study on residue management resulted in enhanced grain yield of *rabi* sorghum by 15.6% grown after preceding mung bean crop in *kharif*, and further residue incorporation of mung bean has substituted 50% NPK demand of *rabi* sorghum crop.

In India, over 70% of the area of pulses is occupied under intercropping systems (Singh et al. 2009a, b). In central and peninsular India, sorghum intercropping with pulse crops in Vertisols was found to be more remunerative and productive. In Vertisols, sorghum + pigeon pea intercropping was recorded to be most productive, whereas pearl millet + pigeon pea intercropping was proved ideal on Alfisols and Entisols (Ali and Singh 1997). Higher grain yield of pigeon pea (2676 kg/ha) and pigeon pea equivalent yield (3146 kg/ha) were attained in sorghum + pigeon pea (2:1) intercropping system at IIPR, Kanpur (Singh et al. 2009a, b), due to differential rooting depth of component crops. Pigeon pea is deep-rooted legume which can tap moisture and nutrients from deeper soil layers, thereby reducing competition for resources when intercropped with cereals. Increase in 20% higher yield of sorghum in sorghum + soybean intercropping system is reported by Fujita et al. (1992), due to

Table 6.3 Major pulse-based cropping systems in central India

Irrigation availability	Cropping systems
Rainfed conditions	Mung bean-sorghum
	Urdbean-wheat
	Mung bean-niger
	Cowpea/urdbean/mung bean-safflower
Irrigated conditions	Maize-wheat-summer urdbean/mung bean
	Maize-wheat-summer cowpea

Table 6.4 Productivity and economics of different cropping systems with and without summer mung bean

Cropping system	Yield (tonnes/ha)			Total productivity (tonnes/ha)	Net returns over variable costs (Rs/ha)	% increase in net returns over RWCS
	Rice	Wheat/ potato	Summer mung bean			
Rice-wheat	7.0	4.8	–	11.8	38,116	–
Rice-wheat-summer mung bean	7.0	4.8	1.16	12.96	48,316	26.7
Rice-potato-summer mung bean	7.0	24.0	1.75	32.75	53,150	39.4

Source: Sekhon et al. 2006

higher N availability in soils. Major cropping systems in central India are given in Table 6.3.

Diversification of cropping systems with pulse crops augments available N in soil and soil moisture conservation and further enhances system productivity. Gan et al. (2015) studied three-year cropping sequence in Saskatchewan with pulse and summer fallow-based cropping systems and revealed that there is a significant increase in grain yield by 33.5%, 50.9% increase in protein yield, and 33.0% rise in N use efficiency of fertilizers in pulse-based cropping system over summer fallow system. Horizontal diversification of existing cropping systems with pulses can act as an efficient alternative to summer fallowing. Higher total productivity (1.16 tonnes/ha) and net returns (Rs 10,200) were observed in rice-wheat-summer mung bean cropping system in comparison with conventional rice-wheat cropping system (RCWS) (Sekhon et al. 2006) (Table 6.4).

At Varanasi, Singh et al. (2011) evaluated the productivity of various cropping sequences on sandy loam soils. Mung bean crop inclusion in RWCS recorded higher system rice equivalent yield (REY) (13.9 tonnes/ha) when compared to conventional rice-wheat cropping system and showed that the effect of crop rotation has a significant positive impact in improving overall system productivity (Fig. 6.1). Inclusion of pulses in RWCS is therefore best alternative to boost farmers' net

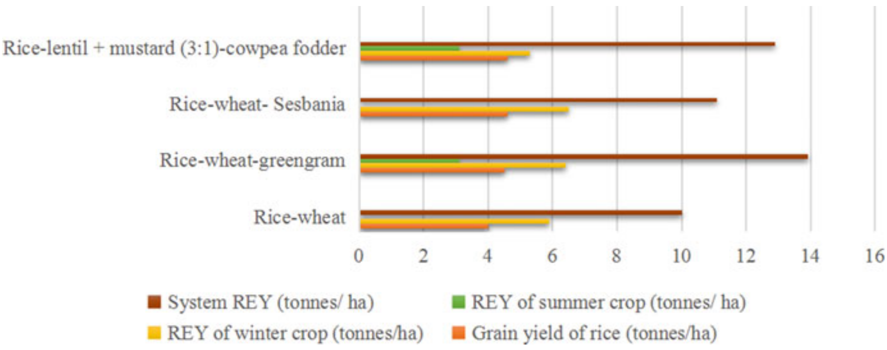

Fig. 6.1 Productivity of different crop sequences at Varanasi on sandy loam soils (modified from Singh et al. 2011)

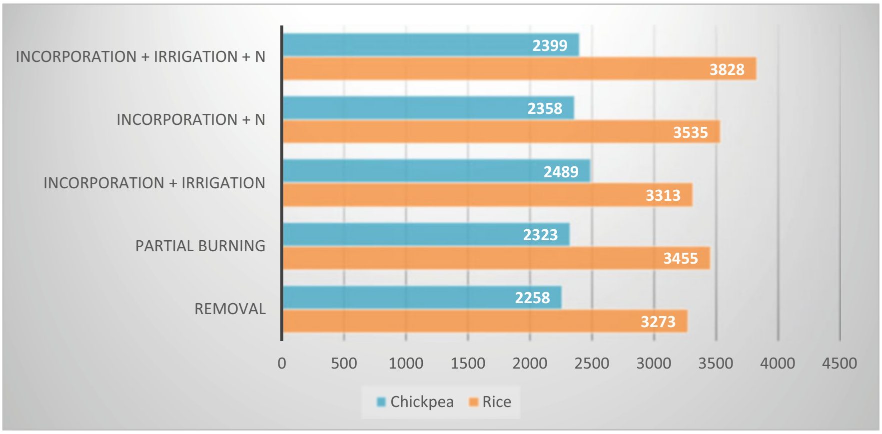

Fig. 6.2 Grain yield of rice and chickpea as influenced by residue incorporation in sequential cropping (Source: modified from 25 Years of Pulses Research at IIPR 2009)

returns. In a long-term experiment, highest overall system productivity is recorded on the basis of chickpea equivalent yield in rice-wheat-mung bean cropping system (10,050 kg/ha) and then followed by rice-chickpea system (8264 kg/ha) and rice-chickpea-rice-wheat system (7305 kg/ha) when compared to rice-wheat cropping system (IIPR 2012).

Incorporation of crop residues is crucial to enhance soil properties, besides the supplement of the fertilizers, and thereby improving crop productivity and fertilizer use efficiency. In rice-chickpea cropping sequence, chickpea yields are influenced by incorporation of rice residue, and higher grain yield was observed in incorporation of chopped straw + irrigation +20 kg N/ha, while the treatment with residue removal recorded lowest grain yield of chickpea (Fig. 6.2).

6.3 Impact of CA on Soil Properties in Pulse-Based Cropping Systems

6.3.1 Physical Properties

Crop residues in CA form an integral component for nutrient cycling and have significant role in sustaining the soil physicochemical and biological properties. Conservation tillage has vital role in improving soil fertility (Sharma and Acharya 2000; Bazaya et al. 2009) and further attributing to overall improvement in soil health, crop productivity, water use efficiency, and farmers' income (Yaduvanshi and Sharma 2008). Benefits from soil conservation tillage over conventional tillage are given in Table 6.5.

Retention and incorporation of crop residues through CA is a prominent source of soil organic matter input addition in soils which eventually improves physical properties of soil. These physical properties in turn affect the level of chemical and biological reactions important for crop growth and development (Sharma and Bhushan 2001). Such incorporation of residues showed decline in soil bulk density and increased rate of infiltration, water holding capacity (WHC), microbial biomass, and soil fertility in comparison to no residue treatment. Sudha and George (2011) reported that both residue management and tillage practices are found to improve soil physical properties like bulk density, porosity, aggregate stability, and water holding capacity which in turn reflected in terms of increased yield and returns. Significant decline in bulk density and increase in soil organic carbon and rate of infiltration in rhizosphere are found with conservation tillage (Singh et al. 2013) (Fig. 6.3).

Compared to conventional tillage (CT), zero tillage (ZT) can encourage aggregation by reducing the destruction of aggregates, by increasing interaction between soil microbes and organic matter, and by forming macroaggregates through enhanced growth of hyphae (Beare et al. 1994; Somasundaram et al. 2017a, b, 2018). Stable state infiltration rate is highest under double ZT in rice-wheat crop rotation when compared to CT (Jat et al. 2009). Increase in levels of soil organic carbon (SOC) was reported in ZT when compacted with CT (Paustian et al. 1997). Improved soil physicochemical properties was observed under ZT, where there is increased stable aggregates by 61%, lowered bulk density by 12%, increased organic matter by 10%,

Table 6.5 Benefits from soil conservation tillage over conventional tillage

Component	Average benefit
Infiltration rate	43% increase
Soil moisture retention (0.8 cm)	18% increase
Soil bulk density	4% improvement
Soil microbes	44% increase
Soil mineral nitrogen depletion	69% reduction
Total oxidized nitrogen emissions	94% reduction
Soluble phosphate emissions	78% reduction

Source: CropLife International (2005)

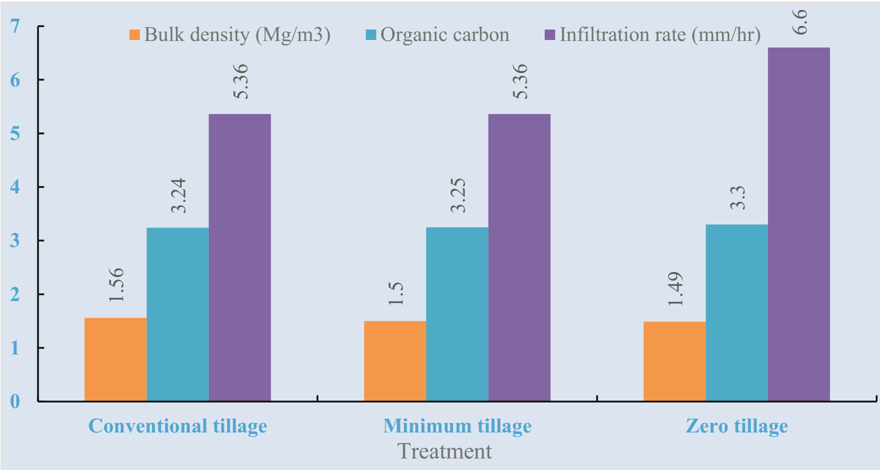

Fig. 6.3 Effect of tillage practices on soil properties in pigeon pea-wheat rotation

and increased total N by 55% in comparison to tillage with mouldboard plough (Vargas Gil et al. 2009).

6.3.1.1 Soil Aggregation

Aggregate stability is a key parameter of soil quality and can be used as an index to assess long-term soil quality shifts. Inclusion of pulses in the cropping system enhances soil aggregate stability and in better soil structure formation. The presence of "glomalin" which is a glycoprotein produced by fungi, present in rhizosphere of pulse crops, favours entrapping minerals, organic matter, and soil debris due to its sticky nature which aids in formation of soil stable aggregates. Therefore, microbial activity in the rhizosphere is responsible for improving soil structure in pulse-based cropping systems. Increase in cropping frequency and inclusion of legume as green manure decreased the wind-erodible fraction of soil which directly corresponds with increase in soil aggregation (Biederbeck et al. 1998). Enhanced soil aggregate stability leads to reduced soil erodibility and crusting by increasing pore space and soil tilth.

6.3.1.2 Bulk Density and Hydraulic Conductivity

Pulses leave a significant amount of residues, which lower the bulk density of the soil and subsequently improve soil structure for the growing succeeding crops in sequence (Ganeshamurthy et al. 2006). In rice-wheat-mung bean cropping sequence, incorporation of mung bean residue resulted in improved bulk density (lower) and increased hydraulic conductivity (IARI 1995). However there is significant improvement in soil physical condition when pulse crop residues are incorporated after harvesting of rice. Inclusion of pulse in maize-wheat crop rotation lowered bulk density of soil (Singh and Sandhu 1980).

Table 6.6 Effect of cropping systems and tillage and crop residue management on soil properties (0–15 cm soil depth), grain N uptake, and yield

Treatment	Bulk density (Mg/m^3)	Hydraulic conductivity (cm/h)	Soil organic carbon (g/kg)	Grain N uptake (kg/ha)	Grain yield (kg/ha)
Cropping system					
M-M-G	1.50	1.55	3.38	30.08	844.3
M-C-G	1.53	1.70	4.03	35.91	899.2
M-L-G	1.63	1.50	3.30	24.26	694.7
M-W-G	1.62	1.50	3.33	22.92	769.2
CD ($p = 0.05$)	0.04	0.36	0.48	6.92	111
Tillage and residue management					
CT-R	1.58	0.74	2.73	26.66	752.7
CT + R	1.50	1.36	3.58	38.16	1062.2
ZT-R	1.65	0.89	3.38	20.10	602.7
ZT + R	1.61	1.26	4.35	28.25	789.7
CD ($p = 0.05$)	0.09	0.20	0.62	6.68	101.3

Maize-mustard-green gram (M-M-G), maize-chickpea-green gram (M-C-G), maize-linseed-green gram (M-L-G), maize-wheat-green gram (M-W-G), +R (with residues), −R (without residues)
Source: Modified from Meena et al. (2015)

Meena et al. (2015) reported that at 0–15 cm soil depth, cropping systems and different tillage practices have shown significant positive impact on soil bulk density. Bulk density (BD) was lower in ZT with addition of residues and in M-M-G and M-C-G cropping systems. Saturated hydraulic conductivity was high in M-C-G cropping system, and addition of residues has increased conductivity under CT and ZT. Higher soil organic carbon was observed in M-C-G system, as chickpea is a legume crop and was more effective in raising soil organic carbon level. Similarly, highest carbon content was observed in ZT + R, which shows the clear advantage of addition of crop residues. Residue addition has positive influence on improvement of SOC in plough sole depth, which in turn resulted in lowered soil bulk density with improved hydraulic conductivity in soil (Meena et al. 2015) (Table 6.6). About 90% of SOC sequestration takes place in soil aggregate which is an important soil physical indicator (Sarker et al. 2018). Residue addition has improved soil aggregation capacity which in turn has positive correlation with SOC content of Indian soils (Das et al. 2014). Further many researchers (Lal 1994) reported conservation tillage can enhance soil organic carbon sequestration.

In the initial years, there is an increase in soil BD in no-tillage treatments, which made soil compacted at surface but relatively less in rhizosphere zone (López-Fando et al. 2007). There is significant enhancement of organic matter in the soil in due course of time, and the surface layer is protected by residue cover against splash effect of raindrops which has contributed to enhance soil aggregation and thus reduce soil compaction under no-tillage conditions when compared to conventional tillage (Osunbitan et al. 2005).

6.3.1.3 Soil Porosity

Pulse crop roots have inherent ability to penetrate deep (2 meters) and root diameter of 1–2 cm opens pathways deep in the soil, which encourage activity of earthworms. Deep root penetration and earthworm activities increase porosity of soil and deep water percolation in the soil.

6.3.2 Chemical Properties

Substantial amount of residual N is left behind by the pulse crops after harvest in the soil and is determined by improved soil microbial biomass (SMBC), soil organic carbon (SOC) and mineralizable organic nitrogen. Incorporation of pulses in cropping system economizes nitrogen demands of crops in cropping system, and on the other hand, it aids to enhance phosphorus use efficiency through solubilization of native P by root exudates (acids) of pulse crop (Saxena 1995). Chickpea is capable of mobilizing Ca-P in the rhizosphere through its root exudation of citric acid in Vertisols (Ae et al. 1991), whereas in Alfisols, pigeon pea has the ability to solubilize soil bound Fe-P (Ae et al. 1991). Pulses in cropping systems enhance availability of available P, K, S, Zn, and B in soils (IIPR 2012) (Fig. 6.4).

Inclusion of pulse crops in cropping systems reported to increase SOC and total N (Singh et al. 2009a, b) (Fig. 6.5). There is an increase of 6% SOC and 85% soil microbial biomass C in rice-wheat-mung bean cropping system when compared to conventional rice-wheat system. Significant positive impact on SOC restoration and carbon management index was observed with inclusion of chickpea by replacing wheat in rice-wheat cropping system (Ghosh et al. 2012). In maize-pigeon pea

Fig. 6.4 Effect of pulse-based cropping system on soil available P, K, S, Zn, and B (kg/ha) (modified from IIPR 2012)

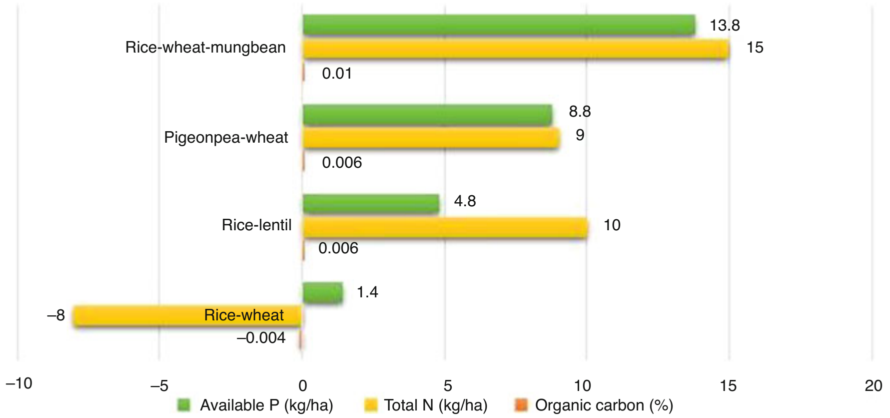

Fig. 6.5 Changes in fertility status of soil under different cropping system (modified from Singh et al. 2009a, b)

cropping system, there is a significant increase in phosphorous uptake in maize crop through enhanced insoluble P mobilization; this could be due to deep rooting characteristics of pigeon pea which facilitated nutrient recycling from deeper soil layers (Kumara Rao et al. 1983). As most of crop residues contain much greater amount of carbon (C) than nitrogen (N), and soil bacteria need both, further the N supplied by pulses enable better decomposition and conversion of crop residues to organic C in soil. Likewise, summer pulses with short duration can be used during fallow period to lower C losses and improve system's C sequestration (Ganeshamurthy 2009).

Soil organic matter (SOM) chelates the soil physically and chemically for formation of better soil aggregates and further stabilizes and resists the soil from disintegration (Hillel and Hatfield 2005). Pulse crop residues with narrow C:N ratios decompose faster, thereby improving SOM which has impact on soil aggregation and lowering of soil bulk density (Yadav et al. 2017).

In intercropping systems, pulse crops supply N to the associated intercrop through nitrogen "sparing" path. A part of prerequisite N is fulfilled through N fixation, as pulse crops utilize less accessible soil nitrogen than cereals thereby subsequently conserving inorganic nitrogen for the associated intercrop. Perhaps, nitrogen saving does not always hold true; in some instances, pulse crops take up significantly higher soil inorganic nitrogen than equivalent cereal crops (Herridge et al. 1995). Some pulse crops like pigeon pea have profound deep roots which mine plant nutrients from deep layers in soil where it can't reach by cereal crops. Owing to residual decay, the nutrients are retained on the soil surface, contributing to nutrient cycling.

Long-term integration of crop residues increases organic matter levels in soil along with macro- and micronutrients. Soil organic matter (SOM) is considered as crucial indicator for evaluation of soil quality (Barančíková et al. 2016). There is decline in rate of soil organic matter decomposition at no ploughing. Accumulation of SOM is higher at surface layer and shows subsequent increase in total carbon content (Yaduvanshi and Sharma 2008). Tillage technologies, i.e. reduced tillage and no-tillage, have impact on the content, nutrient distribution, and soil organic matter.

In Vertisols of central India, higher soil quality index was found in maize-pigeon pea (1:1) intercropping system under reduced tillage, and at no-tillage it was higher in soybean + pigeon pea (2:1) system (Kumar et al. 2017). This shows that minimal/no-soil tillage practices in addition to crop residue retention have improved soil quality index in terms of enhanced soil physicochemical and biological properties, which in turn create optimum conditions for crop growth. No-tillage system has improved 20–43% nitrogen at 0–5 cm depth of soil in comparison to conventional tillage (Gallaher and Ferrer 1987).

Similarly in Germany, Šoltysová and Danilovič (2011) studied the effect of different tillage technologies in relation to soil properties. The total N content has reduced (5.2 rel.%) in reduced tillage, 5.1 rel.% at no-tillage, and 0.7 rel.% in conventional tillage. In case of available P, the P content was increased at the tune of 4.1 rel.% in reduced tillage and reduced at no-tillage and conventional tillage by 9.5 and 3.3 rel.%, whereas different tillage practices didn't show any significant difference on soil available K. Increase in SOC in relation to higher input availability on surface layers, total N (Jokela et al. 2009), phosphorus, and potassium contents (Dong et al. 2009) was observed in top surface layers at no-tillage (NT) in comparison to conventional tillage (CT). In soil-protective tillages, maximum mean of SOC (1.45%) was observed at a depth of 0–0.45 m when compared to CT (1.41%). However there was a significant difference in top 0–0.15 m soil layer, where the organic carbon content in soil is 1.54% and 1.47% in protective and conventional tillages, respectively (Šoltysová and Danilovič 2011). This clearly shows influence of tillage technologies on intensity of SOM decomposition in the soil.

Addition of residue enhanced nitrogen uptake by crop tillage helped out in higher N mineralization from crop residues, resulting in greater grain N in CT + R (Meena et al. 2015) (Table 6.6). In cereal-legume rotation (M-C-G), there is an increase in N availability probably due to biological N fixation in pulse crops (Halvorson et al. 2002). Gupta et al. (2007) found an improved abundance of P and K in soil due to application of crop residues over straw-burned soils for 3 years. In addition to direct application of P, residues can decrease sorption of P and enhance P nutrient availability. Thus the soil has raised inorganic and organic P contents with the addition of straw.

6.3.2.1 Nitrogen Economy

In addition to augmenting soil fertility, pulse crop introduction into cropping systems further enhances nitrogen (N) economy. Pulses are known to have intrinsic capacity to fix nitrogen and are able to meet their own N demands and also aid in economizing N for successive nonlegume crops as a residual effect in sequence cropping. Residual effect of N varies in amount for different pulse crops for use by the succeeding crops. An additional 668,000 tons of nitrogen can be added into the soil by including legumes in crop systems (Singh et al. 2009a, b).

Table 6.7 Nitrogen economy due to inclusion of pulses in sequential cropping

Preceding pulse crop	Subsequent cereal	Fertilizer N equivalent (kg N/ha)
Chickpea	Maize	60–70
	Rice	40
	Pearl millet	40
Pigeon pea	Wheat	40
	Maize	20–49
Mung bean	Rice	40
Urdbean/mung bean	Wheat	30
Lentil	Maize	30
	Pearl millet	40
Rajmash	Rice	40
Cowpea	Rice	40
	Wheat	43
Peas	Pearl millet	40
	Maize	20–32
Lathyrus	Maize	36–48

Integration of rabi pulse crops, viz. chickpea, rajmash, and field pea, in the cropping system instead of wheat economized nitrogen at 40 kg/ha considerably enhanced the overall economic yield of the cropping system under irrigation. Similarly, kharif pulse crops like cowpea, urdbean, mung bean and pigeon pea accounted for an equivalent N economy of 40 kg/ha for successive cereal crops in the system (Table 6.7). Pre-kharif or summer legumes provide an additional yield (7–10 q/ha) and also economize N at the rate of 34 kg/ha for succeeding crops. Among all the summer legumes, mung bean recorded higher system productivity followed by cowpea and urdbean which contributed to the tune of 21 kg N/ha to sequential kharif crop (Singh et al. 2009a). This superiority is due to high N-fixing capacity and plant residue addition which enhance soil fertility and supplement nutrient demands of succeeding crops. In an intercropping system of maize + cowpea, it was estimated about 41 kgN/ha is added into the soil from cowpea crop residue (Eaglesham et al. 1982). N economy has enhanced with the inclusion of pulses in cereal-based cropping system, and similar results were found in pulse-based wheat cropping system (Table 6.8).

6.3.2.2 Soil pH

In general pulses are grown in soil pH of neutral to alkaline conditions. Nutrient availability to pulse crops is not influenced by soil reaction. Further these crops have potential to alter (reduce) rhizosphere soil pH and create small-scale favourable microenvironments for availability of nutrients (Yan et al. 1996). In general, pulses can meet their nitrogen demands through N fixation from the atmosphere in diatomic form rather than NO3 form and results in lower soil pH. Legumes like soybean and alfalfa crops are able to reduce pH of soil by one whole unit. This lowered pH can promote enhanced plant-soil-microbial activities in the rhizosphere, which favours

Table 6.8 Quantum of energy saved through N economy by different pulse crops

Pulse	Succeeding crop	N economy (kg/ha)	Energy saved (10^8J/ha)[a]
Pigeon pea	Wheat	30	24
Pigeon pea + mung bean	Wheat	40	32
Pigeon pea + urdbean	Wheat	45	36
Pigeon pea + cowpea	Wheat	40	32
Chickpea	Wheat	68	54
Lentil	Wheat	30	24
Peas	Wheat	32	26

Source: Ahlawat and Srivastava (1997)
[a]Amount of fertilizer N saved (kg/ha) × 806 J

optimum crop growth. Chickpea is capable of reducing pH of soil, followed by peas and pigeon pea crops (Singh et al. 2009a, b). This reduction in pH is due to release of H+ ions and organic acids (low molecular weight) by the roots of these pulse crops (Tamboli et al. 1999). Higher the rates of exudation from roots and their accumulation in surface layers of soil profile attribute to higher acidification rates (Limousin and Tessier 2007). Further, pulse-based cropping systems along with application of inorganic N reduction in soil pH could be more higher.

6.3.3 Biological Properties

Pulses are proven to augment microbial population in soil rhizosphere (Meena et al. 2015). Pulse inclusion in cropping sequence enhances diversity of soil flora and fauna and their activities which are vital for sustaining long-term soil health and overall system productivity (Kumar 2014). Incorporation of pulse crop residue releases some organic exudates with low molecular weight which act as substrate to soil microbes and further tend to increase soil microbial population build-up in soil (Caon et al. 2016). Microbial activity in soil is measured in relation to the dehydrogenase enzyme activity in soil and is found to increase in soil after harvest of pulse crop which provides greater stability for the soil life (Kumar 2014). Rise in soil microbial activity tends to have a positive impact on mineralization and nutrients (N, P, and S) mobilization according to the prevailing favourable environment. Increase in release of unused fixed N into soil enriches microbial activity in rhizosphere (Herridge et al. 1995) and therefore helps to break down C-rich residues of nonleguminous crops. After incorporation of pulse crop residues into soil, there is significant increase in enzymatic activities such as β-glucosidase, cellulose, arylsulphatase, and amylase in comparison to other treatments with organic manures (Dinesh et al. 2000).

In the rice fallow mung bean system, Tilak (2004) recorded a higher number of soil microbes such as actinomycetes, bacteria, fungi, and phosphorus solubilizing bacteria (PSB) due to incorporation of mung bean residue in the cropping system. Similarly, there is an increase in soil microbial biomass by 10% and 15% and total organic carbon increase by 11% and 10% in maize-wheat-mung bean and pigeon pea-wheat cropping system when compared with conventional wheat-maize cropping system (Venkatesh et al. 2013). Higher soil microbial activity was observed in mung bean in the treatment of chopping + incorporation + irrigation after harvesting of wheat (Table 6.9). Significant higher levels of organic C, N, P, K, and micronutrients and simultaneous increase in soil microbial biomass C, microbial biomass N, and enzymatic activities were found in soils of rice-wheat-summer mung bean cropping system compared to RWCS (Kumar 2014).

Crop residues act as substrate for soil microbes which promote their growth and activities in rhizosphere. CA system is associated with enhancement in soil microbial diversity; it is high especially in more diversified cropping systems (Yang et al. 2012), in particular to nutrient availability such as nitrogen, phosphorus, and sulphur which are hinging on soil microbial population and their activity, which further rely on supply of organic soil substrate. In a long-term experiment, both the conditions, i.e. irrigated and rainfed, showed reduction in soil microbial biomass (carbon and nitrogen), which is correlated to the quantity of residue retention on surface layer with zero-tillage treatment. Soil microbial biomass plays a vital role in aggregate stability, which is a reflection of its capability to retain and cycle plant nutrients and organic matter (Verhulst et al. 2009).

Tillage tends to accelerate the oxidative dissolution of organic matter by speeding up atmosphere CO_2 emissions, exceeding normal soil respiration. With combination of retention of crop residues along with direct seeding, conservation tillage allows detention and raise in organic matter levels and acts as substratum for soil microbial activity and potential capacity of soil to hold carbon and to supply nutrients and water "on demand" to roots for prolonged period of time (Kassam et al. 2009).

Kumar et al. (2017) studied soil biological activity under different tillage systems in central India. Among different cropping systems, soybean + pigeon pea (2:1) recorded higher DHA and FDA activity in rainfed Vertisols which is followed by maize-gram cropping system. Greater activity of DHA and FDA reflects higher biological activity in soils and was found to be higher in conservation tillage when compared with conventional tillage. Pulse-based cropping systems show higher microbial activity due to higher DHA and FDA activity under conservation tillage (Table 6.10). The enzyme dehydrogenase oxidizes organic matter in soil which is achieved through transfer of electrons and protons from the source substrate to the acceptor and is considered to link up with the respiratory pathway of soil microorganisms (Das and Ajit 2011).

CA has significant impact on soil macrofauna such as earthworms, beetles, and termites. They burrow the soil and break down crop residues which is vital in creation of macroporosity in soil as it further enhances infiltration rate and hydraulic conductivity of soil (Spurgeon et al. 2013). These soil macrofauna aid in nutrient cycling and formation of aggregates through mixing of organic material into soil (Spurgeon et al. 2013). In conventional tillage systems, macrofauna are affected by tillage practices, in bringing them near to surface layers and making them exposed to adverse ecological conditions. CA systems enhance macrofauna population, and

Table 6.9 Effect of crop residue incorporation on soil physicochemical properties, soil organic carbon, and microbial biomass carbon

Treatment	Soil physical properties				Available treatment nutrient (kg/ha)			After wheat harvest	
	Bulk density (g/cc)	Particle density (g/cc)	Pore space (%)	Water holding capacity (%)	N	P	K	SMBC (μg/100 g)	SOC (g/kg)
Mung bean[a]	1.38	2.42	45.5	37.3	228.2	18.72	146.4	262	6.71
Urdbean[a]	1.39	2.39	44.7	38.3	222.1	18.16	154.2	222	5.28
Mung bean[b]	1.38	2.38	46.8	38.3	237.8	19.58	152.1	322	8.25
Urdbean[b]	1.38	2.40	47.0	41.6	235.7	17.84	149.2	312	7.60
Mung bean[c]	1.34	2.38	47.3	42.5	240.4	18.91	148.7	327	9.08
Urdbean[c]	1.35	2.39	48.2	45.1	241.1	17.32	147.6	337	9.10
Mung bean[d]	1.32	2.36	49.6	46.4	245.3	17.46	145.7	320	9.14
Urdbean[d]	1.33	2.35	48.2	45.9	246.1	18.02	141.1	347	9.37
Control	1.44	2.50	38.2	33.4	196.8	16.65	130.5	132	9.25
CD ($P = 0.05$)	0.05	0.10	3.5	3.8	14.9	0.78	9.6	132	4.25

Note: [a]Incorporation; [b]Incorporation + irrigation; [c]Chopping + incorporation; [d]Chopping + incorporation + irrigation
Source: Singh et al. (2012)

Table 6.10 Dehydrogenase activity (DHA) and fluorescein diacetate activity (FDA) in Vertisols under different tillage and cropping systems

Conventional tillage				
Cropping systems	Soybean + P. Pea (2:1)	Soybean-wheat	Maize + P. Pea (1:1)	Maize-gram
DHA (μgTPF g^{-1} day^{-1})	91.14	65.03	76.49	75.62
FDA (μg fluorescein g^{-1} $h^{-}1$)	22.98	24.75	22.57	21.33
Reduced tillage				
DHA (μgTPF g^{-1} day^{-1})	152.28	92.79	95.51	98.03
FDA (μg fluorescein g^{-1} $h^{-}1$)	30.95	30.47	27.96	34.03
No-tillage				
DHA (μgTPF g^{-1} day^{-1})	157.11	107.44	111.64	113.21
FDA (μg fluorescein g^{-1} $h^{-}1$)	30.18	26.49	25.17	29.96

Source: Modified from Kumar et al. (2017)

Table 6.11 Effect on soil properties through inclusion of pulse crops in cropping systems

Soil properties	Dominant soil type	Cropping system	References
11% increase in total SOC and 10% increase in soil microbial biomass	Inceptisols	Maize-wheat-chickpea/mung bean	Venkatesh et al. (2013)
Increase in soil microbial biomass, organic carbon levels, total nitrogen, available N, P, K, and micro nutrients	Vertisols	Rice-wheat-mung bean	Kumar (2014)
Improved water holding capacity, lower bulk density, 35.5% increase in SOC, 156% in soil microbial biomass. 24.6%, 11.5%, and 18.5% increase in N, P, and K availability, respectively	Typic Ustrochrept	Mung bean/urd bean-wheat	Singh et al. (2012)
Increased soil microbial biomass and nitrogenase activity	Sandy clay loam soil	Rice-wheat-mung bean	Tilak (2004)

their abundance is highly correlated with the duration of site under CA system (Briones and Schmidt 2017).

6.4 Soil Health Under Pulse-Based Cropping System in CA

Pulse crop residue incorporation is critical in improving soil health and thereby enhancing nutrient use efficiency and productivity of crops in cropping sequence (Table 6.11). Prudent utilization of crop residues is an important concern to minimize nutrient losses through volatilization, leaching, and fixation particularly under adverse circumstances.

6.5 Conclusions

Pulses are proven to augment microbial population in soil rhizosphere. Inclusion of pulses in cropping sequence enhances diversity of soil flora and fauna. Significant amount of leaf litters have been reported in different pulse crops which add nutrients after decomposition to the soil. Crop residues are prerequiste for conservation agriculture (CA) systems; these residues should be used in CA systems to ensure food security and healthy soil resource base and to ensure sustainability in crop production. Cropping systems under CA systems are environment friendly and ecologically sustainable and economically feasible. Conservation tillage with residue incorporation improves soil physicochemical properties when compared with conventional tillage due to high residue retention and minimum soil disturbance in the system. Moreover, pulse crop component attributes to higher system productivity and enhanced soil quality in cropping systems. Inclusion of pulse crops in cereal-based cropping systems in central India can provide greater way for sustainable crop intensification. A paradigm shift in tillage and residue management practices in rainfed areas of central India eliminates majority of unsustainable elements of conventional agriculture practices, which is crucial to enhance crop productivity with minor concern for integrity of resources in the system. The concept of CA has to be infused into the system which is the need of the hour for future enhancement of crop productivity and sustaining soil health in the region.

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7 Impact of Conservation Agriculture on Soil Health and Crop Productivity under Irrigated Ecosystems

T. K. Das, K. K. Bandyopadhyay, and P. K. Ghosh

Abstract

Conservation agriculture (CA), involving no/reduced tillage, continuous residue cover, and crop rotation including legumes, is a paradigm shift from conventional agricultural practices. This practice is envisaged to sustain agricultural productivity at higher level by improving soil health. The effects of CA practices in improving physical (soil structure, aggregation, bulk density, penetration resistance, porosity, hydraulic conductivity, infiltration, runoff, and least limiting water range), chemical (soil pH, CEC, TOC, TON, C:N), and biological (potentially mineralizable N, soil microbial biomass C and N, soil enzyme activities, labile organic C, and N pools) health of soil and soil carbon sequestration under irrigated systems have been discussed. The impact of soil health improvement under CA on the productivity and input use efficiency has also been highlighted. However, there are some constraints in large-scale adoption of this practice. The issues and policy needs have been discussed for large-scale adoption of CA practices. There are needs for fine-tuning of this technology for different crops and cropping systems across the soils/agro-climatic regions and efficient extension services for changing farmers' perceptions about this technology towards adoption. Institutional research and development support, policy initiatives, and extension services altogether would help in overcoming the constraints for large-scale adoption of CA practices.

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Keywords

Conservation agriculture · Soil physical health · Soil chemical health · Soil biological health · Crop yield · Resource use efficiency

7.1 Introduction

Sustaining crop productivity at higher level is the key issue in Indian agriculture to meet the increasing demands of food and fibre for the growing population under the changing climatic scenario (Govaerts et al. 2009; Das et al. 2018). Maintaining soil health/quality is indispensable for sustaining the agricultural productivity at higher level. Soil health can be defined as the continued capacity of soil to function as a vital living system, within ecosystem and land use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health (Doran et al. 1996). The main functions of soil include water flow and retention, solute transport and retention, physical stability and support, retention and recycling of nutrients, buffering and filtering of potentially toxic materials, and maintenance of biodiversity and habitat. Soil health needs to be maintained and improved by following appropriate management practices to sustain productivity continuously at higher levels in the long run.

Conservation agriculture (CA) practices involving no/reduced tillage, continuous residue retention, and crop rotation with legumes has emerged as a paradigm shift in agricultural practices, having favourable impacts on soil health, carbon sequestration and sustainable agricultural production (Das et al. 2014, 2016, 2018), and mitigation of climate change (Bhatia et al. 2013; Gupta et al. 2015, 2016; Naresh et al. 2016). CA as described by FAO (http://www.fao.org.ag/ca) is a concept for resource-saving agricultural crop production, which is based on enhancing natural and biological processes above and below the ground. It emphasizes minimum soil disturbance, permanent soil cover through crop residues or other cover crops, and diversified crop rotation using a legume. It is a promising technology for rational use of available resources and sustainable productivity in the long run.

7.2 Why Conservation Agriculture?

Intensive tillage practice has led to a plethora of problems, the so-called second-generation problems in agriculture. Some of these are stagnating farm incomes and increasing production costs, declining factor productivity, declining groundwater table, development of salinity hazards, deterioration in soil fertility, deterioration in soil physical environment, increased biotic interferences, declining biodiversity, high energy requirements, reduced availability of protective foods, and air and groundwater pollution.

CA can reverse the soil degradation processes and build up soil fertility through increase in water holding capacity and facilitating better infiltration of rainwater and enhancing groundwater storage, enrichment in soil organic carbon (SOC), and enhanced microbial diversity in plants' rhizosphere. It eliminates power-intensive soil tillage, thus reducing the drudgery and labour required for crop production by more than 50% of the small-scale farmers. CA has a long-term and broader perspective, which goes beyond yield improvement.

7.3 Conservation Agriculture: Principles

Conservation agriculture (CA) has three basic principles: (a) minimal soil disturbance (no-till), (b) permanent soil cover (mulch), and (c) diversified crop rotations including a legume. It is a more sustainable cultivation system, which can increase farm system resilience and improve the capacity of farmers to adapt to climate change.

7.3.1 Minimal Soil Disturbance

The practice of CA advocates minimal soil disturbance, and hence much less or no-tilling is carried out. The disturbed area must be less than 15 cm wide or 25% of cropped area (whichever is lower). Periodic tillage operations are not done which could disturb greater area than the aforementioned limits. The practice of ploughing the field to prepare for sowing or seedbed preparation has been in vogue since times immemorial. But, it has thus been found that tillage operations over time cause a decline in soil fertility and overall productivity resulting from deterioration of physical, chemical, and biological properties of soil.

7.3.2 Permanent Organic Soil Cover

In CA, residues are allowed to remain on the soil surface, which act as a layer of mulch/soil cover. At least 30% of the soil surface should be covered with residues or cover crop. This layer protects the soil against harmful effects resulting from exposure to rain and sun, provides microorganisms in the soil with a constant supply of 'food', and alters the microclimate in the soil for optimal growth and development of organisms. The mulch layer plays an important role in improving biological activity and soil organic matter content and in turn helps improve physical, chemical, and biological soil properties.

7.3.3 Diversified Crop Rotation with a Legume

When plant residue is not burnt and soils are not ploughed, control of pests, diseases, and weeds has to be achieved through crop rotation and an integrated pest management approach. Such crop rotation practice interrupts the infection chain between subsequent crops and offers a 'diet' to soil microorganisms. Crop rotation also promotes exploration of nutrients by crops from different soil layers and helps in reducing pressure created and removal of same nutrients by mono-cropping. In the crop rotation, inclusion of legumes is advocated because of its taproot system, nitrogen-fixing ability, and role in soil health improvement.

7.4 Global Area under Conservation Agriculture

Conservation agriculture is practised in around 180.4 m ha area worldwide; most of the areas are in the USA, Brazil, Argentina, Canada, and Australia (Kassam et al. 2018). CA became an acceptable practice for the farmers in these countries due to decades of research and extension and concerns of the farmers, scientists, and the public on soil erosion. Due to the efforts of the Rice-Wheat Consortium and several institutions of the National Agricultural Research System (NARS), zero-tillage technology was introduced into India and neighbouring countries, and it is gradually being adopted by the farmers, largely in the Indo-Gangetic Plains (IGP). In the world, CA has spread mostly in the rainfed agriculture, while in India, its success is more in the irrigated belt of the IGP.

7.5 Soil Health under Conservation Agriculture

CA practices have been reported to improve soil health (Bhattacharyya et al. 2013, 2015, 2018, 2019; Dey et al. 2016; Oyeogbe et al. 2017, 2018a, 2018b) and crop productivity (Das et al. 2014, 2016, 2018; Dudwal et al. 2018; Hajebi et al. 2016; Madar et al. 2017, 2018; Nath et al. 2017a, 2017b; Saad et al. 2015; Sepat et al. 2015). However, soil health/quality cannot be measured directly, but soil properties that are sensitive to changes in management can be used as indicators (Andrews et al. 2004). Soil health/quality includes three groups of mutually interactive attributes, i.e. soil physical, chemical, and biological qualities, which must be restored at its optimum for improving crop growth. The soil health approach is better applied when specific goals are defined for a desired outcome from a set of decisions. Therefore, the soil health/quality evaluation process should consist of the following activities: defining the goal, selection of soil health indicators, determination of a minimum data set (MDS), development of an interpretation scheme of indices, and on-farm assessment and validation.

7.5.1 Soil Physical Health/Quality

Soil physical quality/health is the ability of a given soil to meet plant and ecosystem requirements for water, aeration, and strength over time and to resist and recover from processes that might diminish that ability (McKenzie et al. 2011). Concepts of soil physical quality/health can be applied to individual soil horizons, profiles, or areas classified to a common soil type. Unless the soil physical health is maintained at its optimum level, the genetic realizable yield potential of a crop cannot be achieved even when all the other requirements are fulfilled. Soil physical health also influences and get influenced by the chemical and biological health of soil.

7.5.1.1 Soil Structure and Aggregation

Soil structure is a key factor in soil functioning and is an important factor in the evaluation of the sustainability of crop production systems. Soil structure is often expressed as the degree of stability of aggregates (Bronick and Lal 2005). Soil structural stability is the ability of aggregates to remain intact when exposed to different stresses (Kay et al. 1988), and measures of aggregate stability are useful as a means of assessing soil structural stability. Zero tillage with residue retention improves dry aggregate size distribution compared to conventional tillage (Govaerts et al. 2009, 2007). The effect on water stability of aggregates is even more pronounced with an increase in MWD of wet sieving reported for a wide variety of soils and agro-ecological conditions (Carter 1992; Chan et al. 2002; Filho et al. 2002; Govaerts et al. 2009; Govaerts et al. 2007; Hernanz et al. 2002; Li et al. 2007; Lichter et al. 2008; Pinheiro et al. 2004). Even when conventional tillage results in a good structural distribution, the structural components are weaker to resist water slaking than in zero-tillage situations with crop residue retention, where the soil becomes more stable and less susceptible to structural deterioration. The reduced aggregation in conventional tillage is a result of direct and indirect effects of tillage on aggregation (Beare et al. 1994; Six et al. 1998). Physical disturbance of soil structure through tillage results in a direct breakdown of soil aggregates and an increased turnover of aggregates (Six et al. 2000) and fragments of roots and mycorrhizal hyphae, which are major binding agents for macroaggregates (Bronick and Lal 2005; Tisdall and Oades 1982). The aggregate formation process in conventional tillage is interrupted each time the soil is tilled with the corresponding destruction of aggregates. The residues lying on the soil surface in CA protect the soil from raindrop impact, whereas no such protection occurs in conventional tillage, which increases susceptibility to further disruption (Six et al. 2000). Moreover, during tillage a redistribution of the soil organic matter takes place. Small changes in SOC can influence the stability of macroaggregates. Fresh residue forms the nucleation centre for the formation of new aggregates by creating hot spots of microbial activity where new soil aggregates are developed (De Gryze et al. 2005; Guggenberger et al. 1999). The return of crop residue to the soil surface not only increases the aggregate formation, but it also decreases the breakdown of aggregates by reducing erosion and protecting the aggregates against raindrop impact. Crops can affect soil aggregation by their rooting system because plant roots are important binding agents at the scale of macroaggregates (Six et al. 2004; Thomas and Asakawa 1993).

7.5.1.2 Soil Bulk Density and Penetration Resistance

The effect of tillage and residue management on soil bulk density is mainly confined to the topsoil (plough layer). In deeper soil layers, soil bulk density is generally similar in zero- and conventional tillage (Blanco-Canqui and Lal 2007; D'Haene et al. 2008; Gal et al. 2007; Hernanz et al. 2002; Mondal et al. 2019; Thomas et al.

2007; Yang and Wander 1999). On a silt loam with a maize-soybean rotation in Minnesota, soil bulk densities were higher in the surface layer of zero tillage than conventional tillage after 23 years but lower below 30 cm, reflecting the rupture action of tillage near the surface and the compacting and shearing action of tillage implements below tillage depths (Dolan et al. 2006). Similarly, Gal et al. (2007) observed higher bulk density in the 0–30 cm layer under zero tillage than under conventional tillage on a silty clay loam in Indiana after 28 years but no difference in the 30–100 cm layer. Lal (1997) reported that penetrometer resistance of the 0–5 and 5–10 cm depths was significantly different among tillage treatments and depth of measurement. Similar trends were observed in data for other years. Penetration resistance for the 0–5 cm depth was the least for no-till + mulch treatment (116 kPa), the highest for ridge till treatment (348 kPa), and had a mean value of 243 kPa. In contrast to surface layer, summer ploughing treatment recorded least penetration resistance (249 kPa) at 5–10 cm depth, whereas ridge till treatment recorded the highest (421 kPa) and had a mean value of 321 kPa. The altogether low penetration resistance of the surface soil was probably due to sandy texture and low cohesion.

7.5.1.3 Soil Porosity

Pores are of different size, shape, and continuity, and these characteristics influence the infiltration, storage and drainage of water, the movement and distribution of gases, and the ease of penetration of soil by growing roots. Pores of different size, shape, and continuity are created by abiotic factors (e.g. tillage and traffic, freezing and thawing, drying and wetting) and by biotic factors (e.g. root growth, burrowing fauna) (Kay and VandenBygaart 2002). Pore characteristics can change in both space and time following a change in tillage practices. These changes primarily reflect changes in the form, magnitude, and frequency of stresses imposed on the soil, the placement of crop residues, and the population of microorganisms and fauna in the soil (Kay and VandenBygaart 2002). Total porosity is normally calculated from measurements of bulk density, so the terms *bulk density* and *total porosity* can be used interchangeably (Kay and VandenBygaart 2002). A plough pan may be formed by tillage immediately underneath the tilled soil, causing higher bulk density in this horizon in tilled situations (Dolan et al. 2006; Yang and Wander 1999). A reduction in tillage would be expected to result in a progressive change in total porosity with time, approaching a new 'steady state' (Kay and VandenBygaart 2002). However, initial changes may be too small to be distinguished from natural variation. Kay and VandenBygaart (2002) used three classes (macro-, meso-, and micro-pores) that are distinguished in their functional relation to soil water. Pores with diameters >30μm are referred to as macropores. Water flows primarily through these pores during infiltration and drainage, and consequently these pores exert a major control on soil aeration. In addition, much of root growth is initiated in these pores. Pores with an equivalent diameter of 0.2–30μm are referred to as mesopores and are particularly important for the storage of water for plant growth. Micropores have effective diameters <0.2μm. In general, micro- and mesoporosity are reported to be higher in zero tillage (ZT) compared to conventional tillage (CT), but in some cases no effect of tillage was observed. Yoo et al. (2006) did not find consistent results at three locations, two with a silty clay loam and one with a silt loam soil in Illinois. At one of the three locations with silt loam soil, the volume of small macropores (15–150μm) as well as large macropores (>150μm) was smaller under ZT than CT. In other two locations, small macroporosity (in the silt loam) or large macroporosity was smaller under zero tillage (in the silty clay loam). In the 0–5 cm layer of a 24-year-old experiment on a Paleustalf in Australia, the volume of pores >60μm was significantly greater (more than 11%) under zero tillage with residue retention than under conventional tillage with residue burnt (Zhang et al. 2007).

7.5.1.4 Hydraulic Conductivity

Hydraulic conductivity is expected to be higher in ZT with residue retention compared to CT due to larger macropore conductivity as a result of the increased number of biopores that is commonly observed (Eynard et al. 2004; McGarry et al. 2000; VandenBygaart et al. 1999). However, reported results are not consistent. This might be partly due to difficulty in measuring hydraulic conductivity when a residue cover is present under zero tillage. The presence of residue complicates the installation of measurement instruments or the removal of undisturbed samples and cores and may cause high variation in conductivity values at small scales (cm) due to macropores and other structural attributes that are left intact by the absence of tillage (Strudley et al. 2008). Also differences in soil sampling depth, amount of straw mulch, and site-specific characteristics (e.g. soil texture, slope, tillage) between studies may explain inconsistencies in the observed effects of tillage on hydraulic conductivity and water holding capacity (Blanco-Canqui and Lal 2007).

7.5.1.5 Infiltration and Runoff

In spite of the inconsistent results on the effect of tillage and residue management on soil hydraulic conductivity, infiltration is generally higher in ZT with residue retention compared to CT and ZT without residue. This was probably due to the direct and indirect effects of residue cover on water infiltration. Soil macroaggregate breakdown has been identified as the major factor leading to surface pore clogging by primary particles and microaggregates and thus to formation of surface seals or crusts (LeBissonnais 1996; Lal and Shukla 2004). The presence of crop residues over the soil surface prevents aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of soils (LeBissonnais 1996). Moreover, aggregates are more stable under zero tillage with residue retention compared to conventional tillage and zero tillage with residue removal (Carter 1992; Chan et al. 2002; Govaerts et al. 2009, 2007; Hernanz et al. 2002; Filho et al. 2002; Li et al. 2007; Pinheiro et al. 2004). Under these conditions, wind erosion and rapid wetting (i.e. slaking) cause less aggregate breakdown, preventing surface crust formation (Lal and Shukla 2004; LeBissonnais 1996). In addition, the residues left on the topsoil with ZT and crop retention act as a succession of barriers, reducing the runoff velocity and giving the water more time to infiltrate. The residue intercepts rainfall and releases it more slowly afterwards. The 'barrier' effect is continuous, while the prevention of crust formation probably increases with time. This was confirmed by the results of Ball et al. (1997), who found greater infiltration rates in ZT with residue retention after 26 years than after 9 years. Results indicated that there was significantly higher initial infiltration rate and equilibrium infiltration rate under no-till + mulch than CT treatment (Lal 1997).

7.5.1.6 Least Limiting Water Range (LLWR)

The least limiting water range (LLWR) concept characterizes a single range of soil water content beyond which available water, soil aeration, and mechanical resistance impose significant limitations to root growth. The concept of LLWR was introduced by da Silva et al. (1994), which integrated three factors, i.e. soil water, soil aeration, and mechanical impedance, into a single variable LLWR which was found to be more sensitive to soil structural changes than available water. Upper limit of LLWR is either soil water content at 10% aeration porosity (MC_{ap}). Most of the crops growing on soils with aeration pores space less than 10% of the total pore space will experience aeration stress, which may cause drastic reduction in their yields (da Silva et al. 1994) or soil water content at field capacity (MC_{fc}), whichever is lower, and lower limit is either soil water content corresponding to 2Mpa soil strength (MC_{2Mpa}) or soil water content at wilting point (MC_{wp}), whichever is higher. The structural quality could be considered as 'very good' for LLWR greater than 0.20 $m^3\ m^{-3}$, 'good' in between 0.20 and 0.15 $m^3\ m^{-3}$, 'moderate' in between 0.15 and 0.10 $m^3\ m^{-3}$, and 'poor' is less than 0.10 $m^3\ m^{-3}$ (Kay and Anger 2002). Aggarwal et al. (2013) reported that in a sandy loam soil, both under bed planting (BP) and conventional tillage (CT) systems, θap decreased with increase in BD, whereas θ2MPa increased appreciably with increase in BD. On the other hand, θfc and θpwp did not change much with increase in BD. It was further observed that all throughout the crop growth, for both bed and CT planting systems, θfc was the upper limit and θ2MPa was the lower limit of LLWR except in conventional planting where at higher BD (1.72 Mg/m^3) θap was the upper limit (Fig. 7.1).

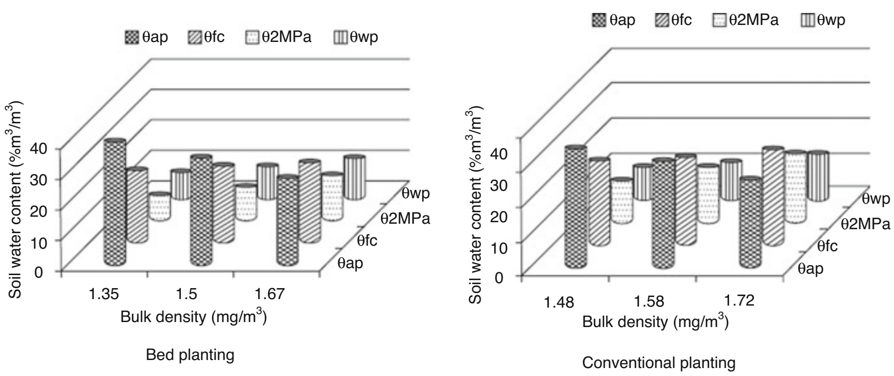

Fig. 7.1 Variation of soil water content at 10% aeration porosity (θap), field capacity (θfc), 2 MPa soil strength (θ2MPa), and wilting point (θwp) under bed and conventional planting

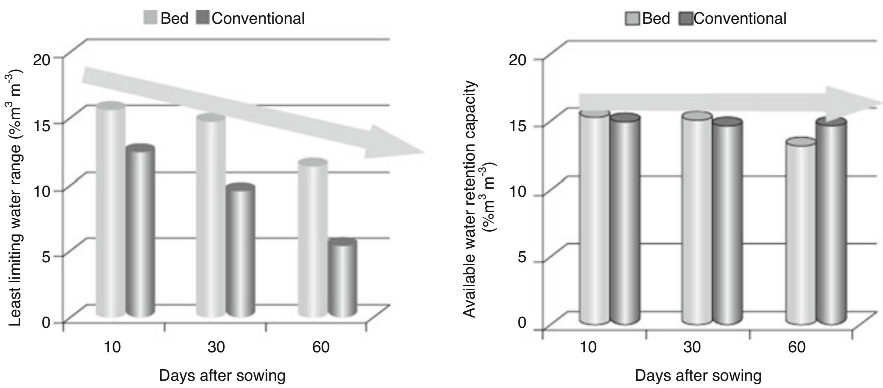

Fig. 7.2 Temporal variation of least limiting water range (LLWR) and available water retention capacity during maize growth

The decline in LLWR was sharper in conventional system than in bed planting system indicating that LLWR remained wider in BP than in conventional all throughout the crop growth (Fig. 7.2). Wider LLWR in BP indicated better structural quality, more water availability, and lesser mechanical impedance to growing roots than in conventional system. Similar trends have also been reported by Aggarwal et al. (2017), da Silva et al. (1994), Mishra et al. (2015), and Rai et al. (2019). On the other hand, available water retention capacity (AWRC) did not show any such variation with increase in BD. The reduction in range of available water due to deterioration of soil structure with time was best reflected in decline in LLWR, whereas AWRC did not show significant temporal changes. The above results thus indicated that LLWR is a better indicator of soil structure quality and water availability than AWRC. The plant water stress period was computed as the number of days water content of soil was outside LLWR or AWRC during various growth periods. It was observed that when stress period was calculated by using LLWR as index of water availability, lower water stress period was obtained under bed planting as compared to conventional tillage (Fig. 7.3), whereas no significant variation in stress was observed among the treatments when stress period was calculated by using AWRC as index of water availability. The above results thus indicated that LLWR seems to be a better indicator of soil water stress than AWRC. Hence, it could be suggested that in order to avoid stress, irrigation should be given as soon as SWC reaches lower limit of LLWR, i.e. θ2MPa, and not lower limit of AWRC, i.e. θpwp.

Mishra et al. (2015) reported that under cotton-wheat cropping system at 0–15 cm soil layer, the plots under permanent broad bed with residue (PBB + R) had nearly 14%, 17%, and 39% higher LLWR than CT (LLWR = 12.3%), permanent narrow bed with residue (LLWR = 12%), and ZT (LLWR = 10.1%) plots, confirming that crop residue retention improved LLWR. The impact of PBB + R on improvement in LLWR over CT plots in the sub-surface layer was much higher than in the surface layer. Residue addition invariably improved LLWR values in both soil layers under

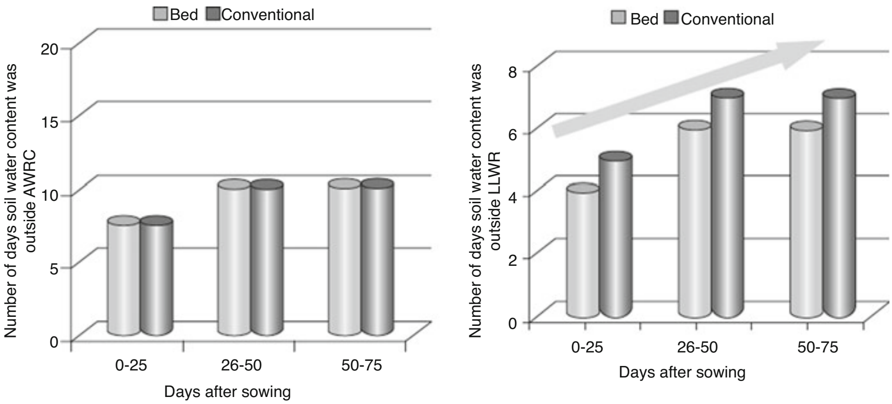

Fig. 7.3 Temporal variation of LLWR and AWRC during water stress period

the cotton-wheat system. There was a drastic reduction in LLWR in the ZT plots in the sub-surface layer than the CT plots.

7.5.2 Soil Chemical Health/Quality

7.5.2.1 Soil pH

Govaerts et al. (2007) found a higher pH in permanent bed (PB) under all the residues retained than with part or all of the residues removed in a rainfed experiment in the highlands of Mexico. Duiker and Beegle (2006) did not observe significant tillage effects on the average pH of the 0–15 cm layer. Kettler et al. (2000) found that the main effect of ploughing on soil pH was more significant at 0–7.5 cm soil depth, and both no-till and sub-till treatments, which leave plant residues at or near soil surface, were of lower pH than mouldboard ploughing treatments at all depths. However, Malhi et al. (2011a) reported that tillage and straw management usually had little or no effect on soil pH in any soil layer. Kumar and Yadav (2005) observed slight decrease in the soil pH than initial values in CT, Chinese seeder, and Pantnagar zero-till drill. One possible way of protecting soil from acidification is by returning the crop residues to the soil (Miyazawa et al. 1993) and pH increased significantly with crop residue application; thus, there are contrasting views about soil pH. The lower pH in ZT was attributed to accumulation of organic matter in the upper few centimetres under ZT soil (Rhoton 2000) causing increase in the concentration of electrolytes and reduction in pH. Similarly, Singh and Yadav (2004) reported that retention of crop residue on the soil reduced the bulk density and enhanced organic carbon and EC but reduced the pH of the soil.

7.5.2.2 Cation Exchange Capacity

Kumar et al. (2015) reported that the cation exchange capacity (CEC) was increased due to tillage and crop establishment methods, but the average CEC in the 0–15 cm layer was not significantly different between tillage systems. This was confirmed by Govaerts et al. (2007), who did not find an effect of tillage practices and crop on CEC. The retention of crop residues, however, significantly increased the CEC in the 0–5 cm layer of permanent raised beds compared to soil from which the residues were removed, but there was no difference in the 5–20 cm layer. However, Mohanty et al. (2015) observed that adoption of minimal tillage enhanced the CEC of soils even within a short span of 2 years, and the increase was in the tune of 11.2% over CT system [~26.2 cmol (p+) kg^{-1}].

7.5.2.3 Total Organic C, Total N, and C:N

Soil organic C (SOC) is an important index of soil quality because of its relationship to crop productivity (Lal 1997). Decomposition rates of soil organic matter (SOM) are lower with minimal tillage and residue retention; consequently SOC content increases with time (Gwenzi et al. 2009). Tillage practice can also influence the distribution of SOC in the profile with higher SOM content in surface layers with zero tillage than with conventional tillage (Bhattacharyya et al. 2013, 2015; Das et al. 2013, 2018) but a higher content of SOC in the deeper layers where residue is incorporated through tillage (Jantalia et al. 2000). Soil C storage is affected more by quantity than by the type or quality of organic inputs. The quality of the residues is determined primarily by the C:N ratio and can be modified by the amounts of lignin and polyphenolics in the material (Palm and Sanchez 1991). Quality may affect short-term soil C storage and dynamics but does not seem to influence the longer-term C stabilization and storage in the soil (Chivenge et al. 2011; Gentile et al. 2011). The quality of the residues may, however, affect soil fertility and thus the amount of residues produced for C inputs. For example, materials with high C:N, characteristic of cereal crop residues, reduce the available N in the soil due to N immobilization and could result in lower crop production, while residues with high N contents and low C:N ratios, as is the case with many legume residues and legume cover crops, increase soil N availability and possibly crop production (Powlson et al. 2011; Palm et al. 2001). It is generally recognized that the differential effects of rotations on soil C are simply related to the amounts of above- and below-ground biomass (residues and roots) produced and retained in the system (West and Post 2002). In Brazil, Boddey et al. (2010) attributed higher soil C storage in NT than CT to the inclusion of legume intercrops or cover crops in the rotations, and not due simply to higher production and residue inputs. They indicated slower decomposition of residues and lower mineral N in NT compared to CT result in higher root:shoot ratios and below-ground C input with NT (Boddey et al. 2010). Crop residues provide a source of organic matter, so when returned to soil, the residues increase the storage of organic C and N in soil, whereas their removal results in a substantial loss of organic C and N from the soil system (Malhi and Lemke 2007). Therefore, one would expect a dramatic increase in organic C in soil from a combination of ZT, straw retention, and proper/balanced fertilization (Malhi et al. 2011b). Naresh et al. (2016) also found significantly higher POC content under NT probably also due to higher biomass C. Results on PON content after 3 years showed that in 0–5 cm soil layer of CT system, there is an increase in PON content from 35.8 mg kg^{-1} in CT to 47.3

and 67.7 mg kg^{-1} without CR and to 78.3, 92.4, and 103.8 mg kg^{-1} with CR at 2, 4, and 6 t ha^{-1}, respectively. The corresponding increase of PON content under CA system was from 35.9 mg kg^{-1} in CT system to 49 and 69.6 mg kg^{-1} without CR and 79.3, 93.0 and 104.3 mg kg^{-1} with CR at 2, 4, and 6 t ha^{-1}, respectively. Small improvement in PON content was observed after 4 years of the experiment. Fine-textured soils have more potential for storing carbon, and ZT practice enhances carbon sequestration rate in soils by providing better conditions in terms of moisture and temperature for higher biomass production and reduced oxidation (Gonzalez-Sanchez et al. 2012). Intensification of cropping systems with high above- and below-ground biomass (i.e. deep-rooted plant species) input may enhance CA systems for storing soil C relative to CT (Luo et al. 2010). Gupta Choudhury et al. (2014) reported that conservation tillage (both RT and ZT) caused 21.2, 9.5, 28.4, 13.6, 15.3, 2.9, and 24.7% higher accumulation of SOC in >2, 2.1–1.0,1.0–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05, and < 0.05 mm-sized particles than CT treatments. Direct seeded rice combined with zero tillage and residue retention had the highest capability to hold the organic carbon in surface (11.57 g kg^{-1} soil aggregates) and retained least amount of SOC in sub-surface (9.05 g kg^{-1}soil aggregates) soil. In comparison with transplanted rice (TPR), direct seeded rice (DSR) enhanced 16.8, 7.8, 17.9, 12.9, 14.6, 7.9, and 17.5% SOC in >2, 2.1–1.0, 1.0–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05 and < 0.05 mm-sized particles. A lower C/N ratio and polyphenol content of green manure are susceptible to rapid decomposition and yield lower values of the MWD as compared to FYM and paddy straw with a greater C/N ratio and lignopolyphenol contents. Aulakh et al. (2013) found that in 0–5 cm layer of CT system, there was increase in TOC content from 3.84 g kg^{-1} in control to 4.19–4.45 g kg^{-1} without crop residue (CR), and to 4.40–5.79 g kg^{-1} with CR after 2 years. The corresponding values of TOC content under CA system were 4.55 g kg^{-1} in control to 4.73–5.02 g kg^{-1} without CR and to 4.95–5.30 g kg^{-1} with CR. Higher soil organic C contents under zero till with residue return than under conventional tillage and under reduced tillage than under conventional tillage (Šimansky et al. 2008) have been reported. The short-term (10 years) effects of management on SOC are complex and vary with soil conditions such as soil texture, climate, cropping system, and kind of crop residue, as well as with the management itself (Al-Kaisi et al. 2005; Munoz et al. 2007). Generally, the SOM in all treatments were higher under conservation than under conventional tillage (Vogeler et al. 2009). Das et al. (2018) reported that retention of both season crop residues in maize-wheat system could significantly improve SOC concentration in surface (0–5 cm) soil. The permanent broad bed with residue retention (PBB + R) resulted in highest SOC pool at 0–30 cm soil layer, which was significantly higher than that in CT. This system showed maximum carbon sequestration potential.

7.5.3 Soil Biological Health/Quality

7.5.3.1 Potentially Mineralizable N (PMN)

Potentially mineralizable nitrogen (PMN), a measure of the soil capacity to supply mineral N, constitutes an important measure of the soil health due to its strong relationship with the capability of soil to supply N for crop growth. Kang et al. (2005) found that application of organic residues increased PMN, which was positively related to increase in TOC content of soil. Aulakh et al. (2013) showed that PMN content after 2 years of the experiment in 0–5 cm soil layer of CT system increased from 2.7 mg kg^{-1} 7 d^{-1} in control to 2.9–5.1 mg kg^{-1} 7d^{-1} without CR and to 6.9–9.7 mg kg^{-1} 7 d^{-1} with CR. The corresponding increase of PMN content under CA system was from 3.6 mg kg^{-1} 7 d^{-1} in control to 3.9–6.5 mg kg^{-1} 7 d^{-1} without CR and to 8.9–12.1 mg kg^{-1} 7 d^{-1} with CR. Doran et al. (1996) reported that microbial biomass and PMN in the 0–7.5 cm surface layer of NT soils were 34% higher than those of ploughed (CT) soils although the opposite was true at 7.5- to 15-cm depth. Wright et al. (2005) found an increase of MBC and mineralizable N in the surface soil with corn and cotton cropping sequences for 20 years under NT and minimum tillage (MT) systems but little change in MBC concentration in the 2.5–20 cm depths. In a Brazilian oxisol, there was a consistent increase in biological activity and N mineralization with no-till management (Green et al. 2007). Similar increases with depth have been observed in arid wheat-based systems where total soil N (TSN) increased by 38–68%. Interestingly, the CT soil mineralized as much N as the NT systems but had less TSN than NT (Purakayastha et al. 2008). Tillage can greatly modify edaphic factors and thereby influence the rate of C mineralization (Huggins et al. 2007; Curtin et al. 2012).

7.5.3.2 Soil Microbial Biomass C and N

Microbial biomass carbon (MBC) is an active component of SOM and constitutes an important soil health parameter as carbon contained within microbial biomass is a stored energy for microbial process. The rapid build-up of microbial biomass in subtropical conditions implies that MBN could serve as a potential source of mineralizable N for plant nutrition in such soils. Thus, MBC and microbial biomass N (MBN), the measure of potential microbial activity, are strongly related to soil aggregate stability. Conversion to CA can improve soil biological quality with respect to microbial communities, microbial growth and decomposition processes (Franzluebbers et al. 1995), soil food web, and C dynamics. Spedding et al. (2004) found that residue management had more influence than tillage system on microbial characteristics, and higher SMB-C and N levels were found in plots with residue retention than with residue removal although the differences were significant only in the 0–10 cm layer. Soil microbial biomass C and microbial biomass N are the sensitive biological indicators and are closely related to the cycle of C and N in the soil (Turner et al. 2001). Meanwhile, the conversion rate of soil microbial biomass C and N can directly or indirectly reflect the changes in soil fertility (Vig et al. 2003). The practice of crop residue retention and minimum tillage, in association with basal fertilizer application, increases the supply of C and N, which is reflected within 1 year in terms of increased microbial biomass, N mineralization rates, and available N concentrations in the soil (Kushwaha and Singh 2005). Studies conducted in Londrina, Brazil, by da Silva et al. (2010) revealed that the microbial biomass carbon and nitrogen (MB-C and MB-N) values were consistently higher up to more than 100% under NT in comparison to CT and were associated with higher grain yields. Population and diversity of genomic patterns of the N_2 fixing *Bradyrhizobium* increased with no-till compared to conventional tillage in Southern Brazil. Nunez et al. (2012) reported bacterial diversity increase in zero-tillage systems as compared to conventional tillage. Zero tillage proved to be more efficient than the other tillage systems (reduced and conventional tillage) in the conservation of organic carbon and microbial biomass carbon at the soil surface depth (0–5 cm) as reported by Costantini et al. (1996). It has been reported that there was higher organic matter content, MBC, MBN, and enzyme activities in more superficial layers of soils under CA than in soils under conventional tillage. The increase in microbial populations, diversity, and other biological indicators of soil health under CA practices can be attributed to a number of factors that favour microbial proliferation and activities, viz. minimum soil disturbance, presence of residue, optimum soil physical environment, etc. Wang et al. (2013) reported increased MBC with crop residue application in comparison to no crop residue application. Nyamadzawo et al. (2009) revealed that the favourable effects of ZT on soil structural properties may also be partly due to more activity of earthworms and more microbial biomass than in CT plots. It was observed that long-term no-tilled soils have significantly greater levels of microbes, more active carbon, more SOM, and more stored carbon than conventional tilled soils. A majority of the microbes in the soil exist under starvation conditions, and thus they tend to be in a dormant state, especially in tilled soils. Pankhurst et al. (2002) found that zero tillage with direct seeding into crop residue increased the build-up of organic C and SMB in the surface soil. This is attributed to higher levels of C substrates available for microorganism growth, better soil physical conditions, and higher water retention under zero tillage. Wright et al. (2005) found MBC to be greatest under no-till management, but only in the surface 2.5 cm with little tillage effect to 20 cm. Gupta et al. (1994) found higher values of microbial biomass in the first 5 cm of the soil profile under NT than under TT after 1 year of conservation management.

7.5.3.3 Soil Enzyme Activities

Microbial activity-based indicators of soil quality may respond to disturbances on a shorter period of time than those based on physical or chemical properties. As a consequence, microbiological properties, such as soil enzyme activities, have been suggested as potential indicators of soil quality because of their essential role in soil biology, ease of measurement, and rapid response to changes in soil management practices (Kandeler et al. 1999). Soil enzyme activity can be used as an indicator of soil quality for assessing the sustainability of agricultural ecosystems (Singh et al. 2018). No-tilled soil have been reported to have higher values of water-soluble C, dehydrogenase, urease, protease, phosphatase, and β-glucosidase activities and aggregate stability than tilled soils under sorghum but had lower values than the soil under native vegetation (Roldan et al. 2005). This was mainly attributed to higher SOC and better microbial proliferation under conservation agriculture practices because of addition of crop residues and minimum soil disturbance. With few exceptions, tillage had negative effects on the hydrolase activities considered in this study (urease, protease-BAA, phosphatase, and β-glucosidase), at all soil depths, mainly with the adoption of mouldboard.

7.5.3.4 Proportion of Labile Organic C and N Fractions in Total Organic C and Total N

Particulate organic matter (POM), dominated by undecomposed plant residues that retain recognizable cell structures including fungal hyphae, seeds, spores, and fungal skeletons, is an active fraction of SOM, which supplies nutrients to the growing plants (Gregorich and Janzen 1996). POM-C and POM-N provide estimates of the intermediate pool of SOM between the active and passive pools (Cambardella and Elliott 1992) and provide substrate for microorganisms and dominantly influence soil aggregation (Franzluebbers et al. 1999; Six et al. 1999). Light fraction organic matter (LFOM), composed primarily of plant-derived remains and microbial and microfaunal debris and other incompletely decomposed organic residues, is more sensitive to management practices than POM (Carter et al. 2003). Aulakh et al. (2013) found that an application of organic and inorganic fertilizers in soybean-wheat cropping system under CA enhanced total organic C (TOC) from 3.8 g kg^{-1} in no NP-FYM-CR control to 5.8 g kg^{-1} in surface layer and from 2.7 to 3.6 g kg^{-1} in sub-surface layer after 2 years leading to the 41% and 39% higher TOC stocks over CT control in 0–15 cm soil layers of CT and CA, respectively. The changes in TOC stocks after 4 years were 52% and 59%. Likewise, the labile C and N fractions such as water-soluble C, POM and LFOM, potentially mineralizable N, and microbial biomass were also highest under this integrated inorganic and organic treatment.

7.6 Crop Yield and Resource-Use Efficiency

CA practices help in improvement of soil health which can lead to enhancement in crop yield (Das et al. 2014, 2016, 2018; Dudwal et al. 2018; Hajebi et al. 2016; Madar et al. 2017, 2018; Nath et al. 2017a, 2017b; Saad et al. 2015; Sepat et al. 2015), and use efficiencies of water (Mohammad et al. 2018), nutrients, energy, labour, pesticides, etc. However, this increase is specific to crops, sites, climates, and times. Many a times the positive effect on crop yield on CA is observed after long-term adoption of this practice. In the initial years of conversion to CA system, it may result in decline or nonsignificant change in yield compared to CT system. Yield of wheat and corn under NT system was 10–14% lower than CT system in plots without nitrogen fertilization. But this decrease was mitigated by nitrogen fertilization (Alvarez and Steinbach 2009). Ngwira et al. (2014) found that the positive effect of NT system with residue retention in maize-cowpea rotation was seen from fifth year in which the crop showed higher yield than conventional agriculture, and also CA was less susceptible to climate variability than CT. The yield of wheat crop was higher in conservation agriculture than conventional agriculture during the driest year having low rainfall but lower in the wettest year having high rainfall (Lopez-Bellido et al. 1998). Diaz-Zorita et al. (2002) suggested that pastures and no-till row crop sequences having maize and wheat increased soil organic carbon in upper 20 cm layer, which had positive effect on crop yield. Under ZT and RT, the increase in yield of spring wheat, flax, and field pea was 21%, 23%, and 9%, respectively, over conventional tillage in an experiment conducted in Western Canada (Lafond et al. 1992). Rieger et al. (2008) found that in cool and humid climate, the wheat development under no-tillage was slightly slower than minimum and conventional tillage in the early stages, but at maturity, the shoot biomass was 2% higher in no-tillage than the other two. The grain yield under no-tillage was 3% less than minimum and conventional tillage due to fewer ears per unit area and lower test weight. Under conservation agriculture in sandy loam or loamy soils having maize-wheat rotation, the equivalent yield of wheat was 47% higher than conventional agriculture (Ghosh et al. 2015).

Zero-tillage farming on 0.25 m ha in IGP reportedly saved 75 million/m^3 water in 2002–2003 (Malik et al. 2004). Hence, a 3.43 million ha of wheat under no-tillage would save an estimated 1029 million m^3 of water every year. It was reported that 13–17 billion m^3 of groundwater is lost permanently from the north-western plains of Punjab, Haryana, and western Uttar Pradesh (Rodell et al. 2009). Triple zero-till conditions in rice-wheat-mung bean system results in 35–40% savings in irrigation water and 91% higher system water productivity (kg grain/m^3 of water) compared to conventional rice-wheat system. In wheat-based cropping systems, the system water productivity (SWP) was highest in zero-till broad bed with residue. Among the cropping systems, cotton-wheat (C-W) resulted in higher SWP compared to pigeon pea-wheat (P-W) and maize-wheat (M-W) systems. There were 60.3%, 67.9%, and 63.5% savings in irrigation water, 49.4%, 56.1%, and 58.7% savings in total water and 215.4%, 172.5%, and 150.8% higher SWP due to C-W, P-W, and M-W systems, respectively, compared to TPR-CTW system. De Vita et al. (2007) observed that NT produced enhanced yield under limited rainfall condition due to less evaporation and more soil water availability than conventional tillage system, but not in case of high rainfall condition in which CT yielded better.

Conservation agriculture practices influence nutrient uptake and nutrient use efficiency due to its effect on root growth and modification of soil physical environment. Bhagat and Acharya (1987) reported that as the mulch treatment enhanced the N availability, the N uptake increased more in mulched treatment than that of without mulch treatment. Under mulch treatment, rooting density and length were also higher than un-mulched treatment. Westermann and Crothers (1993) reported that wheat crop planted in no-till system with stubbles of alfalfa showed 76% apparent N fertilizer recovery and 78% average plant recovery of mineralized N. Das et al. (2014) reported that the mean water productivity of the system in the permanent broad bed with residue (PBB + R) treated plots (12.58 kg wheat grain ha^{-1} mm^{-1}) was 48% higher compared with CT treatment. The above-said PBB+ R plots also had 36% higher net returns compared to CT plots. Therefore, growing cotton-wheat system under permanent beds with residue retention under irrigated conditions in the Indo-Gangetic Plains was recommended due to its potential of increased productivity, profitability, and resource conservation. Das et al. (2016) reported that positive impacts under PBB + R plots over CT plots with respect to yield and system water use efficiency were perceived due to no-tillage and significantly higher amount of estimated residue retention. Thus, PBB + R technologies would be very useful under a pigeon pea-wheat cropping system in the Indo-Gangetic Plains region. Das et al. (2018) reported that PBB + R saved water through higher water use efficiency and lead to accumulation of more carbon in soil with higher sequestration potential, besides giving sustainable production through maize-wheat system over the years.

7.7 Issues Related to Adoption of Conservation Agriculture

Though there are positive effects of CA practices on soil physical health and sustainable crop production, the following constraints inhibit its wider adoption among the farming community:

- Converting to CA needs higher management skills.
- The first years might be very difficult for the farmers; therefore, they might need support—from other farmers or from extension services—and perhaps even financial support to invest in new machinery such as zero-till planters.
- Necessary technologies are often unavailable to farmers.
- Few farmers take the risk of buying new machinery.
- Machinery dealers might not wish to promote CA.
- Cultural background (tradition, prejudice) and mind-set of the farmers to till the soil.
- Lack of knowledge on how to implement CA (know-how).
- Lack of adequate seeding equipment.
- Poor weed control.
- Inadequate policies.
- Poor management of residues and alternate competing demands for residues.

7.8 Conclusions

Conservation agriculture practices result in improvement of the main indicators of soil physical, chemical, and biological health and enhance carbon sequestration and minimize greenhouse gas emissions. These benefits of soil health improvement may not be immediately translated to crop yield, but this has a significant role in improving input use efficiency and long-term sustainability of crop yield. Specialized equipment and know-how for CA should be made available to the farmers, which is the major bottleneck for large-scale adoption of this practice. Legislation should be enacted to stop burning of crop residues by the farmers, and some incentive to the farmers may be given to adopt conservation agriculture rather than burning of crop residues. Conservation agriculture practices hold promise for improving soil health and sustainable intensification of crop yield and hence need to be validated, and site-specific CA practices should be promoted for diverse soil, crop, and agro-climatic situations.

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Impact of Conservation Agriculture on Soil Properties and Crop Productivity Under Rice-Fallow Ecology in Eastern India

8

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Abstract

Opportunity to utilize the carry-over residual soil moisture to produce the post rainy season crops in rice-fallow production systems was one of the basic strategies for improving the livelihood security of the farming community in Eastern India. As per recent estimates, ~22.3 M ha of suitable rice-fallow areas exist in the South Asia, with 88.3% in India, 0.5% in Pakistan, 1.1% in Sri Lanka, 8.7% in Bangladesh, 1.4% in Nepal and 0.02% in Bhutan. These fallow lands are suitable for crop intensification with a short-duration (≤3 months), low water-consuming grain legumes, i.e. chickpea; lentil; black gram and oilseeds, viz. safflower, linseed and safflower, to improve the smallholder farmer's incomes and soil health. There is a great scope in converting theses rice-fallow lands into the productive agro-ecosystems through appropriate crop-based interventions involving the suitable varieties and appropriate resource conservation technologies (RCTs)/conservation agriculture (CA) practices. Pulses/oilseeds, i.e. chickpea, lentil, lathyrus, mustard, linseed and safflower—through rotation or relay with rice—are candidate crops for efficient utilization of conserved and scarce resources including soil moisture. Thus, it is inferred from rice-fallow production system that the efficient agronomic management of soil and land

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resources is crucial for augmenting the crop productivity and soil health as well as enhancing the output in prevalent rice fallow of Eastern India.

Keywords

Conservation agriculture · Crop productivity · Rice-fallow · Soil moisture · Soil health

8.1 Introduction

Unsustainable exploitation of natural resources has led to widespread degradation of land, soil nutrient mining and soil carbon loss and resulted in serious implications for food security and ecological integrity in eastern India. Conservation agriculture is a response to sustainable land management, environmental protection and climate change adaptation and mitigation (Somasundaram et al. 2017, 2018a). FAO (2014) has defined conservation agriculture (CA) as 'an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing resource base and environment'. Sometimes it is also referred to as 'agricultural environmental management'. CA, based on the three key elements of *minimizing soil disturbance* (NT/minimum tillage), *maintaining soil cover* (organic soil mulch cover by crop residues and cover crops) and *crop rotation* (diversification of crop species in sequence or association), enhances biodiversity and natural biological processes above and below ground surface, which contributes to increased water and nutrient use efficiency and to improved and sustained crop production. Overall goal of CA is to make better use of agricultural resources through integrated management of available soil, water and biological resources such that external inputs can be minimized. CA system has been adopted on over 157 M ha globally (Table 8.1) (Kassam et al. 2015). In India, CA system has been partially practised in the form of ZT in winter

Table 8.1 Extent of adoption of CA worldwide (Kassam et al. 2015)

Country	CA area '000 ha (2013 update)
USA	35,613
Brazil	31,811
Argentina	29,181
Canada	18,313
Australia	17,695
China	6670
Russia	4500
Paraguay	3000
Kazakhstan	2000
India	1500
Uruguay	1072
Others	5626
Total	**1,56,981**

crops, mainly in wheat in rice-wheat cropping system (RWCS) of Indo-Gangetic Plains (IGPs). Conservation tillage is a major component of CA, which has been widely advocated worldwide in the present-day agriculture. The US Soil Conservation Service defines conservation tillage (CT) as any tillage system that leaves at least 30% of surface covered by plant residues for the control of soil erosion. CT is a tillage system that conserves soil, water and energy resources through the reduction of tillage intensity and retention of residues. It involves planting, growing and harvesting of crops with limited disturbance to soil surface. CT includes many types of tillage and residue management systems. ZT/NT, reduced tillage, strip tillage, ridge tillage and mulch tillage are various forms of conservation tillage.

8.2 Conservation Agriculture in Rice Fallows

Sustainable, profitable and resilient agriculture for a small farm holder is key to food and nutritional security for the growing populations of India. There is a need to increase and diversify food production to meet the increasing food and nutritional demands of the growing population and to provide additional income to small/marginal farmers. However, increasing production by expanding area is limited due to increasing pressure on croplands for alternative uses. Hence, intensification of cropland is an imperative and variable solution. Rice fallows are those rainy season rice grown areas which remain fallow during winter season due to lack of irrigation facilities; late harvesting of long-duration high-yielding rice varieties (HYVs); soil moisture stress at planting time of winter crops due to early withdrawal of monsoon; water-logging and excessive moisture during November/December and open grazing practice of domestic animals, stray cattle and blue bulls. As per recent estimates, about 22.3 M ha of suitable rice-fallow areas exist in South Asia (Gumma et al. 2016). These areas are suitable for intensification with a short-duration ($\leq$3 months), low water-consuming grain legumes, i.e. chickpea; lentils; lathyrus and oilseeds, viz. mustard, linseed and safflower, to improve smallholder farmer incomes and soil health. Soil-moisture conservation and mitigation of abiotic stresses are two major strategies required for successful trapping of rice–fallows (Kumar et al. 2019a).

8.3 Production Constraints in Rice Fallows

Moisture stress: Lower soil moisture storage and lack of irrigation facilities are major crop production constraints in rice fallows. Although rice-fallow areas receive normal to high rainfall during rice rainy season, most of the rain water is lost due to high runoff and low moisture storage capacity of soils (Kumar et al. 2021). Soil compaction after puddle rice restricts water infiltration into soil and development of deep and wide cracks in soils after rice harvest helps in faster depletion of stored soil moisture through evaporation (Somasundaram et al. 2018b). Soil moisture stress at the time of sowing of fallow season crops results in poor plant stand. Even if crop is established well with residual soil moisture, lack of winter rains towards reproductive stage often leads to complete crop failure (Ghosh et al. 2016). Available soil moisture gets exhausted by the time the crop reaches to reproductive stage, resulting in terminal drought and heat stress. The production constraints in rice fallows are listed below:

- Cultivation of long-duration rice varieties.
- Lack of improved short-duration varieties and quality seeds.
- Narrow sowing window due to fast depletion of residual soil moisture after rice harvest.
- Lower SOM content due to monocropping, open grazing, soil acidity and alkalinity.
- Poor soil physical properties after puddled transplanted rice.
- Excessive weed infestation and lack of selective post-emergence herbicides to control these weeds in pulses and oilseeds.
- Incidence of rust in lentil and wilt in chickpea.
- Poor mechanization due to resource-poor farmers and small and fragmented land holdings.
- Excessive moisture in the coastal region, parts of Bihar and eastern Uttar Pradesh.
- Open animal grazing and problem of blue bulls.

Rice (*Oryza sativa* L.) is the most important crop during the rainy season in Eastern India, covering ~26.8 M ha and accounting for ~63.3% of the total rice acreage, out of which ~11.7 M ha area in the rice production system remains fallow (Fig. 8.1) during the succeeding winter season due to several limitations. Efficient utilization of these fallow lands may improve productivity and sustainability of the regions. Soil properties of the region suggesting that short-duration pulses, i.e. chickpea (*Cicer aerietimum*); lentil (*Lens culanaris*); lathyrus (*Lathyrus sativus*) and oilseeds, viz. safflower (*Carthamus tinctorius*), linseed (*Linum usitatissiumum*) and mustard (*Brassica campestris*), can be grown successfully in rice fallows with supplemental life-saving irrigation. Around 3.0 M ha extra land in pulses and 1.0 M ha in oilseeds can be brought with suitable policy interventions. If location-specific constraint to produce crop be alleviated, these unutilized lands might be converted into productive lands with crop-appropriate planning. Intensification of existing agricultural production systems is need of the hour to take care of the rising demand of food grain production in the country (Kumar et al. 2016a, b). In this perspective, there is an enormous opportunity to increase total cropping area through strategic research in rice-fallow system (Kar and Kumar 2009). However, including second crop in rice fallows is a great challenge as post rainy season often confronts a series of abiotic and biotic stresses (Kumar et al. 2018b). Fast depletion of soil moistures after rice harvest, lack of irrigation facilities, poor access to extra early-duration varieties of pulses/oilseeds, late harvesting of rice, uncertainty in rainfall event, poor soil structure and problems of stray cattle are some of the major constraints in the cultivation of winter crops in rice fallows (Kumar et al. 2018c).

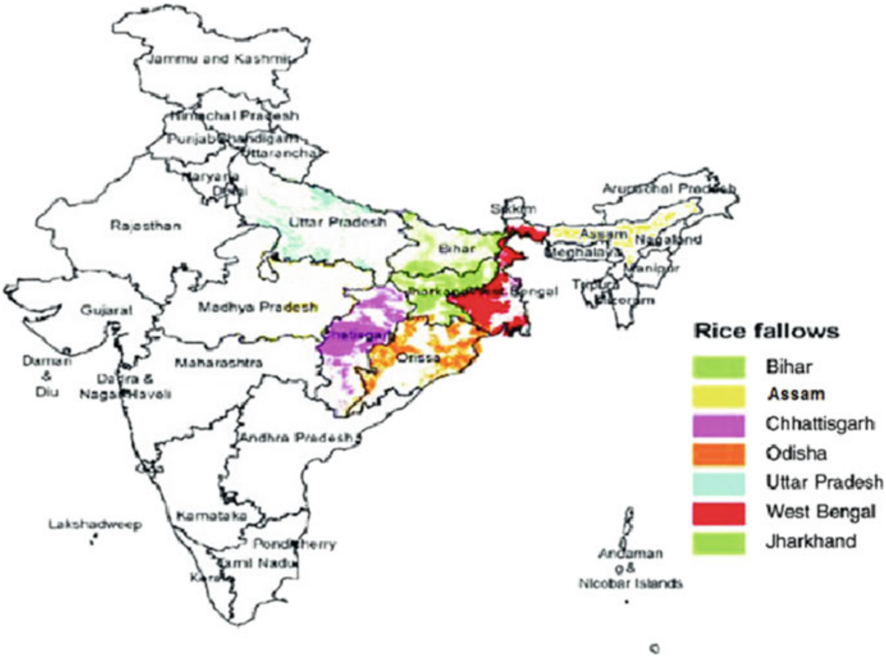

Fig. 8.1 Potential rainfed rice-fallow area for pulses and oilseeds in Eastern India (Modified from Pande et al. 2012a)

Thus, it is a great challenge to researchers, policymakers and stakeholders to extensively utilize rice-fallow areas in Eastern India.

8.3.1 Climatic Variability

The agroclimatic condition of the eastern region is categorized by hot-dry, sub-humid with hot summers and cooler winter. The mean annual temperature ranges between 24 and 26 °C. The mean summer (April–June) temperature varies from 29 to 32 °C, rising to a maximum of 37–42 °C in April/May. The mean winter (December–January/February) temperature varies from 16 to 18 °C and dropping to a minimum of 8–10 °C. The region receives an annual rainfall of 1200–1500 mm and increasing towards the eastern side to 1600 mm. *Kharif* season is humid with excess water of 200–300 mm and potential evapotranspiration (PET) ranges between 1400 and 1700 mm (Bandyopadhyay et al. 2016). Cropping activities start with the commencement of rains, and it ranges between 180 and 210 days in the region except >240 in West Bengal. The soils of the regions have sub-terranean, weakly drained and fine-loamy texture.

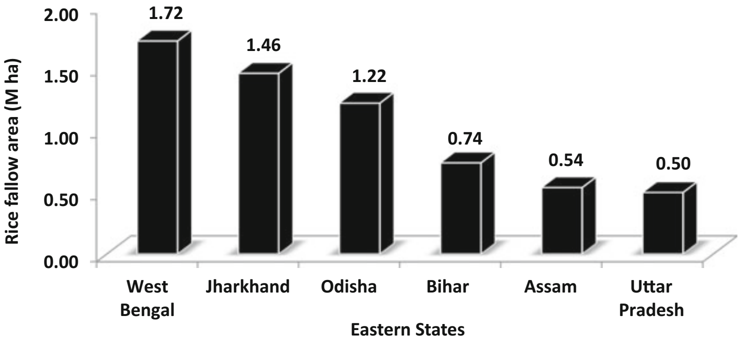

Fig. 8.2 Existing area under rice fallows in Eastern India (Annual Report 2016)

8.3.2 Distribution of Rice-Fallow Areas

As per the recent estimates, ~22.3 M ha of rice-fallow areas exist in South Asia, with 88.3% in India, 0.5% in Pakistan, 1.1% in Sri Lanka, 8.7% in Bangladesh, 1.4% in Nepal and 0.02% in Bhutan (Gumma et al. 2016). These areas are suitable for intensification with a short-duration ($\leq$3 months), low water-consuming grain legumes, i.e. chickpea; lentil; black gram; green gram and oilseeds, viz. linseed, mustard and safflower, to improve smallholder farmer's incomes and soil health (Fig. 8.2). Rice-fallow areas are extensively spread in rainfed ecology of the regions. Soils are mainly deep alluvial, neutral to acidic in nature. The major districts that fall under rice fallows in Eastern India are Lakhimpur, Jorhat, Sibsagar, Dibrugarh, Golaghat, Karbi, Nagaon and Maringon (**Assam**); Kishanganj, Gaya, Aurangabad, Jamui, Nawada, Banka, Katihar and Bhagalpur (**Bihar**); Ranchi, Purbi/Paschim Singhbhum, Hazaribagh, Gumla, Sahibganj, Deogarh, Palamau, Dumka and Dhanbad (**Jharkhand**); Surguja, Jashpur, Raigarh, Durg, Bilaspur and Bastar (**Chhattisgarh**); Koraput, Kalahandi, Sambalpur, Sundergarh, Bhadrak, Cuttack, Puri, Dhenkanal and Mayurbhanj (**Odisha**); Purulia, Bankura, Birbhum, Bardhaman, Medinipur, Murshidabad, South 24 Parganas, Maldhah, West Dinajpur and Cooch Behar (**West Bengal**) and Ghazipur, Bhadohi, Maharajganj, Bahraich, Balrampur, Gonda, Siddarthanagar, Mirzapur, Chandauli, Sonbhadra, Lakhimpur Kheri, Pilibhit and Etawah (**Eastern Uttar Pradesh**) (Annual Report 2016). As per the estimates of the Expert Group on Pulses, the potential pulse area under rice fallows is 2.46 M ha (Fig. 8.3), which is mainly concentrated in the districts of eastern states like Bilaspur, Dhamtari, Kanker, Raipur, Jashpur, Durg, Rajgarh, Kabirdham, Korba, Mahasamund and Rananadgaon (**Chhattisgarh**); Baleshwar, Dhenkanal, Sundergarh, Mayurbhanj, Kalahandi, Balangir, Keonjhar, Puri and Cuttack (**Odisha**); Bankura, Purulia, Medinipur, West Dinajpur, Malda, Jalpaiguri, Bardhaman and Birbhum (**West Bengal**) and Marigaon, Naogaon, Lakhimpur, Kokrajhar, Bongaigaon, Nalbari, Kamrup, Barpeta, Darrang, Cachar, Goalaghat, Jorhat, Dibrugarh, Tinsukia and Sonitpur (**Assam**) (Annual Report 2016).

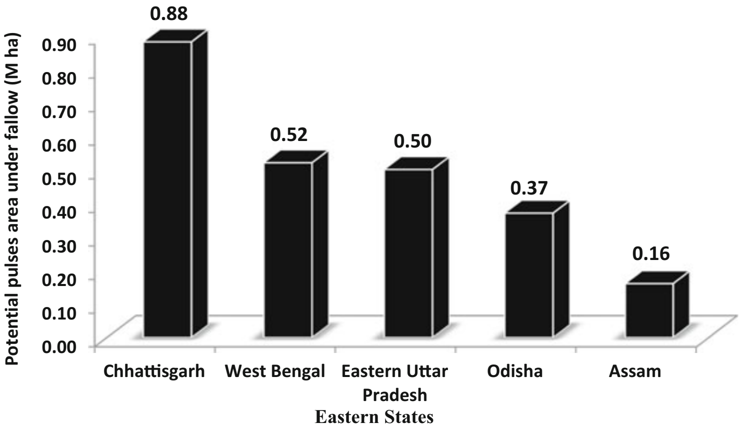

Fig. 8.3 Potential pulse area under rice fallows in Eastern India (Annual Report 2016)

8.3.3 Challenges of Rice Fallow

The total geographical area of Eastern India is 73.66 M ha, which accounts for 22% of the total geographical area of the country (Bandyopadhyay et al. 2016). The net cultivated area in this region is only ~45% (33.6 M ha). This region contributes to ~34.6% of the total national food production. The food-grain productivity in this region is the highest in West Bengal followed by Eastern Uttar Pradesh, Bihar, Assam, Odisha, Jharkhand and Chhattisgarh. Cropping intensity in eastern states ranges from 115% in Chhattisgarh to 177% in West Bengal. This region is inhabited by 38% of the total national population, but the agricultural development is much below its potential levels. As a consequence, employment prospects in farming segment are restricted, compel to a mass of people to stay under poverty and malnutrition. The per capita accessibility of the cultivated land in the regions is the lowest (0.15 ha) in the country (Kumar et al. 2016a, b). A majority of farm possessions are marginal to small and extremely fragmented, which limit the implementation of mechanized farming in this region. The region receives ~1100–1200 mm annual rainfall, which is much enough to meet water necessity of different crops. Much spatial and temporal variation is found in rainfall pattern and distribution that cause volatility in farming process.

Rice is the main crop and mostly grown as transplanted during the rainy season, for which puddling operation is done to create favourable environments. However, puddling creates a slurry of soil through the damage of macropores and aggregates, resulting in lowered bulk density (Cassman et al. 1995). These soils frequently dried out and build up crack at the end of post-*Kharif*, leading to the unavailability of soil moistures to support winter crops. However, ploughing of these soils after harvesting of rice creates big clods with higher breaking strength, decreasing the yields of subsequent crop, perhaps due to restricted root growth (Kar and Kumar 2009). Nonetheless, resource-poor farmers of these regions are not able to meet the expense of irrigation and fertilizers to produce their crop in the post rainy season. Thus, growing of second cropping after harvest of rainy transplanted rice depends on the efficient use of residual soil moisture. Through the appropriate study, plan and expansion efforts on these fallow lands, second cropping through the efficient use of residual moistures may be brought in. After harvesting of rice, the climatic situations of the unutilized land in these regions are appropriate for growing short-duration crop cultivars, namely lathyrus, lentil, chickpea, safflower, linseed and mustard. However, conventional rice pulse relay systems are being followed in Odisha, West Bengal, Chhattisgarh and Jharkhand. But a poor crop establishment of pulses in relay cropping is a major yield-limiting factor in the region (Kumar et al. 2018d). After understanding the system ecology, it has been observed that poor seed-soil contact, low soil-moistures and severe infestation of weeds are the major constraints for the ideal plant population of pulses in rice fallows (Kumar et al. 2016a, b). In lowland soil having higher soil moistures, lentil and lathyrus are suitable for *utera* cropping as compared to chickpea (Mishra et al. 2016; Mishra and Kumar 2018). Residual soil-moistures at rice harvesting are normally enough to raise pulses/oilseed crops in region (Kumar et al. 2018e).

Despite the immense scope, the extensive use of rice fallow for the cultivation of pulses/oilseed crops is mostly restricted because of several biotic, abiotic and socio-economic constraints (Panda et al. 2000). Among the abiotic factors, low soil moisture content and rapid soil moisture depletion frequently led to drought situation at flowering and harvesting (Pande et al. 2012a). Still if a crop is managed well with residual soil moisture, a small amount of winter rains at grain filling stage often led to complete crop failures (Kumar et al. 2016a, b). The lack of irrigation facilities and poor soil moisture, thus, constitute the main limiting factors for the production of pulses/oilseeds in rice fallows. Site-specific nutrient deficiency (P, Zn, S, B and Mo), soil acidity and low soil organic carbon (SOC) directly affect pulse/oilseed production in rice fallows (Pande et al. 2012b). In fact, poor water retention capacities are directly associated with lower SOC. Further, poor soil-physical properties, disturbance of soil structure, soil-water deficit, poor porosity and mechanical impedance of seeding zones create adverse situation for crop establishment in rice fallows. Soil hardiness in puddle rice field gets the worse physical properties of the soil that badly affect moisture allocation/rooting patterns.

- *Soil moisture stress and lack of irrigation*: Although rice-fallow areas receive normal to high rainfall during the rainy season, most of the rain water is lost due to high runoff and low moisture storage capacity of soils. Soil compaction after puddle rice restricts water infiltration, and development of deep and wide cracks in the soils after rice harvest helps in fast depletion of the stored soil moisture through evaporation. Soil moisture stress at the sowing of fallow crops results in poor crop stand (Kumar et al. 2018a). Even if crops are established well with residual soil moisture, lack of winter rains towards reproductive stage often leads to complete failure of the crops (Ghosh et al. 2016). Available soil moisture gets exhausted at that time and crop reaches to flowering stage resulting in terminal drought and heat stress (Kumar et al. 2018b).

- *Shortage of superior cultivars and quality seeds*: Crop cultivars especially suitable for these fallow lands have not been developed; thus, available varieties with relatively higher yields are being suggested (Kumar et al. 2018c). Lack of suitable quality seeds of short-duration varieties of pulses/oilseeds for rice fallows is also one of major constraints.
- *Long-duration rice varieties*: In rice-fallow areas, farmers used to grow the long-duration rice varieties that mature in 160–165 days. This causes delayed sowing of subsequent pulses/oilseeds, resulting in poor yields due to terminal drought. Pande et al. (2012a) reported that >90% farmers viewed lack of suitable crop varieties as the main bottleneck in rice fallows.
- *Severe weed menaces*: Weeds pose severe difficulty in *utera*, because crops are grown without cultivated soil (Ali et al. 2014). Excessive weed infestation in general and the problems of parasitic weed (*Cuscuta* spp. in pulses/oilseeds) and the lack of selective post-emergence herbicides to control these weeds in pulses and oilseeds are other challenges in these areas. Manual weeding is tough due to quick moisture loss from soil surfaces (Kumar et al. 2018a).
- *Soil acidity*: It is an important constraint responsible for lower productivity of pulses in the eastern region. About 50% of the total land and ~ 80% of the cultivated soils are acidic in nature (Kumar et al. 2016a, b). Basically, pulses are sensitive to acidity, directly impacting biological nitrogen fixation (BNF), microbial diversity and plant-nutrient accessibility and having toxic effect to the root (Choudhary et al. 2014). Strongly acidic soil has been noticed in rice fallows of Chhattisgarh and Assam (Kumar et al. 2016a, b).
- *Terminal drought*: Since post rainy season crop is taken on residual soil moisture in rainfed condition, terminal drought badly affects crop yield (Kumar et al. 2016a, b). Drought fastens the leaf senescence and lessens net photosynthesis and translocation from leaf to budding grains. The build-up of poor biomass frequently does not sustain grain formation (Singh et al. 2017). Terminal drought and temperature apprehension consequence in strained ripeness and trim down yield by 50% (Reddy 2009).
- *Poor crop management*: Winter crop in these fallows are considered as bonus cropping (Ali and Kumar 2009). In view of the risk concerned for growing of second crops due to the limitation of soil moistures and socioeconomic hindrance, the farmers do not give more attention in crop management, i.e. selection of suitable cultivars, seed rate, crop protection, *Rhizobial* treatment, foliar feeding of nutrition and farm mechanization (Singh et al. 2017).
- *Socioeconomic constraints*: Poor economic condition and low purchasing capability induce farmers to leave a field unused after rice harvest. Besides fragmented land holdings, shortage of labour, non-availability of inputs, limited access to institutional credit, lack of market and lack of knowledge among farmers on water conservation techniques, poor extension service directly or indirectly discourages the farmers for taking second crops (Joshi et al. 2002). Animal grazing or free grazing by *nilgai* (*blue bull*), monkeys and boars causing severe damage in Bihar to pulses is another potential threat to rice fallows (Pande et al. 2012a).

8.3.4 Scope for Cultivation of Pulses and Oilseeds in Rice Fallows

The introduction of lentil/lathyrus/chickpea/linseed/safflower/mustard in these areas through suitable agricultural production techniques might usher in the Second Green Revolution in such diffident, poverty and underprivileged regions (Singh et al. 2017). Normally, the available water storage ability of soil in the following paddy harvest ranges between 150 and 200 mm (Das et al. 2017). Research finding reveals that these unutilized areas can be converted into second cropping by utilizing the residual soil moisture during *Rabi* (Das et al. 2014). Oilseeds, viz. linseed and safflower, can be grown in moisture stress condition (Kumar et al. 2018a; Mishra and Kumar 2018). With appropriate crop varieties and agricultural practices, the productivity of these pulses and oilseeds can be improved in rice fallows (Kumar et al. 2018b). Pulse/oilseed crops are considered as the main crop to strengthen these fallow areas (Table 8.2). Special advantages with pulse crop being short-duration, resilient and low-input requiring in nature suggest an incredible prospect to the use of residual soil moisture (Kar et al. 2004; Kar and Kumar 2009). It has distinct characteristics of biological nitrogen fixation (BNF), profound root growth and prospective to set up by means of broadcasting of the seeds in standing paddy

Table 8.2 Suitable crops and varieties for rice-fallow areas of Eastern India

Crop	Varieties	States
Lentil	HUL 57, KLS 218, Narendra Masoor, Arun, DPL 15, DPL 62, Vaibhav, Pusa Masoor, IPL 316, IPL 01, IPL 406, Ranjan, K 75	Assam, West Bengal, Bihar, Odisha, Eastern Uttar Pradesh, Chhattisgarh and Jharkhand
Lathyrus	Ratna, Prateek, Mahateora	Tal area Bihar, Chhattisgarh and West Bengal
Pea	Arkel, Azad pea, Rachna	Jharkhand, Chhattisgarh and Eastern Uttar Pradesh
Chickpea	GCP 105, Pusa 372, JG 11, JG 14, JG 16, Pant G 186, Rajas, Pusa 547, Pusa 256, Vaibhav, GCP 105, GNG 1581	Chhattisgarh, West Bengal, Bihar and Jharkhand
Mungbean	SML 668, Pusa Vishal, Samrat	Odisha, Chhattisgarh, Jharkhand and Bihar
Urdbean	Navin, T 9, ADT 3, ADT 4	Odisha and Jharkhand
Mustard	Pusa Bold, Kesri Gold	Eastern Uttar Pradesh, Bihar and Jharkhand
Groundnut	JL 24, ICGS 1, TAG 24	Bihar, Odisha and Assam
Safflower	PBNS 12, Manjira, Bhima	Eastern Uttar Pradesh, Bihar and Jharkhand
Linseed	Sweta, Uma, Shekhar, Indu, RLC 133, RLC 138, RLC 143, SLS 79, JLS 95, BAU 06–03, BAU 2012–1,BAUP 101	Eastern Uttar Pradesh, Bihar, Jharkhand and Assam
Toria	TS 36, TS 38, TS 61, M 27	Assam, Bihar and Jharkhand

Modified from Ghosh et al. (2016)

field. It is best fitted in these areas due to cost-effective approaches (Pande et al. 2012b). Therefore, strategic-oriented option needs to be worked out to manage adverse challenge of nature. More focused research should be carried on maximizing the productivity in rice fallows with inclusion of suitable pulses and oilseeds. In India, pulses are grown on ~24–26 M ha land with yearly production of 17–18 MT (Singh et al. 2017). At present, because of the large gap between supply and demand of pulses, the prices of pulse in the country had imported a huge quantity. So as to meet the rising needs of pulses, it should be included as an integral part in rice fallows with dual advantage of area expansion and sustainable production. Hence, the promotion of pulse/oilseed crops in these unutilized lands would improve the sustainability of paddy cultivation in addition to attractive productivity and the augmentation of the incomes of farming community of the regions (Reddy and Reddy 2010). For efficient utilization of rice fallows with the inclusion of pulses/oilseeds, a location-specific and economic viable technique is required to be identified through the proper understanding of system ecology.

8.3.5 Initiated Research and Development Programmes on Pulses and Oilseeds

Various intervention schemes had a greater impact on the exploitation of these unutilized fallows for growing of pulses/oilseeds and acceptance of recent technology by resource-poor farming community of the regions. Around one-third of land is presently unutilized after paddy harvest; it can be transformed into productive farming, and 3 M ha of additional land under pulses and 1 M ha oilseeds can be brought with appropriate policy intervention. Promotion of pulses mainly lentil, lathyrus and chickpea in rice fallows with the support of National Food Security Mission (NFSM) has shown a positive impact in the region. NFSM on Pulses and National Mission on Oilseed and Oil Palm Project (NMOOP) are implemented in Eastern states. Therefore, a differential approach is required for improving the profitability of rice-based cropping system through the intensive cultivation of pulses and oilseeds under the rice fallows. Rice fallows have immense potentials for growing of extra early-duration pulse/oilseed crops. Nonetheless, modest effort had been used in these areas with suitable technological support.

In All India Coordinated Research Project (AICRP) on Mungbean, Urdbean, Lentil, Lathyrus, Rajmash and Pea (MULLaRP), inadequate effort on managing and expansion of early-duration HYVs of lathyrus and lentil earlier conceded in this region. Recently, Department of Science and Technology (DST) sponsorship project had been implemented in Jharkhand to tackle the problems of rice fallows. Parallel effort are being completed in National Fund for Basic, Strategic and Frontier Application Research in Agriculture (NFBSRA) Project of ICAR on extenuating abiotic stress and improving resource use efficiencies in pulses under these fallows. NFSM, Department of Agriculture and Cooperation (DAC), Ministry of Agriculture, Government of India had funded unique project to global institute on rice fallow. International Crop Research Institute for Semi-Arid Tropics (ICRISAT) launched

NFSM-funded project on "Enhancing chickpea production in rainfed rice fallow land of Chhattisgarh and Madhya Pradesh" in collaboration with the National Agricultural Research System (NARS) for 2008–2012. Another project on "Enhancing lentil production for food, nutritional security and improved rural livelihood" was also approved by the International Center for Agricultural Research in Dry Areas (ICARDA) during 2010, which is being implemented in Assam, Bihar, Eastern Uttar Pradesh and West Bengal in association with NARS. Likewise, a unique project on "Enhancing grass pea production for safe human food, animal feed and sustainable rice-based production system in India" was supported by the NFSM to ICARDA and is being launched in Bihar, Chhattisgarh, Eastern Uttar Pradesh and West Bengal. On the other hand, varietal assessment and production of seeds are the most important mandates, whereas managing soil and crop aspects remained untouched in these projects. Small-seeded pulses find eminence in *utera*. In a similar line, the Consortium Research Platform (CRP) on CA was initiated by the ICAR with broad objectives of development, adaptation and refinement of location-specific CA practices for enhancing the productivity of rainfed ecosystems, and the results revealed that soil and water are the two major restraining attributes responsible for the lower production of crops in these fallows.

8.3.6 Strategies for the Production of Pulses and Oilseeds

Pulses and oilseeds are largely grown in similar agroecologies and considered as companion crop for mitigating adverse weather situations. Pulses have an additional advantage with their soil-enriching capabilities and good-quality fodder supplementation in rice fallow. Key interventions such as the demonstration of improved production technologies with cluster approach, augmentation of availability of good-quality seed, seed priming and treatment with *rhizobium*/fungicide, micronutrients, insect-pest management and protective irrigation will be supported for visible impacts in rice fallows. Resource conservation technologies (RCTs) may be suitable to tackle exertion in these fallow areas. After harvesting of rice, lower soil moisture content with subsequently quick turn down in water table with the progression of winter resulting in mid- and terminal drought at reproductive phases affects yield. Therefore, if the crop residue is retained on soil surface combined with appropriate establishment methods, it might lessen the severe stress by protecting soil moistures. ZT with minimum disturbance of the soil and retaining crop residues might favourably impact the soil property that further enhance overall productivity in rice fallows. This helps in reducing the cost of cultivation and improved input use efficiency. Fodder scarcity for livestock during *Rabi* is also an important issue in rice fallows. Improving cropping intensity of rice fallows may, in turn, help in meeting out fodder requirement during lean period. Simple technologies such as seed priming, spraying of 2% urea and DAP and micronutrient at vegetative stages increase productivity to remunerative level for resources-poor farmers (Kumar et al. 2018a).

Water harvesting and storage: In spite of heavy rain in *Kharif* (July–October), moisture becomes foremost limiting factor for raising second crops in *Rabi* (October–March) as most of the overflow is washed out. Thus, it is essential to construct arable farm ponds and community water reservoir in such areas with the support of governmental agencies. It will serve as vital means for life-saving irrigations during *Rabi*. For obtaining optimum productivity in rice fallows, it is necessary to have proper soil moistures at sowing and water facility for at least one life-saving/supplemental irrigation at the most critical stages. Since plenty of water in these areas is lost during rainy season through runoff, there is a need to harvest this excess rainwater and store in small farm ponds or reservoirs to provide life-saving irrigation to succeeding fallow crops. Construction of farm pond or community water reservoirs to harvest excess rainwater during rainy season is a feasible strategy to provide life-saving irrigation to successive pulse/oilseed crops in the rice fallows. Excess runoff available to an extent of 300–400 mm can be harvested in silpaulin-lined pond to make available at critical stages of crop growth through supplemental irrigation. This helps in increasing the overall land productivity. In higher rainfall areas of north eastern hilly (NEH) states, technological options have been identified for two contrasting conditions of abiotic stresses, i.e. excess soil moisture at rice harvesting in land-locked areas and valleys of hill and fast depletion of the soil moisture in upland, terraces and plains (Das et al. 2014).

The use of resource conservation technologies (*RCTs*): RCT such as ZT/reduced tillage (RT), retention of rice crop residue/mulching at 5 t/ha or 30–40 cm stubble have been found effective in the soil moisture conservation and increasing crop yields and monitory returns in rice fallows. Reduced tillage has increased yield of pulses (lathyrus, green gram, black gram) by 33–44% over conventional tillage (Kar and Kumar 2009). Retention of rice stubble/mulching and ZT sowing of pulses significantly enhanced the productivity of pulses in rice fallows (Ghosh et al. 2016). Retaining 30% of the rice residues on soil surface and ZT sowing with Happy Seeder increased yields of succeeding lentil, chickpea, safflower, linseed and mustard by 3.1, 11.7, 19.1, 14.4 and 12.3%, respectively (*Unpublished results*, CRP on CA Project at ICAR RCER, Patna). Utera cropping performed better than ZT (with or without mulch) and produced maximum seed yield due to advantage of early sowing and better utilization of residual soil moistures. Among different crops, lathyrus followed by linseed and lentil recorded the maximum yields and profits (Mishra et al. 2016). ZT after rice harvest also facilities timely planting of winter pulses and helps to escape the negative effects of terminal drought and rising temperature in spring to summer in rice fallows. The results of the farmers' participatory trials on ZT lentil and chickpea in Eastern IGPs during 2009–2010 showed that using ZT with reduced seed rate (30 kg/ha for lentil and 80–100 kg for chickpea) and deeper seed placement (5–6 cm for lentil) improved crop establishment and crop productivity and reduced wilt incidences (Singh et al. 2012). A survey on farmers' participatory adoption of ZT-seeded lentils in rice fallows (200 ha) of Nawada, Bihar, showed that ZT planting of lentils together with the suitable and improved agronomic packages resulted in higher yields (13%) and a reduced cultivation cost by Rs. 3800/ha, thereby increasing farm profitability of Rs10,000/ha (Singh et al. 2012). In lowlands having high moisture after rice harvest, draining excess water at physiological maturity of rice by providing drainage channels at appropriate intervals creates a favourable soil condition for ZT of winter pulses (Layek et al. 2014). But in the case of a dry soil at rice harvest, NT along with standing residue retention at 5 t/ha along with life-saving irrigations could give a reasonable lentil yields (Das et al. 2013). Mulching with paddy straw/water hyacinth was found to increase productivity of groundnut sown after rice harvest (Choudhary et al. 2014). At the Indian Institutes of Pulse Research, Kanpur, ZT drill for small farmers having low purchasing power was developed for line sowing in rice fallow, which helped in moisture retention as least disturbances of soil occurred. The use of NT drill and seeding was performed timely at reduced cost. Experiences from several locations in the IGPs showed that ZT farmers saved on preparatory operation by Rs.2500/ha and reduced diesels of 50–60 l/ha (Sharma et al. 2005).

- *System mode of crop production*: In order to efficiently utilize soil moisture and maximize system productivity of rice fallows, long-duration rice varieties need to be replaced with short- to medium-duration varieties for early harvesting and timely sowing of succeeding crops. Even for *para*/*utera* (relay) cropping, where seeds broadcasted in standing rice 10–12 days before crop harvest, rice fields need to be properly levelled for maintaining uniform soil moisture to facilitate uniform seed germination. Mechanical transplanting or line transplanting of rice gives higher yield of fallow *paira* crops. Kumar et al. (2019b) reported that lathyrus and lentil were the potential winter crops for sustainable cropping intensification of rice-fallow areas, and productivity potential of these crops could be further enhanced following the utera crop establishment technique. Also, higher system productivity was associated with grain legumes (chickpea and lentil) and safflower inclusive crop rotations (Kumar et al. 2020).
- *Suitable crops and varieties*: Availability of quality seed is regularly a most important limitation for late sowing and reduced yield of winter crops in rice fallow**.** Thus, community-based seed multiplication plan needs to be launched with suitable dispensation and storeroom facilities. National/state seed corporations have to toughen their actions in such area for helping the farming community. Growing early- to medium-duration rice varieties (Prabhat, Naveen, Swarna, Shreya) enables the farmers to advance sowing of succeeding crops for efficient utilization of stored soil moisture. Residual moisture left in the soil at rice harvest is often sufficient to support short-duration crops. In the eastern region, short-duration varieties of pulses like lentil; lathyrus; chickpea; mungbean; urdbean and oilseeds such as mustard, groundnut, linseed and safflower could be cultivated profitably in rice fallows under ZT or *utera*. In low land areas with excessive soil moisture, lentil and lathyrus can be grown successfully as *utera* cropping. Small-seeded varieties of pulses are better than large-seeded. In Jharkhand and Chhattisgarh, the cultivation of bottle gourd was found promising with limited irrigation facility. Lentil cultivars 'Pusa Masoor 5', 'Vaibhav', 'HUL 57', 'KLS 218' and 'Arun'; 'Pusa 256', 'JG 14' and 'Vardan'; linseed 'Uma', 'RLC 143', 'BAU 06–03 and 'RLC 138′; grass pea 'Ratan' and 'Prateek' have

been found promising in the rice fallows (*Unpublished results*, CRP on CA Project at the ICAR RCER, Patna). In other studies, linseed was found to be most productive/remunerative at Pusa, Bihar, under rice fallows. Among winter crops, safflower was most remunerative followed by black gram, lentil, mustard and niger in rainfed condition. Kar and Kumar (2009) reported safflower as the most remunerative crop in rice-fallow areas in Odisha. Extensive trapping of the rice fallows needs short-duration and hardy pulse varieties that can efficiently avoid terminal drought. Pulse genotype with fast-growing and wide canopy coverage could minimize evaporation losses from soil surface. Besides, growing early- to medium-duration rice varieties enables farmers to advance sowing of pulses/oilseed for utilizing residual moistures efficiently. Thus, there is an urgent need for developing an extra-early-duration cultivar of oilseed/pulses for fallow areas (Mishra and Kumar 2018).

- *Seed priming and optimum seeding rate*: It is an important cost-effective technology to obtain better crop stand and high yields of pulses in rice fallows (Ali et al. 2005). Seed priming, i.e. overnight seeds soaking with water or nutrient solution before sowing, is an important low-cost technology to improve the germination and seedling emergence. It is recommended to increase seed rate by 20–25% to have a desired plant population in rice fallows (Bhowmick et al. 2005). Lathyrus is mostly grown on residual soil moisture as *utera* cropping in rice-fallow areas (Gupta and Bhowmick 2005; Mondal and Ghosh 2005). But lower yields especially in *utera* system are a major problem associated with these crops (Bhowmick et al. 2005). There is a limited scope for agronomic manipulation under rice-*utera* system, although it has a potential to increase cropping intensity in considerable areas that remain idle after *aman* rice (Rautaray 2008). Pre-sowing soaking of seeds with KH_2PO_4/Na_2HPO_4/water has been reported to improve seed germination, seedling vigour and early root growth, resulting in good establishment, better drought tolerance and more yields (Solaimalai and Subburamu 2004). Bhowmick et al. (2014) conducted a field trial at Pulses and Oilseeds Research Station, Murshidabad, West Bengal, during the *Rabi* season to evaluate the different levels of seed priming (water soaking, 2% KH_2PO_4 solution and sprouted seeds) along with varying levels of foliar nutrition (water spray, 2% urea/DAP/KCl spray) using crop lathyrus cv. Ratan. Results revealed that the use of sprouted seeds had the highest seed yield (1021 kg/ha) followed by seed soaking in 2% KH_2PO_4 (964 kg/ha). Planting of primed seed either sprouted seed or 2% KH_2PO_4 soaked followed by twice foliar application of 2% urea/DAP at pre-flowering stage and 10 days thereafter would be a potential cost-effective technique for augmenting the production of lathyrus under *utera* cropping in the rice fallows (Bhowmick et al. 2014).
- *Seed treatment and foliar plant nutrition*: Pulse seed should be treated with fungicides followed by *Rhizobium*, PSB and VAM and *Trichoderma* inoculation before sowing for disease-free plant and better nodulation. Besides, foliar nutrition may be a useful option particularly for these areas, whereas soil application of fertilizers often leads to locking/loss of nutrients. With this technique, nutrients can reach the site of food synthesis, leaving no wastage, and thereby the

requirement of fertilizer may be cut short from a huge bulk to a handful (Bhowmick 2008). Foliar spraying of KNO_3/Ca $(NO_3)_2$ at 0.5% significantly improved the productivity of pulses (Sarkar and Malik 2001; Layek et al. 2014). Amongst the foliar sprays, Bhowmick et al. (2014) reported that the application of 2% urea at pre-flowering stages had the maximum seed yield (1040 kg/ha) and followed by 2% DAP spray (983 kg/ha). Apart from moisture stress, winter crops in rice-fallow experiences uneven degrees of nutrient stresses. Because of the poor physical condition of the soil and low native *Rhizobium* in typical rice fallows, nutrient mobilization is substantially reduced (Ali et al. 2014). Deficiency of micronutrient is also very common, and the supplementary application of these inputs especially Mo is necessary in acidic soil of rice fallows. In acidic soils, the application of lime/seed priming with Mo was found to be most effective (Kumar et al. 2016a, b).

- *Pest management*: Diseases, namely root rot, powdery mildew and yellow mosaic, and insects like pod borer cause heavy damage to pulse crops in rice-fallow areas. For the management of insect, pest and diseases, IPM strategy involving seed treatment with fungicides and biocontrol agent *Trichoderma*, selection of disease-tolerant varieties and spraying of need-based fungicides/insecticides will be useful. Taking after IPM like bird perches, spraying of NPV/chemical pesticides is useful for controlling pod borer in pulses. Genotypes having resistance to wilt in chickpea and rust in pea/lentil should be promoted. Small-sized lentil cv. WBL–77, KLS–21, NM–1 and DPL–15 have resistance to rusts and is performed well in Eastern India. To check seed-borne diseases, seed treatment with suitable fungicides/insecticides/plant growth-promoting rhizobacteria is required. Seed treatment with *Trichoderma* + carboxin/alternately carbendazim + thiram for root rot, colour rots/wilt in chickpea, lentil, mungbean/urdbean is useful for pulses.
- *Weed management*: IWM strategies including crop residue mulching, ZT sowing and application of post-emergence herbicides like quizalofop for grassy weed control and need-based manual weeding should be adopted (Kumar et al. 2016a, b). Effective post-emergence herbicides are not accessible in rice fallows. Intercultural operations are additionally troublesome, as the soil turns out to be hard. In this way, hand weeding is the main choice that must be done at the early stages of crop growth (Ali et al. 2014). Actually suitable post-emergence herbicides are not available for pulses/oilseeds, and carrying out intercultural operation is hard owing to the compactness of soil; thus, manual weeding is the only alternative that has to be completed at the initial stages of crops (Singh et al. 2017). The use of imazethapyr at 100 g/ha has been found to be relatively efficient in pulses (groundnut/urdbean/mungbean) at the initial stages of crop growth against narrow-leaved weeds (Ali et al. 2014). The application of glyphosate/paraquat to check the growth of rice stubbles that cause significant moisture losses in rice fallows is required before sowing of winter crops (Kumar et al. 2018a). The application of quizalofop at 50 g/ha at 15–20 days after sowing (DAS) has also been found to be effective in checking the regrowth of rice as well as the grassy weeds (Kumar et al. 2016a, b).

- *Soil moisture conservation*: In rice fallows, an effective moisture conservation practice can mitigate the moisture-related stress as well as terminal drought. Approaches of RCTs that prevent the rapid loss of soil moisture in the soil profile (Kar et al. 2004) improve SOC, and biophysical properties (Gangwar et al. 2006) could be strategic approaches in rice fallows (Ali et al. 2014). For better utilization of residual soil moisture, pulses/oilseeds need to be sown immediately after rice harvest. ZT prevents soil moisture loss and advances planting time by 7 days (Mishra et al. 2016). Kar and Kumar (2009) reported that RT increases pulse (lathyrus/lentil/chickpea) yield by~33–44% over conventional tillage in rice fallow. They also confirmed that moisture conservation potential of RT is better than NT/relay cropping. Similarly, higher yield of pulses with RT had reported by Ghosh et al. (2010). The fundamental principles of CA, NT and residue retentions on the surface had been followed in *utera* (Ali et al. 2014). Multi-location trials at Kanpur (UP), Kalyani (WB) and Raipur (Chhattisgarh) revealed that retention of rice stubbles/mulching and NT sowing of pulses (chickpea, lentil, lathyrus) had significantly enhanced productivity in relay cropping by maintaining higher soil moisture and improving soil attributes in rice-fallow areas of Eastern India (Ali et al. 2005).
- *Crop establishment techniques*: Mishra et al. (2016) evaluated the performance of three winter pulses, viz. lathyrus (Ratna), chickpea (JG 14) and lentil (HUL 57), under ZT and ZT with straw mulch at 5 t/ha (ZTM). The results revealed that ZTM had higher yields of pulses. ZTM in rice fallow had significantly higher rice equivalent yield (2.03 t/ha) and system rice equivalent yield (6409 kg/ha) as compared to ZTM and ZT. A long-term field experiment initiated by Kumar et al. (2018c) had results revealing that ZT-DSR had the maximum rice yield (5.14 t/ha) followed by conventional tillage-transplanted puddled rice (CT-TPR) (5.05 t/ha). In general, the productivity of succeeding crops was higher under ZT-DSR. Among winter crops, chickpea (1559 kg/ha), lentil (1515 kg/ha) and safflower (1761 kg/ha) recorded higher yield in ZT-DSR than that of the UPTR- and CT–puddled rice. Comparatively superior yield was recorded with 30% residue retention under RT. Similarly, system productivity was higher with chickpea (5799 kg/ha), lentil (5408 kg/ha) and safflower (5325 kg/ha). Retaining crop residue on soil surfaces seems to be a good option than incorporating it as it helps in reducing erosion and evaporation, evades the short–term association of nutrition and suppresses weeds. Under NT, residue retention had significant effect in soil sealing, crust formation and at the same time bringing an overall enhancement in resource managing (Bandyopadhyay et al. 2016). Marginal and small landholders in countries like India face challenges in managing crop residues. Residues are separated entirely and utilized as bio-fuel or farm animal feed or graze (Ghosh et al. 2010). Although the residue had high values and still little quantity is retained subsequent to harvest, it increases over the years and significantly affects soil qualities (Das et al. 2018). Information on residue retentions coupled with appropriate sowing like *utera* helps in the mitigation of terminal drought in pulses/oilseeds through protecting soil moisture and sinking evaporation in these fallows (Layek et al. 2014). Therefore, suitable skill of the cost-

effective conservation tillage and resilient cropping are feasible options to growing lentil, lathyrus and chickpea in fallow land. Therefore, transplant of paddy at the right timing with early-duration varieties might sustain the moisture deficits and terminal drought. Retaining paddy stubble will modify soil surface feature, influence thermal property of soil by sinking evaporations, which render additional water availability to the crops (Cutforth and McConkey 1997).

- *Planting strategy:* In rice-based systems, productivity of succeeding winter crops is influenced by the crop establishment methods due to the late harvest of HYV-transplanted rice, particularly in the eastern parts of the country, which delays sowing of succeeding winter crops, resulting in lower crop yields and input-use efficiency (Mishra and Singh 2011). In rice-fallow areas, crop sowing is normally late. In *utera* system, seeds have to be broadcasted 10–15 days before harvesting of paddy (Mishra et al. 2016). ZT seed-cum-fertilizer drill/Turbo Happy Seeder should be used wherever feasible for planting in these areas. It is compulsory to use early−/medium-duration rice cultivar for appropriate planting of *Rabi* crop (Table 8.1).
- *Ensure well-timed accessibility of crucial input*: Usually, post-rainy season crops are grown on residual soil moistures with traditional cultivars devoid of using crop nutrition, bio-fertilizers, pesticides and agrochemicals owing to non-availability. However, yields are the driving force for land growth that is subjected with improved practices. Therefore, attention needs to be sited on well-timed accessibility of this required crucial input in these areas.
- *Rural credits facility and marketing infrastructure*: Underprivileged socio-fiscal condition and purchasing power of farmer also force them to leave second cropping subsequent to paddy towards denial inputs used. Thus, subsidy on farm input, credit and crop insurance schemes must be implemented. The market plays a key responsibility in motivating farmers to produce crops.
- *Safeguard from stray cattle*: *Nilgai*/stray cattle cause serious damages to fallow crops; therefore, farmers discourage growing *Rabi* crop in these areas. However, suitable policy is compulsory to deal with these menaces.

8.4 Soil Properties

Typically low moisture content in soil profile after rice harvest followed by fast decline in water table with advancement of winter season further leads to seasonal (mid-season and/or terminal) drought at critical stages of crop (i.e. flowering and pod filling stages) that adversely affects productivity even popular chickpea crop. Extreme moisture stress (especially terminal drought) coincides with flower/pod initiation, and their development increases leaf senescence and decreases net photosynthesis and translocation from leaf to developing grains. In addition, this hostile environment creates unfavourable condition for microbial activity, nutrient availability, root growth and water and nutrients uptake (Bandyopadhyay et al. 2016). As a consequence, soil resources in rice fallows remain mostly underutilized and prone to diverse and differential losses with time and space (Singh et al. 2016). Research evidence suggests that residue retention on soil surface or mulch had a favourable effect on soil health involving diverse physical, chemical and biological properties of soil for which it invites the use of appropriate resource conservation technologies (RCTs) to amalgamate for sustainable farming. Resource conservation through appropriate choice of rice and pulse varieties could further boost the overall resource use efficiency (RUE) of rice fallows (Singh et al. 2016). Similarly, on integration with suitable agronomic practices, these areas could be made green (cultivable) following adequate and timely utilization of residual soil moisture (Patil et al. 2013). Besides alleviating the soil moisture depletion, these measures (residue retention and varietal intervention) could build-up organic matter content in soil, enabling further improvement in soil's physical and microbial health (Praharaj et al. 2017). Besides the constraints observed inherent to rice fallows including growing of profitable pulse cultivation in rotation with rice, suitable strategies for alteration in sowing windows with short-duration varieties could boost the conservation of natural resources and result in higher productivity realization (Singh et al. 2016).

8.5 Soil Moisture Content and Water Use Efficiency

For winter crops, the treatment ZTM had higher soil moisture in both surface (0–15 cm) and subsurface soil layer (15–30 cm). In general, higher soil moisture depletion was observed in *utera* system compared to ZT and ZTM (Fig. 8.4). As no supplemental irrigation was applied to winter crops, the estimated WUE of winter crops was primarily influenced by the productivity of winter crops. In parallel to

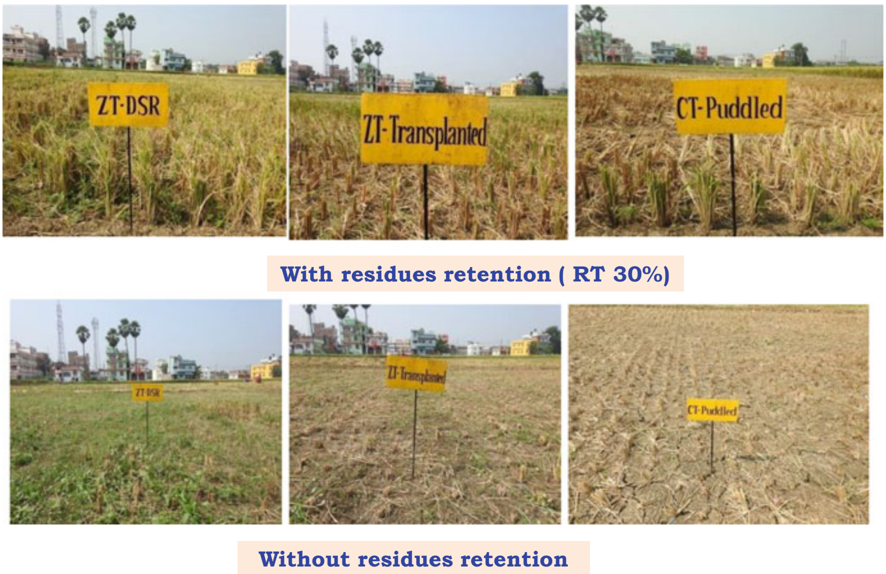

Fig. 8.4 Cereal crop fields with conservation and conventional agricultural practices

grain yield, maximum WUE was recorded in lathyrus and lentil in *utera* cropping, while the WUE of the other crops were low. The *utera* production system had significantly higher WUE (84.8 kg ha-cm^{-1}), which had 121% and 80% higher over ZT and ZTM, respectively. Among the winter crops, lathyrus was found with the highest WUE (120 kg ha-cm^{-1}), whereas it was the lowest in mustard (24 kg ha-cm^{-1}) (Fig. 8.5). Mean data demonstrated that mulching under ZT system significantly improved the productivity of lentil, mustard and linseed, which was primarily because of the higher soil moisture content in ZTM over ZT. Increased availability of soil moisture in ZTM, which may lead to the efficient utilization of moisture throughout the crop-growing period, reflected higher crop yields and utilization of soil moisture (Kumar et al. 2016a, b). Further, the loss of soil moisture through evaporation in *utera* and ZTM may be an additional factor, which affects the pattern of soil moisture use. Another important reason for higher crop productivity in ZTM over ZT may be reduced weed population and weed biomass due to mulching.

8.6 Soil Moisture Variability in Winter Crops in Rice Fallows

After the harvest of paddy, the soil moisture content was very high in all the experimental plots of Jharkhand and Chhattisgarh. In 0–15-cm depth, the soil moisture varied from 31.7% to 45.6%, while at 15–30-cm depth, it ranged between 31.0% and 42.1% among various CA practices and crops. In linseed plots, the soil water gradually decreased, and it neared the critical level in the first week of February 2018. Irrigation was applied when soil water content was 16.8%, 15.2% and 17.8% in ZTT, DSR and farmers' practice, respectively (Fig. 8.6) (Unpublished results, ICAR-RCER Patna, Bihar, India).

In the case of mustard, one life-saving irrigation was applied in first week of February when soil water content reached 17.8%, 18.2% and 17.1% in ZTT, DSR and farmers' practice plots, respectively. The application of one critical irrigation maintained optimal moisture conditions in crop root zone leading satisfactory growth and yield from these crops.

8.7 Crop Productivity

In order to efficiently utilize soil moisture and maximize the system productivity of rice fallows, long-duration rice varieties need to be replaced with short- to medium-duration varieties for early harvesting and timely sowing of succeeding crops. Even for *para*/*utera*/relay cropping, where seeds are broadcasted in standing rice crop about 10–12 days before harvest, rice fields need to be properly levelled for maintaining uniform soil moisture to facilitate uniform seed germination. Mechanical transplanting or line transplanting of rice gives higher yield of fallow *paira* crops. Growing early- to medium-duration rice varieties enables farmers to advance the sowing of succeeding crops for efficient utilization of stored soil moisture. Residual moisture left in soil at rice harvest is often sufficient to support short-duration crops.

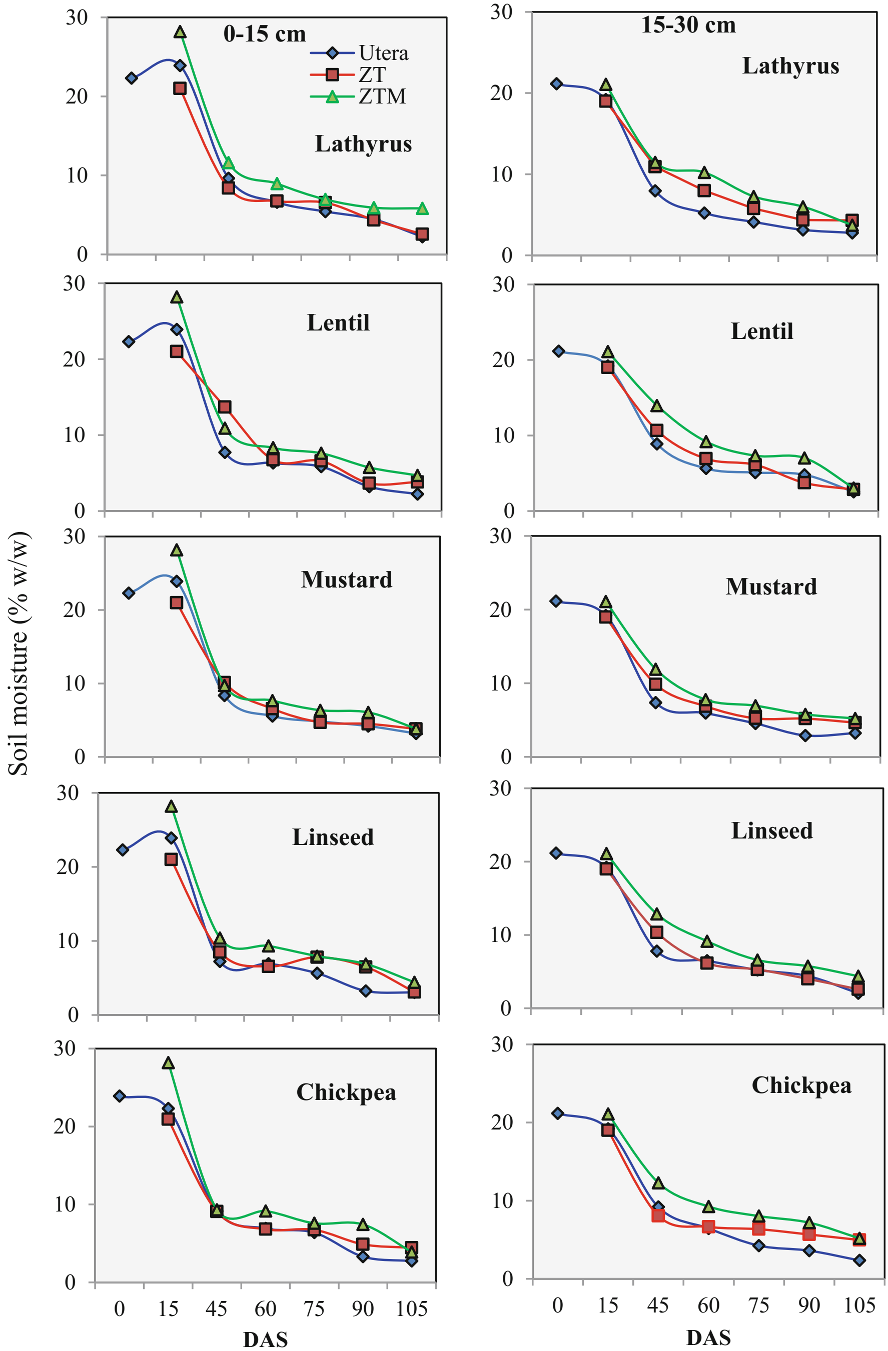

Fig. 8.5 Periodical soil moisture content (w/w) in surface (0–15 cm) and subsurface soil (15–30 cm) in post rainy season crops under different crop establishment practices, ZT: zero tillage; ZTM: zero tillage with mulch

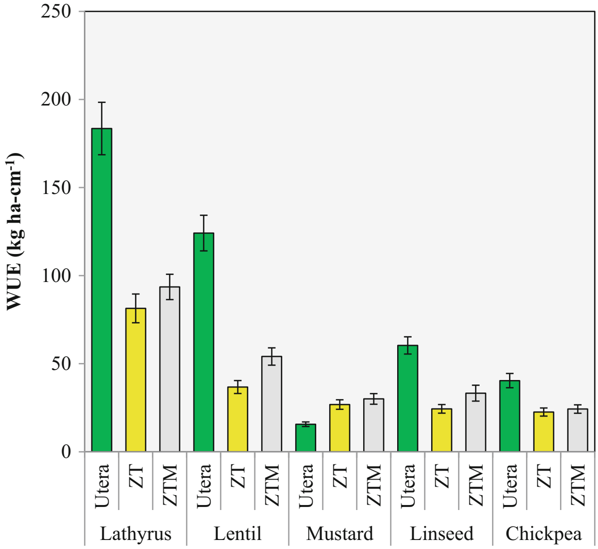

Fig. 8.6 Water use efficiency (kg ha-cm^{-1}) of winter crops under different crop establishment practices in rice fallow (mean of 2 years)

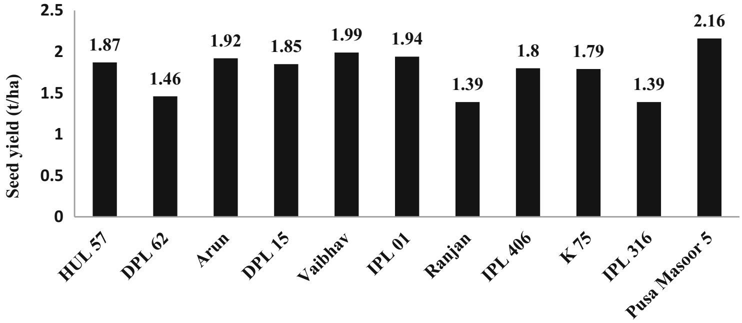

Fig. 8.7 Productivity of lentil cultivars under ZT in rice fallows

In the eastern region, short-season pulses like lentil, grass pea (lathyrus), chickpea, field peas, urdbean and oilseeds (i.e. mustard, groundnut, linseed and safflower) could be cultivated profitably in rice fallows under ZT/*utera*. In low land areas with excessive soil moisture, lentil and lathyrus can be grown successfully as *utera* cropping. Small-seeded varieties of pulses have been found better than the large-seeded. In Jharkhand and Chhattisgarh, the cultivation of bottle gourd was also found promising with limited irrigation facility. **Lentil** cv 'Pusa Masoor 5', 'Vaibhav', 'HUL 57' and 'Arun'; **chickpea** 'C 235', 'Pusa 256', 'JG 14' and 'Vardan'; **linseed** 'Uma' (1.21 t/ha), 'RLC 143', 'BAU 06–03 and 'RLC 138′; **grass pea** 'Ratan' and 'Prateek' have been found to be promising in rice fallows (Fig. 8.7) (Unpublished results, CRP on CA, ICAR-RCER Patna, Bihar, India).

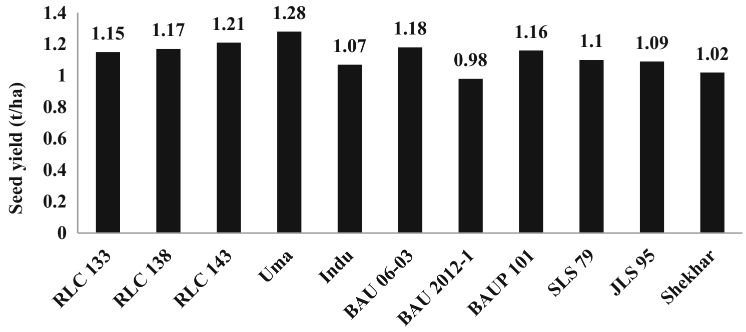

Fig. 8.8 Productivity of linseed cultivars under ZT in rice fallows

Seed priming, i.e. overnight soaking of seeds with simple water or nutrient solution before sowing, is an important low-cost technology to improve the germination and seedling emergence. It is always recommended to increase the seed rate by 20–25% in rice fallows to have a desired plant population. For obtaining optimum productivity in rice fallows, it is necessary to have proper soil moisture at sowing and water facility for at least one life-saving/supplemental irrigation at the most critical stage. Since plenty of water in these areas is lost during rainy season through runoff, there is a need to harvest and store this excess rainwater in small farm ponds/ reservoirs to provide life-saving irrigation to succeeding fallow crop (Fig. 8.8).

Resource conservation technologies (RCTs), i.e. ZT/RT and retention of rice crop residue/mulching at 5 t/ha or 30–40-cm stubble height, have been found effective in soil moisture conservation and increasing crop yields and monitory returns in rice fallows. RT has increased yield of pulses (lathyrus, green gram, black gram) by 33–44% over the conventional system (Kar and Kumar 2009). Retention of rice stubble/mulching and ZT sowing of pulses had significantly enhanced the productivity of pulses in rice fallows (Ghosh et al. 2016). Retaining 30% residue on soil surface in RT and ZT sowing with Happy Seeder increased the yields of succeeding lentil, chickpea, safflower, linseed and mustard by 3.1, 11.7, 19.1, 14.4 and 12.3%, respectively [*Unpublished results*, CRP on CA Project at ICAR-RCER), Patna]. Similarly, *utera* system of cropping performed better than ZT (with or without mulch) and produced maximum seed yield due to the advantage of early sowing and better utilization of residual soil moistures. Among different crops, lathyrus followed by linseed and lentil recorded maximum yields and profits (Mishra et al. 2016). ZT after rice harvest also facilities timely planting of winter season pulses in rice fallows and helps to escape the negative effects of terminal water stress and rising temperature in spring-summer. The results of the farmers' participatory trials on ZT lentil and chickpea in Eastern-IGP during 2009–2010 showed that using ZT with reduced seed rate (30 kg/ha for lentils and 80–100 kg for chickpea) and deeper seed placement (5–6 cm for lentils) improved crop stand establishment and crop productivity and reduced the wilt incidences (Singh et al. 2012). A survey on the farmers' participatory adoption of ZT-seeded lentils in rice fallows (200 ha) of

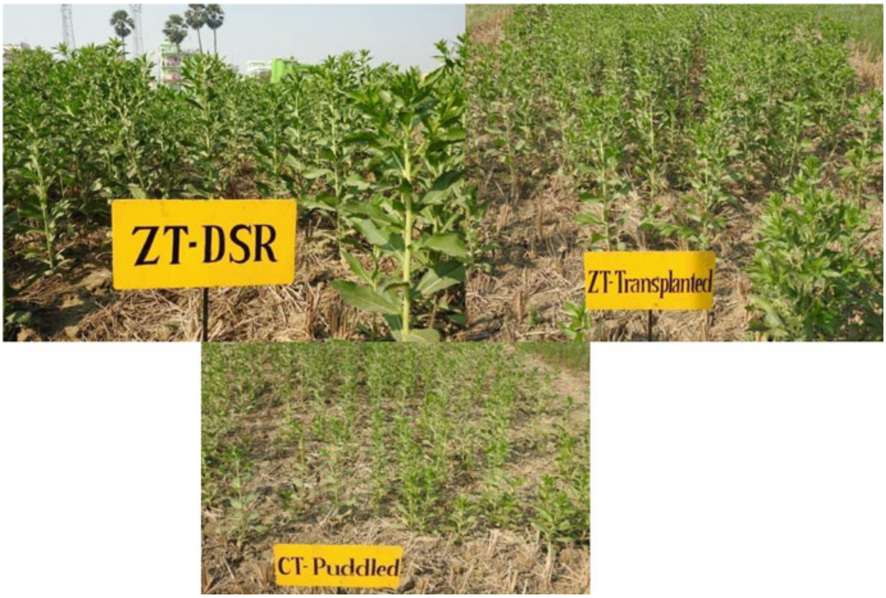

Fig. 8.9 Pronounced differences in crop vegetative growth as influenced by establishment methods

Nawada, Bihar, showed that ZT planting of lentils together with suitably improved agronomic packages resulted in higher yield (13%) and a reduced cultivation cost by ~Rs.3800/ha and thereby increasing farm profitability of ~Rs10,000/ha (Singh et al. 2012). Pulse seed should be treated with fungicides followed by *Rhizobium*, PSB and VAM fungi and *Trichoderma* inoculation before sowing for disease-free plant and better nodulation. Foliar spraying of KNO_3 and Ca $(NO_3)_2$ at 0.5% significantly improved the yield of grass pea in rice fallows (Sarkar and Malik 2001) (Fig. 8.9).

Foliar spraying of nutrient solution like urea and DAP at 2% at vegetative stage or before flowering stages enhanced the productivity of pulses (Layek et al. 2014). Diseases, i.e. root rot, powdery mildew and yellow mosaic, and insects like pod borer cause heavy damage to rice-fallow pulse crops. For the management of insect, pest and diseases, an integrated pest management strategy involving seed treatment with fungicides and bio-control agent *Trichoderma*, selection of disease tolerant varieties and spraying of need-based fungicides/insecticides will be useful. Similarly integrated weed management strategies including crop residue mulching, ZT sowing and application of post-emergence herbicides like quizalofop for grassy weed control and need-based manual weeding should be adopted. ZT-DSR followed by ZT chickpea/lentil/safflower with 30% residue retention is a better option for realizing the higher productivity in rice fallows of IGPs.

A field experiment was conducted during 2017–2018 in a farmer's field at two locations, viz. Chene, Ranchi and Jharkhand and Condora, Jaspur and

Chhattisgargh. CA practices comprised of ZT transplanted rice with mulch (ZTT-M), ZT-transplanted rice without mulch (ZTT-NM), directly seeded rice with mulch (DSR-M), directly seeded rice without mulch (DSR-NM) and farmer's practice without mulch (FP-NM) were evaluated on winter crops like lentil (variety: KLS-218), mustard (variety: Pusa-26), linseed (variety: BAU 06–03) and safflower (variety: PBNS-12) after harvesting the rice. The rice straw mulch was applied at 5 t/ ha at the time of sowing of the winter crops in CA practices (Unpublished results, CRP on CA, ICAR-RCER Patna, Bihar, India). The different winter crops like lentil, mustard, linseed and safflower were grown in rice fallows under different CA practices. Lentil and safflower did not come to germination due to higher soil moisture after rice harvesting. In mustard, higher grain yield of 3.07 q/ha has been recorded in DSR-NM followed by 3.05 q/ha in DSR-M. CA practices of DSR-M, DSR-NM and ZTT-M recorded significantly higher grain yield over the farmer's practice (FP). The CA practice of DSR-M and DSR-NM had the highest root length of 11.23 and 10.36 cm, respectively; however, there is no significant difference in root length among the CA practices and farmer's practice. The grain yield of linseed was highest at 2.23 q/ha and was found to be significantly better than the other CA practices and farmer's practice (Unpublished result, CRP on CA, ICAR-RCER Patna, Bihar, India). Mulched treatment of CA practice, i.e. ZTT-M and DSR-M, recorded 5% and 16.7% increases in grain yield over their corresponding non-mulched CA practice, i.e. ZTT-NM and DSR-NM, respectively. At Kandora village, Jashpur (Chhattisgarh), lentil, mustard, linseed and safflower were grown in rice fallows under different CA practices. The highest grain yield was 2.68 q/ha in ZTT-M and was significantly at par with FP-NM (2.16 q/ha). Higher grain yield was observed in mulched treatment compared to non-mulch both in ZTT and DSR. The grain yield of mustard was significantly influenced by different CA practices. Highest grain yield was 4.39 q/ha in ZTT-M followed by 3.39 q/ha in FP-NM with a non-significant difference between the two practices. The highest root length was 8.37 cm in FP-NM and was at par with ZTT-M, DSR-M and DSR-NM. Root volume was found to be non-significant among the different CA practices; however, the highest root volume of 12.67 cm^3 was recorded in FP-NM. The highest linseed grain yield was 2.74 q/ha in DSR-M and was significantly better than DSR-NM and FP-NM. The highest grain yield in DSR-M resulted in 26.4% increase over FP-NM (Unpublished results CRP on CA, ICAR RCER Patna, Bihar, India).

8.8 Conclusions

Rice fallows offer a great opportunity to maximize the area of pulses and oilseeds with adoption of improved agrotechniques. Soil moisture conservation and mitigation of abiotic stresses are the two major strategies required for a successful use of rice fallows production system. For better usage and understanding, intensive research is needed to understand the rice-fallow ecology for strategic crop management. Location-specific CA technologies, early duration and drought-tolerant varieties of pulses/oilseeds are essential for this region. If these location-specific constraints are managed, these unutilized lands may be transformed into growing of suitable pulse/oilseed crops by appropriate crop planning; the poverty and malnutrition in the region may be eradicated to a greater extent.

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Exploring Conservation Agricultural Practices in Bundelkhand Region, Central India

9

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Abstract

Bundelkhand region is largely characterized by shallow red soils, undulating topography, extreme weather conditions, and recurrent droughts, making the agriculture in the region more difficult leading to low crop productivity, crop intensity, and higher soil loss through erosion and runoff. Low moisture holding capacity of soils in the region makes it difficult to cultivate crops on residual moisture during post rainy season. This region consists of six districts of Madhya Pradesh (Datia, Tikamgarh, Chatarpur, Damoh, Sagar, and Panna) and seven districts of Uttar Pradesh (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda, and Chitrakoot) of Central India which are jointly known as Bundelkhand region. Thus, conservation agriculture (CA) practices aims at minimal soil disturbance, permanent soil cover, and crop diversification and helps in decreasing or reverting the negative effects of conventional farming. CA practices reduce the production cost, greenhouse gas emission, soil erosion, and runoff losses and improve the soil health and crop productivity. Currently, CA has covered about <5 M ha area in India, and its adoption is increasing but is either slow or nonexistent in

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Bundelkhand region. In this chapter, an attempt has been made to explore the CA practices for Bundelkhand region of Central India. More attention is given to the three basic principles of CA with in situ moisture conservation practices, keeping in mind the general climatic and soil properties of Bundelkhand region.

Keywords

Bendelkhand · Conservation agriculture

9.1 Introduction

Bundelkhand region is situated in the core of north Central India that spreads across 13 districts: 6 in Madhya Pradesh (Datia, Tikamgarh, Chattarpur, Damoh, Sagar, and Panna) and 7 in Uttar Pradesh (Jhansi, Jalaun, Lalitpur, Hamirpur, Mahoba, Banda, and Chitrakoot) (Fig. 9.1). The region is positioned underneath the Indo-Gangetic Plains (IGP) toward the north with the undulant range of Vindhya mountain along the northwest to the south (23°20′ and 26°20′ N latitude and 78°20′ and 81°40′ E longitude), covering an area of 7.08 M ha (Gupta et al. 2014).

The Bundelkhand name is derived from its lengthiest governing empires, the Bundela Rajputs, who dominated for the longest duration. Life in the region is influenced by several factors such as vagaries of climate, geographical features, topography, and environment issues. The region is having undulating topography in many parts; however, flat lands are present in the central part of the region. This requires technologies for sustainable agriculture and water conservation. The location is wealthy in herbal sources, plant life, and minerals. The availability of ground water, however, isn't always very good. The excellent property of Bundelkhand had been its huge range of surface water tanks constructed loads of years ago by the Chandela and Bundela kings, and these have been the sustenance of agriculture and lifestyles assets. But, in contemporary years, these had been violated, damaged, or spoiled, with none satisfactory replacement. The vicinity becomes recognized for decades, both in the earlier and adjacent present to gift as an agriculturally wealthy region (HDR 2012). With its percentage of intermittent droughts, this effective aspect of the place is more and more under pressure, because of ecological and human aspects and insufficient organized tasks to govern and cope-up the drop in agricultural richness. The continuous harm to the surroundings, i.e., deforestation, decreasing forest cover, unjustifiable withdrawal of river beds, human violation on catchment areas of watershed, and water basins, might also have caused an adverse effect on natural resources. Besides fluctuating monsoon, a decline within the count of rainfall days, repeated droughts, a decrease in the amount of available irrigation and drinking water are the frequent problems in the region. This severely affected agriculture, troubling the already suffering small and marginal farmers (HDR 2012).

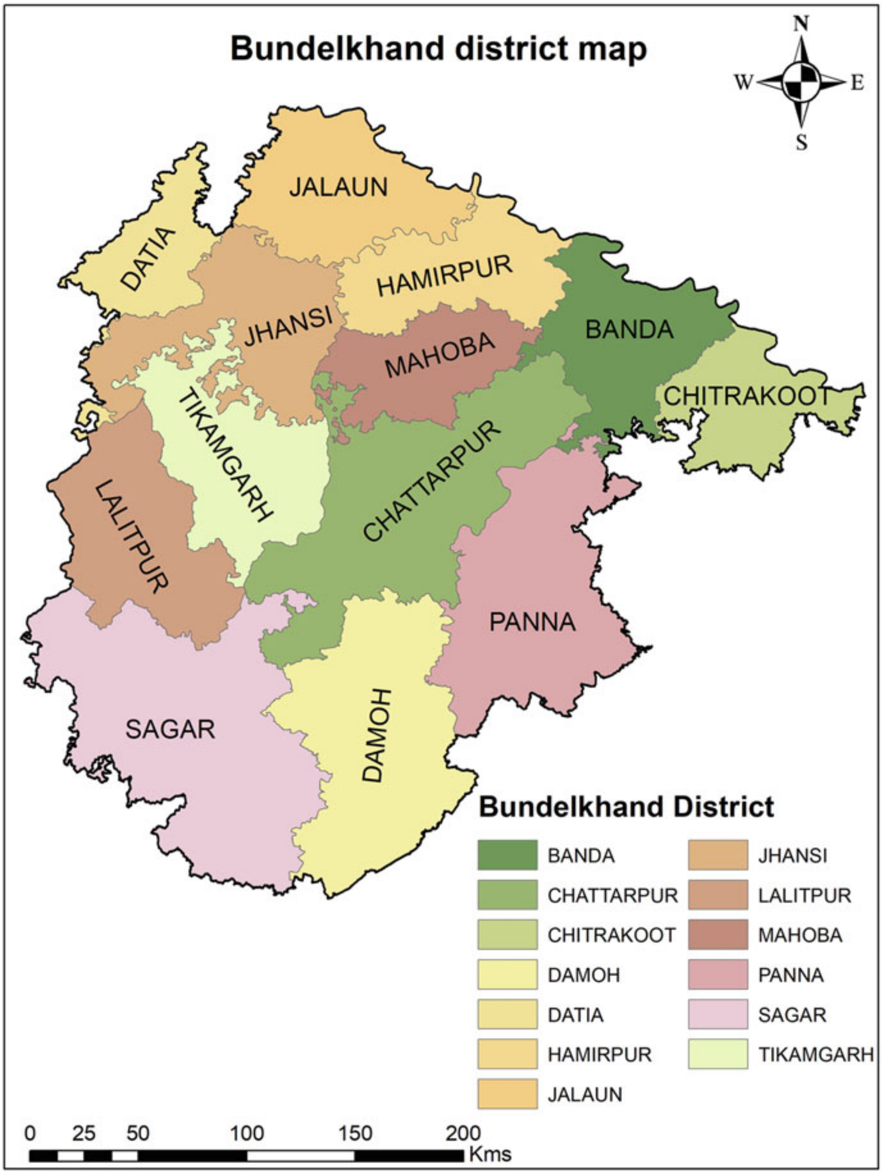

Fig. 9.1 Bundelkhand region consisting of 13 districts of Central India

9.1.1 Soils

In general, soils of Bundelkhand are a mixture of black and red soils. The red soils of the region are newly formed, with gravels and quite shallow in depth (Lakaria et al.

Table 9.1 Classification of soils of Bundelkhand and their physical-chemical properties

Soil type	*Rakar*	*Parua*	*Kabar*	*Mar*
Classification	Lithic ustorthents	Typic ustochrepts, typic haplustalfs	Vertic ustochrepts, typic ustochrepts	Typic haplustelfs, typic chromusterts
Characteristics	Red, coarse-textured gravelly upland soils with high infiltration rate and poor water holding capacity	Mixed red and brown, fine-textured loamy upland soils with medium infiltration rate and low water holding capacity	Black-brown, fine-textured loamy medium- to lowland soils with moderate infiltration and water holding capacity	Black, clayey lowland soils with poor drainage, swell-shrink characteristics, cracks during summer
Sand (%)	66–72	66–68	44–46	26–30
Silt (%)	18–22	19–22	28–31	22–32
Clay (%)	10–12	11–13	24–26	38–52
pH	7.6–8.0	7.5–7.9	7.4–7.5	7.4–7.5
EC (dS m^{-1})	0.10–0.17	0.09–0.18	0.15–0.28	0.16–0.22
Organic carbon (%)	0.26–0.28	0.32–0.36	0.36–0.38	0.43–0.55
Available N (kg ha^{-1})	160–230	235–260	201–270	260–330
Available P (kg ha^{-1})	7–10	10–15	13–18	15–19
Available K (kg ha^{-1})	200–300	290–340	450–500	630–757
Fe (mg kg^{-1} soil)	3.0–3.9	3.8–4.2	4.8–5.2	4.7–5.4
Mn (mg kg^{-1} soil)	1.5–1.8	1.6–2.1	2.5–3.1	2.3–2.8
Cu (mg kg^{-1} soil)	0.1–0.2	0.1–0.4	0.2–0.7	0.5–0.8
Zn (mg kg^{-1} soil)	0.2–0.4	0.6–0.8	0.5–0.8	0.7–0.9
Field capacity (%)	13–15	15–17	15–18	18–22
Permanent wilting point (%)	4–6	5–7	5–7	6–8

Source: ICAR-Indian Institute of Soil and Water Conservation Research Center, Datia (MP)

2011). These soils are not supposed to retain the moisture well and unable to support *rabi* crops on the basis of residual moisture. Soils of Bundelkhand region are classified in four classes [*rakar* (17.6%), *parua* (38.5%), *kabar* (31.4%), and *mar* (12.4%)] based on their characteristics (Table 9.1). The *rakar* soils are excessively permeable with shallow depth and coarse-grained. The *parua* soils are alluvial soils, a mixture of red and brown soils with medium infiltration rate. *Mar* and *kabar* are black soils, extending up to a depth of 1 m. These are fine-textured soils having the swelling and shrinking properties and develop cracks during summer (Somasundaram et al. 2018). Red soils are generally shallow with low moisture retention capacity and are predominantly found in the north-western region, while black soils are mostly found in the southern region. Black soils are the farmer's choices for rice, wheat, chickpea, and sugarcane cultivation because of the better water retention capacity of these soils. Persistent top soil erosion and deforestation are the major threats to the region leading to low productivity of crops. Hilly terrain and poor quality of soils aggravate the problem of soil erosion, leading to the formation of widespread gullies.

9.1.2 Climate

The climate of Bundelkhand region is defined as hot and semi-arid. The region has extremes of temperature, which crosses 40 °C during summer and falling down as low as 1 °C during winter; however, the average annual temperature is 25 °C. May and June are the months with extreme temperature, which drops to the lowest during December and January. The distribution pattern of rainfall is highly uneven, and more than 85% rain received during June to September months (Fig. 9.2) with average annual rainfall of around 850 mm. Most of the rainfall received in this region is lost through runoff (HDR 2012). Some amount of rainfall is also received during winter months, which facilitates some moisture to the *rabi* crops; however, the rainfall received during winter months is not sufficient to meet the water requirements of the crops grown in this region; hence, this necessitates the need for supplemental irrigations. The droughts and drought-like situations are very frequent during the summers, and sometimes rains create floods during monsoon. The northern part of the region receives less amount of rainfall compared to the southeastern part of the region (HDR 2012).

9.1.3 Water Resources

The Bundelkhand collects water from a number of continuing streams. The Yamuna and Ken rivers in north and east and Betwa and Pahuj in the west are the main four rivers of the region. The Betwa river contributes around 50% of the water available in the Bundelkhand upland and Bundelkhand plin sub-regions; the Ken contributes another 25% (Gupta et al. 2014). The Betwa, Ken, and Pahuj are important for irrigation in the region. However, the irrigation security is undermined due to their seasonal fluctuations. Erstwhile, a number of large, medium, and small tanks were built by the Bundela kings in the region and maintained them for rainwater harvesting. These water harvesting structures got filled with water during the monsoon season, ensuring adequate supplies of water for both domestic and agricultural uses throughout the year. These water harvesting tanks and forests of the region also helped in recharging and maintaining groundwater level. Failure of locals to

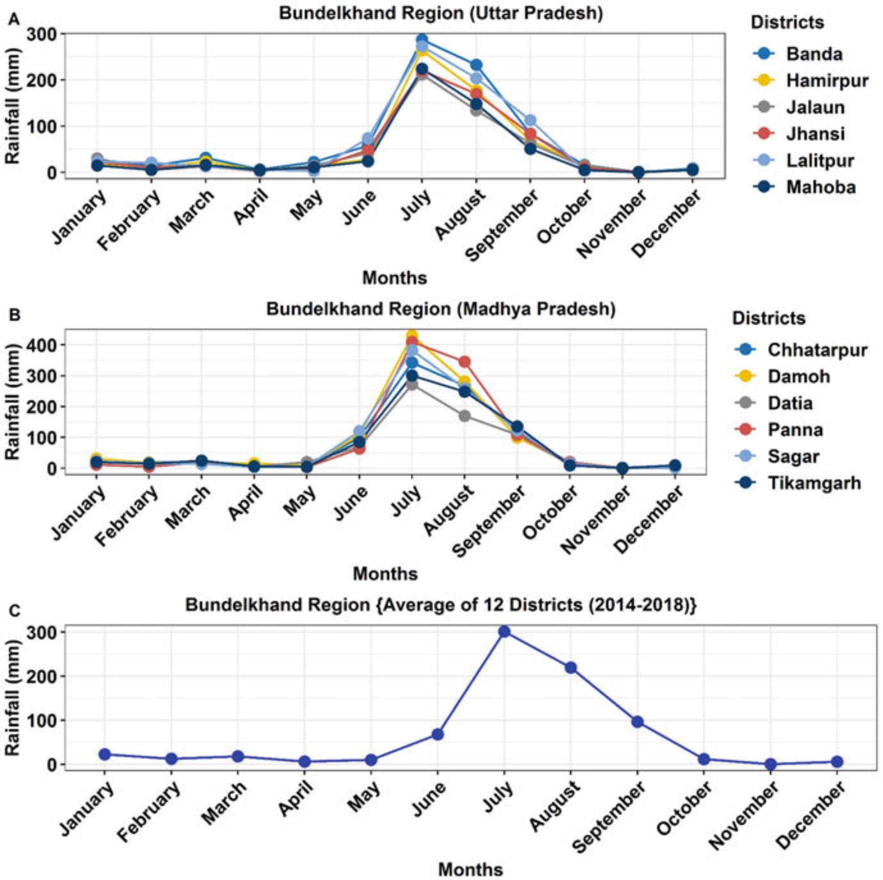

Fig. 9.2 Month-wise rainfall in different districts of Bundelkhand region (mean of 5 years, 2014–2018). (Source: http://hydro.imd.gov.in/hydrometweb/(S(x5k4n3q4rza3vmru0spa4z45))/DistrictRaifall.aspx)

manage these structures clubbed with deforestation has distorted the situations of the region during the last five to six decades (Prakash et al. 1998). This has converted the region into more drought-prone. As the region has less capability to conserve water, a very small deviation in monsoon leads to drought situation in the area. The availability of water for irrigation has severely reduced due to the tumbling water levels and drying of surface water sources. Faulty water management practices linked with climate change exaggerate the problem of water scarcity, and this has led to insufficient and inefficient irrigation, thus directly affecting agricultural productivity. During the last 2.5 decades, water was pumped out from the ground using tube wells, leading to drying up of natural water sources. As a result of overexploitation, the groundwater table now has gone down up to 600 to 750 ft (SCSI 2012). Shallow soil depths, light-textured soils, and hard rocky substrata make it difficult to store water in aquifers and to conserve soil moisture. Hydrological and meteorological droughts are very frequent in the region, resulting in groundwater-level depletion at an alarming rate, and 70% of the water bodies has become dry (IMST 2008). About 45.6% and 44.7% of net sown area (NSA) in UP and MP, respectively, are watered by dug wells, canals, lift irrigation, shallow tube wells, and other flows. Of this, 26.7% and 31.7% of NSA in UP and MP, respectively, are irrigated by groundwater only. On the other hand, surface water contributes 18.9% in UP and 12.9% in MP (IMST 2008).

9.1.4 Land Use Pattern and Agricultural Land Use

According to the data available, out of the total geographical area of Bundelkhand (7078.8 thousand ha), about 61% area is cultivable, and the rest is classified as several other land uses including 20% forest cover (DACFW 2019). District-wise data presented in Table 9.2 indicates that the region has 3835.6 thousand ha of net sown area and 4822.20 thousand ha of gross cropped area. Cropping intensity of the region is 126%, which is quite less than the national average (DACFW 2019). The region has 2074.43 thousand ha of net irrigated area (only 48% of total cultivable area and 54% of net sown area) and 2305 thousand ha of rainfed area (DACFW 2019) that totally depended on rainfall as a source of moisture to the crops.

The agricultural productivity (per person and per ha) of the region is extremely low, and it is a well-established fact that agricultural poverty cannot be removed without substantially increasing per capita and ha profitability and productivity. The size of average landholding is 1.54 ha, and 77% of landowners own only 39% of land (HDR 2012). Coupled with the common feature of water scarcity in the region that has been a feature of Bundelkhand for long, it is no wonder that agricultural productivity is low. In the cultivated area, the major crops cultivated are cereals, pulses, and oilseeds. Farmers of the region largely cultivate food grains, while fruits and vegetables are grown for family consumption with rare level of horticulture commercialization. Among cereals, wheat is the major crop being cultivated on 14.62 lakh ha followed by rice, which is being cultivated on 2.33 lakh ha (APS 2019). Black gram and chickpea are the two most important pulse crops (cultivated in 6.82 and 6.37 lakh ha area, respectively) preferred by the farmers of the region (Fig. 9.3). Oilseeds like soybean and sesame are also some of the preferences by the farmers and ranked in the top five crops (area wise) of the region (APS 2019). Lentil, red gram, mustard, groundnut, sorghum, green gram, barley, and sugarcane are the other important crops being cultivated in the region. Crops like millets are cultivated in the region, but on a very small scale. As the most farmers in the region are small-scale farmers and the cultivation of crops is only inept to sustain their family needs, rearing of buffaloes/cows/goats/sheep in small numbers is a common practice. This provides cash to supplement farm income and much needed nutrition for their own consumption. Commercialized cultivation of fruits and vegetables is rare in the region; instead they are grown in farm peripheries for family consumption.

Table 9.2 Agriculture land use of Bundelkhand region

District	Net sown area (‘000 ha)	Area sown more than once (‘000 ha)	Gross cropped area (‘000 ha)	Cropping intensity (%)	Net irrigated area (‘000 ha)	Gross irrigated area (‘000 ha)	Rainfed area (‘000 ha)	Data source
Datia	195.959	34.533	230.492	117.6	172.43	175.73	58.06	http://agricoop.nic.in/sites/default/files/MP4-Datia-26.6.2012.pdf
Sagar	537.4	198.9	736.3	137	241	241.1	296.4	http://agricoop.nic.in/sites/default/files/MP29_Sagar_20.05.2013.pdf
Panna	234.1	34.8	268.9	115	78.5	78.6	155.6	http://agricoop.nic.in/sites/default/files/MP33_Panna_30.05.2013_0.pdf
Tikamgarh	208.8	92.2	301	144	110.3	145.2	98.5	http://agricoop.nic.in/sites/default/files/MP36_Tikamgarh_30.05.2013.pdf
Chhatarpur	319.9	84.8	404.7	127	157	157	162.9	http://agricoop.nic.in/sites/default/files/MP37_Chhatarpur_30.05.2013.pdf
Damoh	311.4	94.2	405.6	130	115.8	118.6	195.6	http://agricoop.nic.in/sites/default/files/MP44_Damoh_24.09.13.pdf
Banda	343.5	84.9	428.5	124.7	157.7	205.9	185.7	http://agricoop.nic.in/sites/default/files/UP37-Banda%20draft%20plan-10.07.14.pdf
Chitrakoot	174.5	–[a]	–[a]	–[a]	42.2	–[a]	129.3	http://agricoop.nic.in/sites/default/files/UP38-Chitrakoot%20draft%20plan-10.07.14.pdf
Hamirpur	294.2	50.9	345.1	117.33	134.7	135.3	159.5	http://agricoop.nic.in/sites/default/files/UP39-Hamirpur%20draft%20plan-10.07.14.pdf

Jalaun	346.7	62.8	409.5	118	225.7	242.4	121.1	http://agricoop.nic.in/sites/default/files/UP40-Jalaun%20draft%20plan-10.07.14.pdf
Jhansi	332.3	–[a]	432.4	130.14	237.2	–[a]	95.1	http://agricoop.nic.in/sites/default/files/UP41-Jhansi%20draft%20plan-10.07.14.pdf
Lalitpur	301.1	–[a]	–[a]	130.1	301.1	211.1	512.3	http://agricoop.nic.in/sites/default/files/UP42-Lalitpur%20Draft%20plan-10.07.14.pdf
Mahoba	235.7	84	319.7	121	100.8	101.6	134.9	http://agricoop.nic.in/sites/default/files/UP50-Mahoba-26.07.14.pdf
Bundelkhand (total)	3835.6	822.03	4282.20[b]	125.99[b]	2074.43	1812.53	2304.96	

[a]Data not available
[b]Data excluding the districts whose data was not available

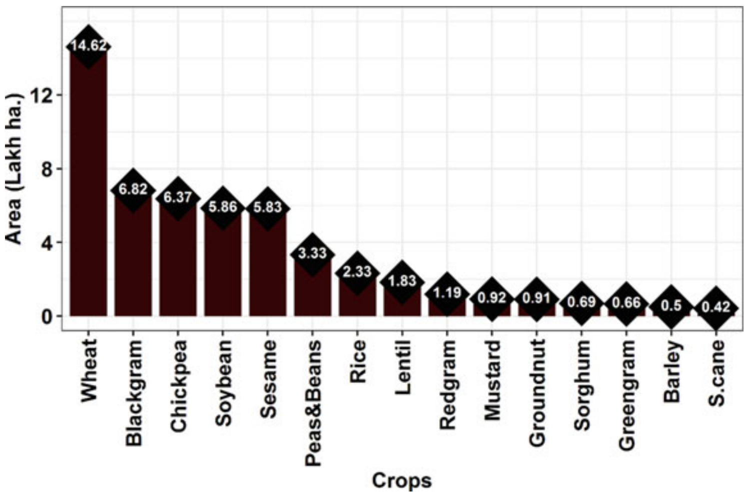

Fig. 9.3 Important crops of Bundelkhand region and their acreage

9.2 Conservation Agriculture in the Region

Conservation agriculture (CA) is a process of environmental protection, climate change adaptation, and mitigation through sustainable land and agriculture management. CA is described as resource-saving farming production system to intensify production and achieve high productivity while sustaining the natural resources with the incorporation of the three important principles, besides other good production principles and practices of pest management and plant nutrition (Abrol and Sangar 2006). FAO describes conservation agriculture as resource-saving agricultural production concept based on enhancing the above and below the ground biological and natural processes (FAO 2007).

CA system is 20–50% less labor-intensive, requires lower energy inputs, and contributes to reduced greenhouse gases emission and higher nutrient use efficiencies. CA shields and stabilizes soil to break down and release carbon to the atmosphere. At the same time, CA offers a long-lasting agricultural production system; protects and enriches the natural resources; enhances agricultural biodiversity on a micro- and macro-agricultural production system; and increases the activity of various types of soil biota, fauna, and flora without sacrificing yields with high production levels.

9.2.1 Key Principles of Conservation Agriculture

9.2.1.1 Permanent Soil Cover

Covering the soil surface with a permanent protective layer of crop residues (more than 30%) or vegetation helps in reducing soil erosion, suppresses the growth of weeds, helps in soil moisture conservation, and improves the physical properties of the soil (FAO 2019). Permanent protective vegetative cover over the soil surface can be maintained with the help of crop biomass retention, cover crops, root stocks and stubbles, and other sources of ex situ biomass.

9.2.1.2 Minimum Soil Disturbance

This indicates minimum soil disturbance through mechanical means, no tillage, reduced tillage, or minimum tillage (Somasundaram et al. 2017). Tillage can be reduced to a minimum level by omitting the operations that are not economical or by combining the two operations together (ferti-seed drill) or by direct seed placement. The practice of minimum soil disturbance reduces soil erosion and acts as a sink for organic carbon and contributes in controlling air pollution. In agriculture, tillage is one of the most energy-, time-, and money-consuming practices. By omitting or reducing tillage operations, farmers can save 20–50% of energy, time, labor, and fossil fuels.

9.2.1.3 Crop Rotation

Diversifying crops consist of at least three different crops suited to local conditions through varied crop with well-arranged crop rotations which promote the soil and crop biodiversity, improve soil structure, endorse soil flora and fauna, regulate the nutrient cycle, enrich plant nutrition, and prevent pests and diseases (Fig. 9.4) (FAO 2019).

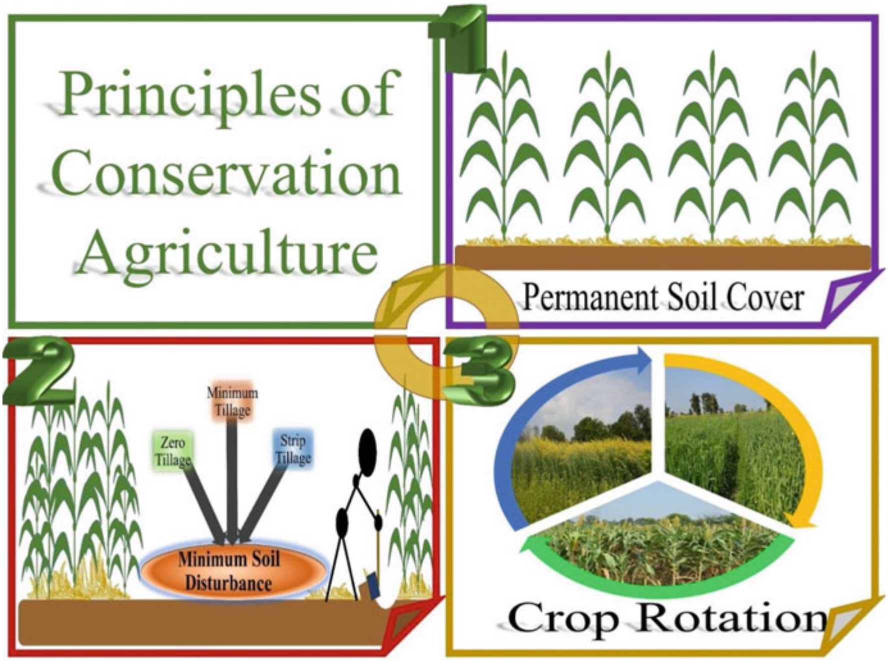

Fig. 9.4 Three basic principles of conservation agriculture

9.2.2 Conservation Agriculture in India and Bundelkhand (History and Current Status)

Edward Faulkner in the book *Ploughman's Folly* (Faulkner 1945) and Masanobu Fukuoka with his book *The One-Straw Revolution* (Fukuoka 1975) for the first time elaborated the concepts of CA principles. But it was only in 1960 when no tillage came into the farming practice in the USA due to the hike in fuel prices (Derpsch 2004; Kassam et al. 2010, 2014a). Later in 1990, CA was introduced in India along with Bangladesh and Pakistan (Friedrich et al. 2012). India organized its first CA global conference in 2009 in New Delhi as the fourth World Congress on Conservation Agriculture (WCCA). The global cropping area recorded under CA in 2008–2009 was 106 M ha which increased to 145 and 157 M ha by 2010–2011 and 2013–2014, respectively (Friedrich et al. 2012; Kassam et al. 2014b). The latest estimated global cropland area under CA is reported to be about 180 M ha for 2015–2016 (Kassam et al. 2019).

CA adoption is still in very initial phase in India. During the last few years, CA adoption has covered about 1.5 M ha area throughout the country (Jat et al. 2012). Zero-till (ZT) sowing of wheat in the rice-wheat crop system of the Indo-Gangetic Plains (IGP) is a major adopted CA practice. In India, the spread of CA is rapid in the rice-wheat cropping systems of irrigated IGP. CA systems have not been promoted in other rainfed, semi-arid, and arid agro-ecoregions. Rice-wheat consortium for the IGP, SAUs, and ICAR institutes is putting continuous efforts to develop and spread CA techniques such as zero-till seed-cum fertilizer drill for sowing of wheat in rice-wheat system, broad bed and furrow planting, raised bed planting, furrow-irrigated ridge-till bed planting system (FIRBS) of wheat, laser land leveling, crop residue management, and crop diversification. Sangar et al. (2005) reported a rapid increase in the area planted under zero-till wheat, and about 25–30% of the total wheat area of IGPs is zero tilled. Despite the considerable area under rice and wheat cultivation, CA techniques like zero-till planted wheat, FIRBS, crop residue management, permanent raised bed planting, etc. have not gained desired popularity in Bundelkhand region. However, laser land leveling and field bunding are much popular practices among rice growers. After the harvest, wheat is cultivated with conventional method. Green manuring, trenching, contour bunding, intercropping, surface mulching, etc. are some of the major CA practices being adopted by the farmers of Bundelkhand region in a limited extent.

9.2.3 Need and Importance of Conservation Agriculture for Bundelkhand Region

In spite of many positive changes such as adoption of new techniques and water-saving techniques for ensuring good crops in the farm sector of the region, the challenges like (1) enhancing and maintaining agricultural productivity under the situations of undulant topography, rainfed farms, and recurring droughts; (2) risky continuous monocropping, leaving the large fields follow during rabi season; and

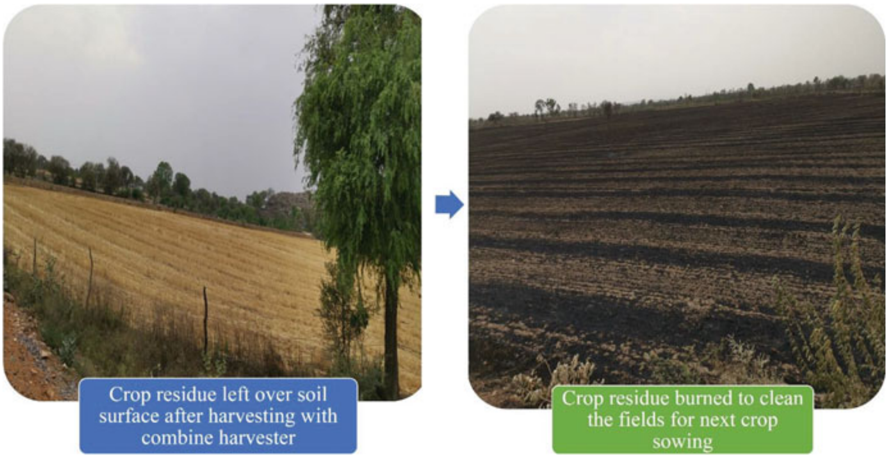

Fig. 9.5 Fields of leftover crop residues and burned crop residues in the Sewda block of Datia

(3) crop productivity far below the national and state averages are still existing and need to be resolved. Despite many challenges and being a drought-prone area, the CA practices are not widely adapted by the farmers of the region. Farmers of the region are not aware about the CA principles and concept and applying only a few water and soil conservation measures without using the basic principles of CA. Conservation agriculture has gained no popularity among the farmers of the region despite many government programs and schemes to popularize conservation agriculture. Existing rice-wheat cropping system and residue burning problems are the growing challenges to the agriculture of Bundelkhand region. Rice in the *kharif* season and wheat in the *rabi* season are the two important cereal crops in the region. Despite being a drought-prone area, rice-wheat cropping system is being followed by the farmers of almost all districts ranging from 5000 to 65,000 ha in the region. As the farmers following the trends of increased mechanized harvesting of rice and wheat in the line of farmers of IGP, the problem of residue burning is arising in the region (Fig. 9.5). Besides repeated droughts and water scarcity problems, the rice cultivation area is more or less similar during the last two decades (Fig. 9.6). After the harvesting of rice with the combined harvester, the rice residues are burned, and wheat is sown by conventional method. Under this situation, CA practice like zero-till sowing of wheat can be very beneficial for the farmers of the region. However, zero-till wheat farming after rice is completely avoided by the farmers due to the lack of awareness. Despite this, the other problems discussed in the introduction part such as undulating topography of region, soil- and erosion-related problems (Fig. 9.7), and climate vagaries increase the importance of CA in Bundelkhand region.

To overcome these problems such as residue burning, climate vagaries, undulating topography, and soil erosion led to gully head formation, and conservation agriculture is a basket of option offering the best management practices to solve all these problems of Bundelkhand region.

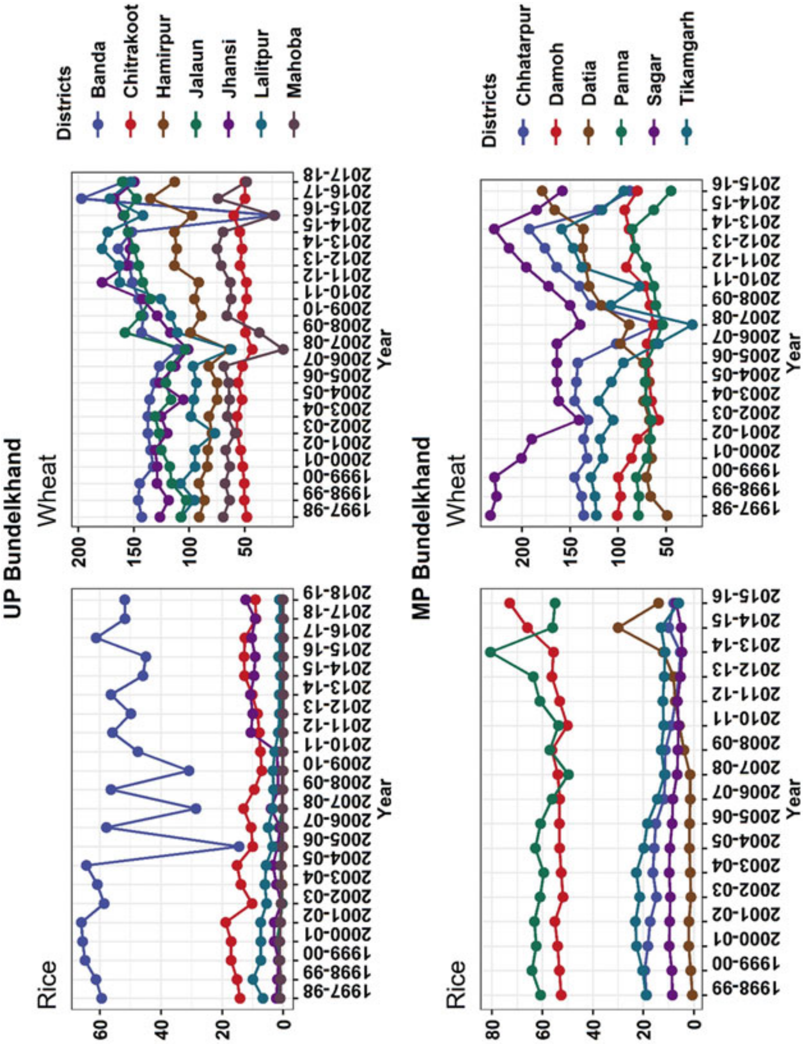

Fig. 9.6 Area under rice and wheat crops in different districts of Bundelkhand region

Fig. 9.7 Soil erosion in cultivated field in Bundelkhand region

9.3 Conservation Agriculture Techniques for Bundelkhand Region

9.3.1 Conservation Tillage

Conservation tillage is also referred as minimal soil disturbances with appropriate residue management system. In this system of tillage, some crop residues remain on the soil surface. Conservation tillage helps in improving the soil health, controlling soil erosion and moisture conservation (Busari et al. 2015; Bista et al. 2017). Zero tillage, minimum tillage, much tillage, strip tillage, etc. are common systems of conservation tillage. But these systems of conservation tillage are not adopted by the farmers of Bundelkhand region. However, with context to rice-wheat crop system as well as soil and climate conditions of the region, conservation tillage system can change the face of this region's agriculture. Very limited research studies are conducted by various organizations to explore the beneficial effects of conservation tillage in the red and black soils of and different crops of the region. In the red and black shallow soils of the region, zero-tillage planted wheat after the mechanical harvesting of rice can be extremely beneficial for the farmers who have adopted the rice-wheat crop system.

Conservation tillage systems have reported several advantages over conventional tillage (CT) with respect to soil properties and crop productivity. Butorac (1994) developed the fact that well-drained light- to medium-textured soils with low organic carbon content gives better performance with conservation tillage. No-tillage technology is effective in reducing erosion losses, balancing the soil evaporation and crop residue disturbance reduction (Lal et al. 2007). Kargas et al. (2012) found that the amount of water retained by no-tillage plots were higher than tilled plots. Minimum tillage increases the storage pores (0.5–5 mm) and improves the soil pore system (Pagliai et al. 2004). McVay et al. (2006) reported higher water content or water holding capacity of topsoil (0–10 cm) under no tillage compared to after plowing. Therefore, traditional/conventional tillage practices need to be replaced with conservational tillage practices to improve soil physical conditions and water use efficiency (Fabrizzi et al. 2005; Silburn et al. 2007). In general, chemical properties of the surface soil layer are more positive under the no-till system compared to tilled soil (Lal 1997). Busari et al. (2013) observed that compared to zero and conventional tillage, minimum tillage soil had a significantly higher pH. Though, effective cation exchange capacity (ECEC) and soil organic carbon (SOC) were significantly greater in ZT compared to CT. A less intensive tillage also encourages the activity of surface feeder earthworms (Kemper et al. 1987). Under a 6-year study, significantly higher population of earthworms was found in no-tilled soil compared to plowed soils (Anderson 1987). According to the FAO (2012) report, climate adaptation benefits of no tillage can be significant. The report stated that in Kazakhstan during 2012's drought, wheat crops under no tillage were more robust and performed with higher yields over the conventionally cultivated. Apart from this, the conservation tillage-reported carbon sequestration at the rate of 367–3667 kg CO_2 ha^{-1} year^{-1} (Tebrügge and Epperlein 2011) and reduced CO_2, nitrous oxide (N_2O), and methane (CH_4) emission (Parkin and Kasper 2006; Steinbach and Alvarez 2006). In the red soils of Jhansi district of Bundelkhand region, Ram et al. (2016) reported that the yields of green gram and black gram under minimum tillage were statistically similar with the conventional tillage. However, the application of *leucaena* as residue management practice resulted in 11.89% and 14.17% higher seed yield of green gram and black gram as compared to without crop residue.

Therefore, conservation tillage practices are the very potential technologies in order to improve overall soil health, reduce soil disturbance and erosion, and improve crop production under harsh climatic conditions with least harmful impact on the environment under the drought-prone regions like Bundelkhand.

9.3.2 Crop Diversification/Rotation

Addition of novel crops or new cropping system into an existing crop system or agriculture production system is called as crop diversification. In India, crop diversification refers to a shift from conventionally grown less remunerative crops to more remunerative crops (Hazra 2001). It depends on several factors such as the climate of the region, soils, market, farmer's family needs, consumer's preferences, and technological growth of the area. Crop diversification is intended to meet the increasing demand of cereals, pulses, oilseeds, vegetables, fruits, etc. Crop rotation refers to cultivation of different types of crops in sequences in the same field. Crop rotation is an important component in conservation agriculture. Incorporation of shallow, deep-rooted crops alternatively improves overall soil health. However, these beneficial effects of crop rotation with respect to soil health depends on several factors such as incorporation of different types of legumes in cropping system (Whitebread et al.

2000), type of the tillage (Halvorson et al. 2002), and cropping intensification (Benjamin et al. 2007). In an ideal crop rotation, the alternative involvement of three dissimilar crops with shallow and deep-rooted systems has been advised. Grant and Lafond (1993) reported that crop rotation under CA reduced bulk density compared to conventional agriculture. It is evident that crops with strong deep tap root system in crop rotation can overcome soil compaction problems (Hamza and Anderson 2005). Systematic application of minimum tillage, crop residue retention in combination with different crop rotation reduces soil erosion (Ailincai et al. 2009), improves infiltration and water holding capacity and reduces soil crusting problems (Christian et al. 2006). In spite of several advantages of crop rotation and the fact that crop systems in small farms are rather diversified, monocropping is a common farmer's practice in Bundelkhand region. The reason behind is the repeating droughts in the last several years clubbed with the soil conditions of the region. The shallow and coarse-textured soils with less moisture retentive capacity do not support *rabi* crops on residual moisture. However, the farmers having medium-depth black soil fields with irrigation facility relies more on rice and wheat cropping system. A few farmers also cultivate sugarcane with assured irrigation facility. Instead of rice, cultivation of any other remunerative cereal; pulse; or oilseed such as maize, sorghum, soybean, sesame, groundnut, etc. can prove to be more efficient with respect to soil, water, and environment conservation under climate change scenario. Maize, pearl millet, sorghum, minor millets, mungbean, urdbean, soybean, groundnut, sesame, safflower, and red gram for the *kharif* season and wheat, barley, chickpea, lentil, linseed, rapeseed and mustard, toria, berseem, etc. for the rabi season are the best suited crops in accordance to Bundelkhand regions climate, soils, and markets. In a study at ICAR-IISWC RC, Datia, groundnut, castor + green gram, clusterbean, and sesame are found to be suitable crops for minimizing the runoff and soil erosion loss and can ensure production even during the poor rainy season in the red soils of Bundelkhand region (Lakaria et al. 2010). However, while taking three crops in a rotation for the same year in a field under CA system, the criteria for soil, climate, irrigation facilities, market preferences and prices, family needs, labor, and input availability should be followed before choosing the best combination of crops to be grown in a rotation under CA.

9.3.3 Green Manuring

Red soils cover about 50% area of Bundelkhand region (Narayan and Lal 2006). These soils pose restrictions to crop production due to poor fertility and shallow to medium depths. These soils are found in foot hill areas with steep slopes, and the major part of rainfall is lost as surface runoff. Fallow-wheat crop system in the red soils of the region leads to soil erosion and nutrient losses (Sharda et al. 1991). The practice of green manuring in the red soils of the region during the *kharif* season helps in minimizing soil erosion and improving the moisture retention, physical structure, and fertility status of the soil. For the soils of Bundelkhand region, sunhemp, *Sesbania*, etc. are suitable green manuring crops for in situ rainwater

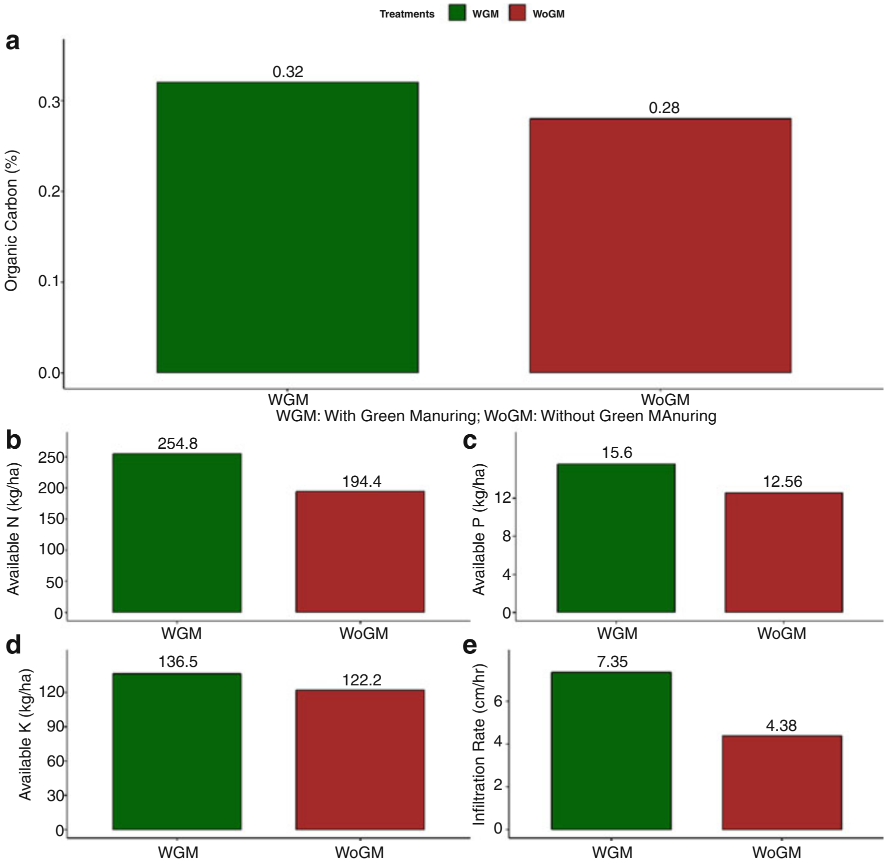

Fig. 9.8 Organic carbon (**a**), available nitrogen (**b**), available phosphorus (**c**), available potassium (**d**), and infiltration rate (**e**) in red soils of Bundelkhand region as influenced by green manuring (after 5 years of cropping). (Source: Narayan and Lal 2006)

conservation and soil fertility augmentation. In this practice the green manuring crop like sunhemp is sown at the rate of 60 kg ha^{-1}, with the onset of monsoon showers. Then the standing green manure crop is incorporated into the soil after 45–50 days of sowing with the help of soil turning or moldboard plow. Green manuring during monsoon season can considerably improve the fertility of soils and productivity of *rabi* cops in red soils of Bundelkhand region. Narayan and Lal (2006) reported that green-manured red soils of Bundelkhand region had deposited considerably higher amounts of organic carbon, available N, P, and K. Infiltration rate in green-manured red soils of Bundelkhand region was almost double compared to the soils without green manuring (Fig. 9.8). This shows the importance of green manuring for the moisture conservation, runoff, and erosion reduction which reflects ultimately in higher crop productivity.

9.3.4 Vermicompost

Besides supplying nutrients, organic manures provide nutrients essential for crop growth, improve soil condition, and add in vegetative growth of crops, leading to the better development of canopy and reduction in soil erosion. Organic manures also improve infiltration rate and reduce soil erosion. There is a huge possibility of using organic manures in Bundelkhand region due to enormous livestock population. Vermicomposting is one of the most popular techniques; it is the procedure of composting the waste farm or nonfarm material with the help of earthworms. Vermicomposting is faster than the conventional composting, which required only 65–90 days for composting than the conventional composting of 5–6 months. ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Datia, has developed low-cost vermicomposting techniques, where the vermin beds are laid on a hard ground surface comprising of cattle dung and other farm and nonfarm waste and fine soil. With the availability of dung, 5–6 cycles of composting can be accomplished in a year with this method of vermicomposting. Vermicompost is the mixture of excreta of earthworms, living and dead earthworms, and eggs of earthworms. Vermicompost is enriched with almost all the nutrients essential for plant growth, some growth regulating hormones such as auxins, etc., and useful microorganisms such as actinomycetes, etc. It is believed that vermicompost is highly beneficial for in situ moisture conservation as it improves soil physical and chemical conditions through their churning and turning action (Mishra and Nayak 2004). Niranjan et al. (2010a, b) reported that the application of cow dung-based vermicompost in both red and black soils of Bundelkhand region produced a maximum grain yield of mungbean, and the maximum values for OC, N, P, K, Ca, Mg, S, and Fe in soil vermicompost at 2 t ha^{-1} under aonla-based agri-horti system increased the intercropped green gram and mustard yield by 49% and 52%, respectively, over control (no fertilizer application). Besides this, it also enhanced aonla growth and increased soil organic carbon by 29% and available N, P, Fe, Mn, Cu, and Zn when compared with control and 100% RDF during 5-year time span compared to other organic manures (Biswas et al. 2012).

9.3.5 In Situ Moisture Conservation

In the areas like Bundelkhand, where rainfall is low and dry spells are more common during the rainy season, the maximum amount of water needs to be stored for further use or to retain as residual moisture for the next *rabi* season crops. Some moisture conservation measures such as broad bed and furrows (BBF), inter-row and inter-plot water harvesting, small scoops on land surface, ridges and furrows, tie ridging, mulching, dead furrows, vegetative barriers, contour farming, contour bunding, trenching, etc. are known as in situ rainwater harvesting or moisture conservation.

More than 70% of the total geographical area in the region is severely affected by varying degree of erosion hazards. Despite receiving more that 80% of total rainfall during the monsoon season, existing water stress conditions are very common even during the rainfall season (Narayan and Biswas 2012). Moreover, the high intensity of rainfall results into a huge loss of rainfall as runoff results in 50–60% of rainfall lost causing 8–9 t ha^{-1} soil loss on 2% slope. In the recent past years, Bundelkhand region has witnessed concurrent drought situations (Samra 2008) and faced water scarcity for agricultural purpose as well as drinking. Even a short dry spell during the monsoon season leads crops to the yield penalty and sometimes led to failure of crop under such situations (Narayan and Biswas 2012). As a solution of these problems, various in situ moisture harvesting/conservation techniques specific for Bundelkhand region have been developed at ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Datia, Madhya Pradesh, for the resource conservation and crop productivity augmentation (Narayan et al. 2017a).

9.3.5.1 Mulching

Mulching with any organic material or crop residues is a very effective technique for in situ moisture as well as soil conservation. In the red soils of Jhansi district, FYM application as mulch material produced highest green chili yield (50.40 q ha^{-1}) followed by mulching with local grass material (47.50 q ha^{-1}). The highest yield of green chili (50.40 q ha^{-1}) was obtained with the application of FYM as mulch of moisture conservation technique, followed by grass mulch (47.50 q ha^{-1}) and planting in 20-cm-deep furrow + black polythene mulching (46.60 q ha^{-1}) compared with no mulch practice which produced only 34.20 q ha^{-1} of green chili. The study indicated that dry grass mulching can be used as an option for low-cost mulching material for soil and moisture conservation with higher productivity (Kumar et al. 2018a). In situ surface mulching of sunhemp with deep tillage and two-hand weedings in sorghum crop were found to be suitable for runoff reduction, increased soil profile moisture, and higher grain and stover yields in the red soils and semi-arid climate of Bundelkhand region (Narayan et al. 2009).

9.3.5.2 Trenching and Microcatchments

Predominance of moisture stress conditions, low and erratic rainfall, and soil conditions make establishment and growth of vegetation, fruit, and forest plants even more difficult. Therefore, to support the establishment and growth of plants, management of moisture supply through in situ conservation of moisture is essential. Approximately 55–60% of degraded forest needs to rehabilitate by planting locally available forest and fruit trees, with proper adoption of moisture conservation measures (NRAA 2008). The moisture availability to the plants can be assured with the adoption of some in situ soil and moisture management practices as the water availability for the survival and growth of trees is essential. Some in situ moisture conservation practices such as microcatchments, single and double trenches or pits closed to the root zone of trees proved to be beneficial for the establishment and growth of various forest and fruit trees. These trenches and microcatchments not only conserve the moisture in soil but also prevent soil erosion, which arrests the land degradation. Construction of trenches of suitable size under tree plantation is a feasible and remunerative technology for the establishment of tree plantation on degraded lands of Bundelkhand region. In the degraded red soils of

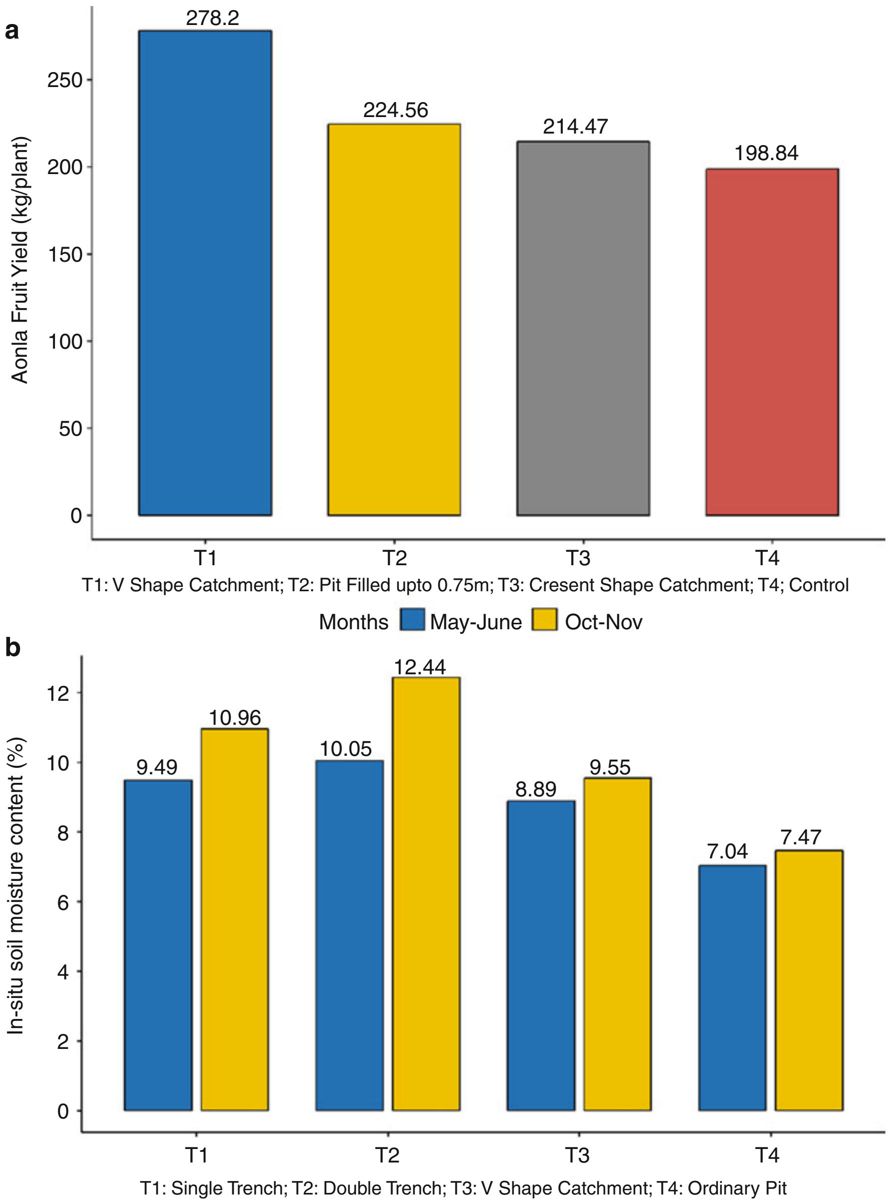

Fig. 9.9 Aonla yield (**a**) and in situ soil moisture content (**b**) as influenced by various soil moisture conservation techniques. (Source: Narayan et al. 2017b and Kumar et al. 2019)

Datia district under *Azadirachta indica* (neem), *Pongamia pinnata* (karanj), and *Madhuca indica* (mahua) with double, single trenches and V-shaped catchment retained significantly higher moisture content over ordinary pit planting (Figs. 9.9b and 9.10). Trees planted with double trenches recorded superior growth parameters,

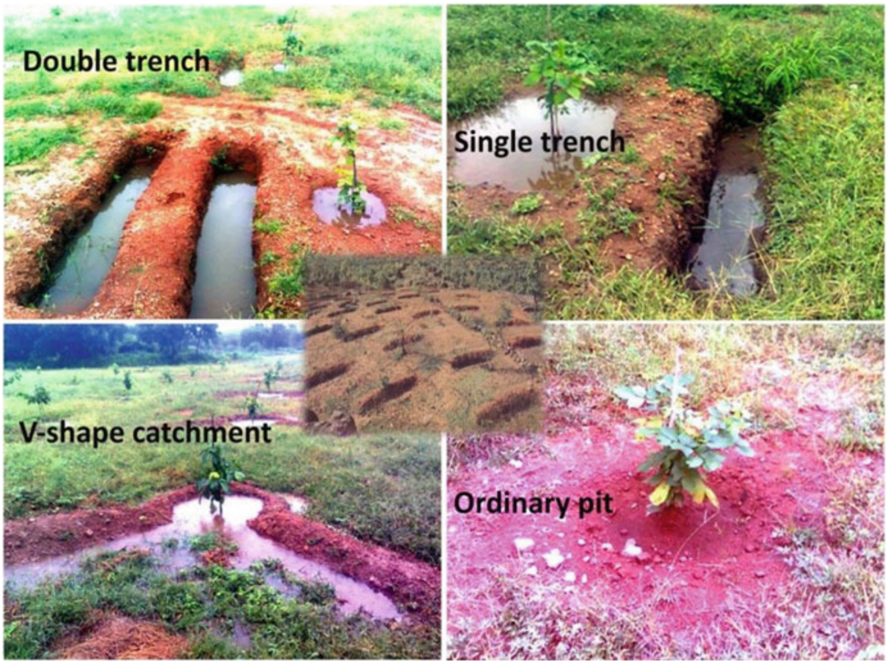

Fig. 9.10 In situ moisture conservation measures for degraded lands in Bundelkhand region

viz., plant height, stem diameter, number of branches, and canopy spread, than the other moisture conservation techniques (Kumar et al. 2019). V-shaped microcatchments can also be suitable in situ moisture conservation for various agri-horti systems. Under aonla-based agroforestry systems on sloppy red soils of Bundelkhand region, V-shaped microcatchment recorded lowest runoff and soil and nutrient loss with higher growth and yield of aonla (Fig. 9.9a) and yields of intercropped mustard and black gram. Crescent-shaped microcatchment was also found to be effective against farmers' practice (Kumar et al. 2018b; Narayan et al. 2017b).

9.3.5.3 Contour Bunding

Contour bunding is another simple method and promising option of soil and water conservation. In the soils, having less than 6% slope, contour bunds play an important role for conserving soil and water. Agriculture can be practiced in the space between the two contour bunds. During rainy events, the contour bunds act as a barrier for the runoff water, and hence reduce the chances of erosion. Contour bunds allow water to infiltrate in soil. In Bundelkhand region, a large portion of agricultural lands are barren and sloppy. Due to soil and nutrient erosion in sloppy lands, farming on such lands is uneconomical. Such soils can be managed and maintained to productive level by constructing contour bunds across the slope. Contour bunds are built out of the soil dug from pits of 2.5-m-wide and 0.3-m-deep cut. Spacing of bunds depends on the degree of slope. A vertical interval of 0.7 m had been suitable for the fields with 3% slope in prevalent red soils of Bundelkhand region. To stabilize the bunds, sodding of beneficial grasses such as *Cynodon dactylon*, *Cenchrus ciliaris*, and *Dichanthium annulatum* should be done. Bunds with top width of 0.45 m, bottom width of 1.80 m, height of 0.45 m, and side slope of 1:1.5 are most suitable for the sloppy lands of Bundelkhand region. Water stagnated in excess of 0.3 m should be drained by the provided masonry outlet structures. Results indicate that contour bunds conserved 42% higher rainwater as runoff was only 3% in contour bund plots compared to 31.6% under farmers' practice. Contour bund also reduced soil loss by 97% and reduced loss of nutrient (OC by 96%, N by 92%, P by 89%, and K by 81%) with 11% higher grain yield of sorghum over farmers' practice (Narayan et al. 2014).

9.4 Obstacles in the Adoption of CA in Bundelkhand Region

Despite having several advantages in the context of crop productivity, environment protection, soil health, crop biodiversity, and farm income, the adoption of conservation agriculture (CA) practices/techniques by the farmers of the Bundelkhand region is very small or negligible. The obstacles in the adoption of CA in the region are listed here under:

(a) The implementation of zero tillage implies a heavy investment and the financial conditions of the majority of the farmers in Bundelkhand region make them hesitate in investing for zero-tillage implementation. On the other hand, the markets for the zero-tillage implementation are absent in the region.
(b) The crop residue burning has become a common story in the rice-wheat crop systems in Bundelkhand region. Due to the lack of machinery availability, farmers were forced to burn rice residues and left over soil after mechanical harvesting for timely planting of succeeding wheat crop. Farmers even burn wheat residues after the harvesting of wheat by combine harvester to keep their fields clean. Crop residue burning creates air pollution and also affects the microorganism in soil due to high temperature during burning.
(c) Due to the unavailability or sometimes high cost of green manuring crop seeds, farmers avoid growing green manures which also costs the whole crop season.
(d) Monoculture is prevalent in the region. The combination of an appropriate crop rotation/system has not been properly identified for the region.
(e) The unavailability of crop residues poses a big difficulty in maintaining the permanent cover on soil surface. Under rainfed conditions of Bundelkhand region, crops produce very less biomass which farmers use for livestock feeding and as a source of fuel in kitchens.
(f) CA research programs are lacking in the Bundelkhand region. Very little research efforts have been made to demonstrate and diffuse the CA technologies among the farmers of the region.

9.5 Conservation Agriculture in Bundelkhand Region: A Way Forward

Despite the huge advantages, the adoption of CA is very less, and the rate of its spread is almost negligible due to farmers' less interests and knowledge about CA, mindset about prevailing tillage practices and crop systems in the region, and noninvolvement of the government and nongovernmental organizations in the diffusion of CA within the region. The adoption and spread of CA in Bundelkhand region can be promoted by establishing a collective network involving scientists, national, international and regional organizations, farmers, industrialists, and other shareholders. For the fast and effective spread of CA in the region, there is a need for basic and exploratory research in CA systems. Crops and crops systems specific to Bundelkhand region need to be evaluated with CA technologies to identify suitable CA techniques for specific crop system under rainfed conditions of Bundelkhand region. The CA techniques developed by several national and international organizations also needs to be evaluated in Bundelkhand region, and promising technologies need to be demonstrated and modified on the farmers' fields. Crops, land, water resources, and livestock need to be integrated with conservation agriculture research. The several beneficial and promising CA techniques like diversification with maize-based cropping systems, furrow-irrigated raised bed system, permanent raised bed planting (FIRBS), and zero-tilled wheat remain to be introduced in the rainfed and drought-prone Bundelkhad region. The better anticipation and prognostications will minimize the uncertainty about the impact of CA techniques in Bundelkhand region.

9.6 Conclusions

The climatic extremes such as low temperatures, uncertain rains and concurrent droughts, and different soil types (red and black soils with shallow depth and low moisture holding capacity) and topography (undulating sloppy and rocky terrains) of Bundelkhand region are the major factors responsible for low crop productivity, poor soil conditions, and poverty of the farmers. The adoption of rice-wheat crop systems in some parts of the regions is forming new threats to already degraded soils and depleted water bodies including crop residue burning issues in the drought-prone and water-scarce Bundelkhand region. Conservation agriculture (CA) practices including the three basic principles such as minimum soil disturbance, permanent soil cover, and crop rotation/diversification have several benefits such as soil and moisture conservation, improved soil health, and higher monetary returns. Having many beneficial effects, CA practices like zero tillage is still absent or nonexist in the region; however, the potential of zero tillage and crop residue management have been explored/modified vis-à-vis Bundelkhand region from proven technologies developed from worldwide research studies. In addition, green manuring, vermicomposting, and crop rotation have proved themselves beneficial for conserving soil and water resources, improving soil health and crop productivity in shallow soils of Bundelkhand region. In situ moisture conservation techniques such as single or double trenching and microcatchments are very useful for the establishment of tree or forest plantation and for improving crop productivity and several horti/silvi-agri systems. Contour bunding is also a promising technique for reducing soil erosion and runoff with the maintenance of higher crop productivity. Despite the huge advantages, these CA techniques are limited to research, and adoption of these techniques by farmers is much lower. Several restrictions such as machinery, crop residue availability, etc. are responsible for low or non-adoption of these techniques in the region. Drought-prone Bundelkhand region needs to be introduced with several promising CA techniques like maize-based crop rotations, FIRBS, raised bed planting, appropriate crop residue management, etc., and these techniques coupled with crop systems should be evaluated and demonstrated on farmer's field for a speedy spread and adoption of CA techniques in Bundelkhand region.

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Conservation Agriculture in the North Eastern Himalayan Eco-Region of India

10

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Abstract

The north eastern region (NER) of India (26.3 M ha geographical area) comprises seven hill states (Arunachal Pradesh, Manipur, Mizoram, Nagaland, Meghalaya, Sikkim, and Tripura) and parts of hilly region of Assam popularly referred as North Eastern Himalayan Region of India (18.37 M ha) and the pain and valleys of Assam (7.84 M ha). The hill and mountain ecosystems of the region need to be protected, rehabilitated, and developed with much more emphasis than any other ecosystems as the health of the hill will decide the health of the plains. More than 95% of the soils of the NER are acidic due to leaching of basic cations because of heavy rainfall. Intensive natural resource mining and continuous degradation of natural resources (soil, water, vegetation) under conventional agriculture practices are a threat to sustain farm productivity and food security for posterity. It is observed that improved conservation effective techniques like minimum and/or no till practices, crop diversification, cover crops, and in situ moisture conservation practices using locally available biomass and substitution of bulky organic nutrient sources by at least 30–40% of the crop residues or weed biomass can address land degradation issues and provide solution for sustainable soil health management to the resource-poor farmers of the region. Similarly, inclusion of short-duration crops in cereal-based cropping system and legume

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co-culture is found to be potential resource conservation options to sustain the soil health and enhance cropping intensity in NER. The conservation agriculture (CA) practices developed elsewhere in the world and India like those in Indo-Gangetic Plains may need to be refined for their applicability to the hill and mountain ecosystem of NER. For the promotion of CA practices across diverse agro-ecologies of eastern Himalayas, appropriate policy and institutional measures and technology support would be a prerequisite.

Keywords

North eastern hill region · Soil health · Conservation tillage · Crop diversification · Integrated nutrient management · Resource conservation technologies

10.1 Introduction

The north eastern region (NER) of India covers about 26.3 M ha geographical area and lies between 22°05′ and 29°30′ N latitudes and 87°55′ and 97°24′ E longitudes. The NER of India comprises seven hill states (Arunachal Pradesh, Manipur, Mizoram, Nagaland, Meghalaya, Sikkim, and Tripura) and Karbi Anglong and North Cachar Hills of Assam (about 18.37 M ha) and plains of Assam (7.84 M ha). The degradation of agricultural lands in the region began with the start of shifting cultivation in 7000 BC, and with the increase in population pressure (about 49 million), the degradation has increased many folds in the last few decades. The region has around 56% of the area under low altitude, 33% mid-altitude, and the rest under high altitude. Traditionally, farmers both at upland terrace and valley land follow monocropping of rice in rainfed conditions, occupying more than 80% of the cultivated area. The region is characterized by diverse agro-climatic and geographical problems such as (1) steep slopes, (2) continuous removal of topsoil through soil erosion (Fig. 10.1), (3) poor to medium organic matter status under upland and sloping lands, (4) water logging in land-locked areas and valleys, (5) soil acidity due to washing of cations, (6) reduced infiltration due to poor soil properties, (7) nutrient leaching due to heavy rain undulating topography and poor management practices, (8) burning of vegetation under shifting cultivation and other areas, (9) decline in vegetation covers due to deforestation, and (10) loss of biodiversity and many more. Farming in rainfed NER is complex, diverse and risk prone (Bhatt and Bujarbaruah 2005; Saha et al. 2012). Further, the transfer of soil and nutrient load along with runoff due to high rainfall and steep topography has much implication for the resource base and environment in the region (Sharma and Sharma 2004; Saha et al. 2012). More than 95% soils of the region are acidic due to leaching of basic cations because of heavy rainfall and undulating topography. Intensive natural resource mining and continuous degradation of natural resources (soil, water, vegetation) under conventional agriculture practices pose a real challenge in sustaining farm productivity and food security for the coming years. Even though the ethnic inhabitants of the region have been practicing some of the important indigenous

Fig. 10.1 Intensity of soil and water erosion in hills of the north eastern region of India

resource conserving technologies, they remained mostly confined to their place of origin. Increase in population pressure is also forcing farmers to adopt intensive method of cultivations. In the rainfed hill zones, marginal mechanization is mainly due to difficult terrains, small holdings, and poor economic condition of the farmers.

Conservation agriculture (CA) is one such approach that has the potential to reverse the trend of degradation to a greater extent through the addition of crop residues, which can add organic matter, nutrients, and other soil-binding cations that help in the formation of soil micro- and macroaggregates. Furthermore, efficient crop rotations would help increase soil organic carbon (SOC) content with inclusion of leguminous crops. Thus, in order to keep the production system in a sustainable way under different land situations, CA based on minimum tillage (MT)/no-till (NT) system is an alternative to reconcile agriculture with its environment and overcome the imposed constraints of climate change and spiraling input costs. In addition to this, resource conserving techniques (RCTs) using locally available resources encompass practices that enhance resources or input-use efficiency and provide immediate, identifiable, and demonstrable economic benefits such as reduction in production costs; saving water, fuel, labor requirements; and timely establishment of crops resulting in improved yields (Yadav et al. 2018b). CA refers to a set of agricultural practices encompassing the elimination of soil disturbance, use of cover crops and crops rotations with enrich diversity, surface cover of soil with crop residue permanently and integrated plant nutrient supply systems to mitigate soil erosion, and improve soil fertility besides delivering soil functions. The CA is used for conserving, improving, and making more efficient use of resources under crop production systems. It has many tangible and intangible benefits in terms of reduced cost of production, saving of time, increased yield through timely planting, improved

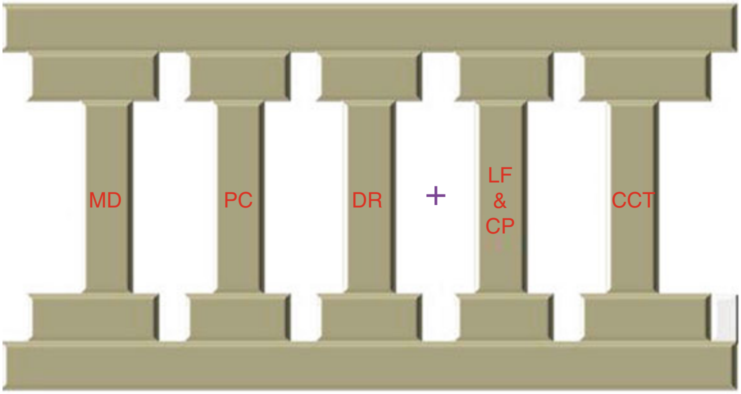

Fig. 10.2 Conservation agriculture with some additional principles proposed for hilly eco-region. *MD* minimum soil disturbance, *PC* permanent soil cover, *DR* diversified crop rotations, *LF* land forming/shaping, *CP* crop planning/selection, *CCT* conservation contour terracing

water productivity, adaptation to climate variability, reduced disease and pest incidence through stimulation of biological diversity, reduced environmental footprints, and ultimately improvements in soil health (Yadav et al. 2018b). Furthermore, this practice of agriculture improves SOC content (Yadav et al. 2019) which ultimately leads to an increase in input use efficiency.

As the topographical situation of hills differs from the plain, thus the implementation of CA in hilly eco-regions needs location-specific set of management practices, in addition to its basic principles, e.g., land forming/shaping and crop planning/selection, conservation contour terracing, and many more as suited by the farmers of the region. A pictorial presentation of additional principle for implantation of CA in the hilly region is presented in Fig. 10.2, and details are discussed as followed.

10.1.1 Land Forming/Shaping and Crop Planning/Selection

Agriculture in hills are generally characterized by varying degrees of slope from 4% to 40%. Sometimes hill farmers cultivate even in lands with 100% or more slope, leading to the degradation of soil health. Thus, problem of soil erosion and high runoff are embroiled in cultivation practice in the region. Therefore, it is essential to shape the land under different configuration by ways of adopting various agronomical measures and engineering, e.g., contour bunding, graded bunding, contour terracing, bench terracing, half-moon terracing, and most importantly stabilizing the soils with suitable vegetative barriers like growing of shrubs and grasses on slopes and risers. Therefore, land forming/shaping is prerequisite for wider adoption of CA in hilly eco-regions. Generally, these are the fundamental principles to improve the productivity of hill agriculture and conserve soil and water in the region. Crops may be cultivated in alternate strips, parallel to one another. Some strips may be allowed to remain fallow, while in others different crops may be sown, e.g., grains, legumes, small tree crops, grass, etc. Various crops ripen at different times of the year and are harvested at time intervals. This ensures that at no time of the year the entire area is left bare or exposed. Further, hilly or sloping fields can be loosely separated into three main groups based on topographic location and water supply (Sharma et al. 1995):

1. Upper toposequence position, where net outflows of water and soil erosion are very high and surface water accumulation is least; and drought risk is highest; and dominated by forest trees, shifting cultivation, monocropping of rice.
2. Mid toposequence position, where runoff are both inflows and outflows of water to the field; with moderate surface water accumulation, moderate soil erosion, and moderate drought risk; and dominated by mono cropping of upland rice or maize/ with component of trees.
3. Lower toposequence position, where rainfall, seepage, water table, and runoff provide water to the field with reliable and early surface water accumulation, hence drought risk is lowest, although excessive inundation risk is highest and lowland rice cultivation with one or two crops in a year.

Thus, approaches of selection of crops and trees to different toposequences are varying. A framework of selection of trees, grasses, and crops according to different toposequences is presented herein for better understanding (Fig. 10.3). Micro-rain water harvesting Structures like agri-film (250 GSM) lined *Jalkund* (30,000 L capacity) may be constructed at mid-hills slope for life saving irrigation to crops during dry season.

10.1.2 Conservation Contour Terracing

Conservation contour terracing (CCT) is more pertinent for improving productivity and health of hill soils. The CCT may be constructed by cut and fill method of land along the contour line according to the slopes, and a sizable area may be earmarked to be a CCT for efficient utilization of resources; thus, a range of crops can be grown on it. A CCT-based farming system model have been developed at ICAR-Tripura Centre, Lembucherra, Tripura for enhancing the productivity, and resource use efficiency of hill agriculture is presented herein for improved understanding (Fig. 10.4).

Further, the region has been divided into three altitudinal region such as (1) low altitude (56%), (2) mid-altitude (33%), and (3) high altitude (11%). Thus, the CA approaches in relation to different altitudinal situations are discussed herein.

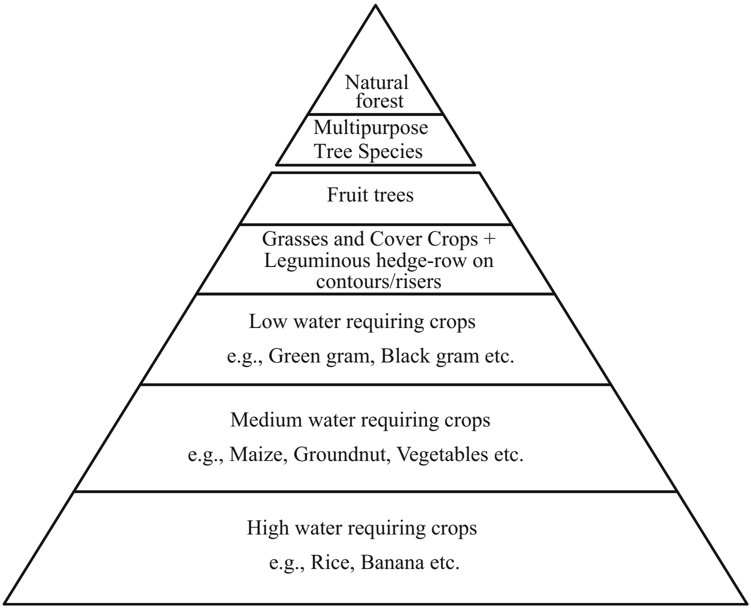

Fig. 10.3 A framework of crop planning/selection for hilly regions

10.2 CA Approaches for Low Altitude Region

Low altitude hills of eastern Himalayas include the state of Tripura and Manipur of the NEH region of India. The region receives >2000 mm of annual rainfall (Yadav et al. 2017). However, an erratic and uneven distribution of rainfall leads to short- and long-dry spells, which cause the moisture stress during cropping season in the coarse-textured soils (Yadav et al. 2018a). Also, the intense and extreme rainfall events aggravate the risks of water runoff and soil erosion, which exacerbate moisture deficit during the growing season (Yadav et al. 2018a). Drought, both agronomic and pedologic, are experienced in 1 out of 3 years in the region (Patel et al. 2010) and warrant identification and promotion of conservation-effective practices of crop production (Yadav et al. 2018b). Thus, CA plays a vital role in conserving soil and water, enhancing biodiversity, and increasing SOC contents. A series of field experiments on CA with mulch and different nutrient management for rice and maize have been conducted under both lowland and upland ecology of West Tripura. In a field experiment, NT with residue retention (RR) and mulches reduced weed growth and increased soil moisture storage, productivity, and profitability of upland direct-seeded rice (DSR) during 2012–2013 in Tripura. This 2-year study revealed that the NT-RR recorded less total weed density (75–161 weed m^{-2}) and biomass (8–155 g dry weight m^{-2}) than those under convention tillage (CT) with residue incorporation (RI). In addition, NT-RR stored (122–172 mm) more soil

Fig. 10.4 Conservation contour terrace-based land use model. (**a**) Maize on conservation contour terraces; (**b**) brinjal on conservation contour terraces; (**c**) bund stabilization with hybrid napier grass; (**d**) conservation contour terraces

moisture (0–40-cm soil depth) in comparison to CT-RI treatment (110–161 mm). NT-RR also reduced the cost of cultivation of direct-seeded upland rice by 31.5% compared to CT-RI (INR4 1677 ha^{-1}, 1 US \$ = INR 64.5). Thus, the net returns under NT-RR for the direct-seeded upland rice were 3 and 7.5 times more than those for the CT-RI in 2012 (INR 5523 ha^{-1}) and 2013 (INR 1946 ha^{-1}), respectively (Yadav et al. 2018a). Under the same set of treatment combinations after four cropping cycles, it was also observed that the adoption of NT-RR significantly (p = 0.05) reduced the energy use (16,727 MJ ha^{-1}), carbon footprint (CF) (2013 kg CO_2-e ha^{-1}), and cost of production (INR 54,271 ha^{-1}, 1 US \$ = 64.46 INR) over those under CT-RI (27,630 MJ ha^{-1}, 2307 kg CO_2-e ha^{-1}, and INR 76,903 ha^{-1}, respectively). Thus, NT-RR also substantially increased the energy use efficiency, energy productivity, net returns, and reduced CF of the system over those under CT-RI. Various mulching also increased the energy use efficiency, system productivity, and net returns over those under NM (Yadav et al. 2018b). In another study, changes of CT to NT with land configuration had increased the root length density (RLD) and root mass density (RMD) in all the layers of soil in their respective tillage system. NT-RB (raised bed) had significantly more RLD and RMD than all other tillage and land configuration systems. NT-RB produced significantly higher leaf area index and dry biomass accumulation. NT-RB produced higher green cob, fodder, and yield components (number of cobs ha^{-1} and cob weight) (Yadav et al. 2018c). Soil organic carbon (SOC) was higher with NT-FB (flat bed) followed by NT-RB > NT-RF (ridge and furrow) > CT-RB > CT-RF > CT-FB. The NT-FB registered 13.2% higher SOC than CT-FB. However, the CT-RB recorded higher soil pH as compared to all other treatments. The available N, P, and K were higher with NT systems compared to CT systems. Thus, maize-maize-field pea cropping system under NT-RB has been recommended for higher productivity and profitability and for sustaining the soil health in the region (Yadav et al. 2015).

In Manipur, monocropping is prevalent in valley region, and most of the valley areas are dominated by rice-fallow system. Inclusion of pulses/oilseeds in rice-fallow system is one of the best options by adopting NT to enhance the productivity through the utilization of available residual moisture under CA (Das et al. 2016). Inclusion of lentil (HUL-57, Pl-06, and PL-08) under rice fallow system provided 0.65 to 1.00 Mg ha^{-1} yield in addition to rice yield (Ansari et al. 2017). Hence, rice-lentil cropping system was introduced by ICAR Research Complex for the NEH region, Manipur Centre, from 2013, especially in Thoubal, Imphal West, Imphal East, and Bishnupur districts. Rice-lentil cropping system also was successfully demonstarted in terraces in hill agriculture (Ansari et al. 2015). Other cropping systems, such as rice-vegetable pea, rice-lathyrus, rice-vegetable broadbean, and rice-sweet corn/baby corn, could be promising options under CA (Bhadana et al. 2013; Ansari et al. 2017). The NT allows farmers to plant 15 days earlier than usual practices. Since the cost of land preparation is meager, it also generates higher net income. The cultivation of rapeseed in *kharif* rice fallow under NT as a resource conservation technology has been taken up in many villages on a cluster form, and bee-keeping units were introduced in the rapeseed field. The average productivity (1.0 Mg ha^{-1}) was higher than the state average (0.65 Mg ha^{-1}). Under apiary, honeys could also be produced by the farmers giving an additional return of Rs. 2000 per farmer. The system is popular in more than 1500 ha in Manipur valleys (Singh et al. 2012). In a study, Ansari et al. (2017) reported that the highest mustard equivalent yield (MEY) and water use efficiency (WUE) were recorded under reduced tillage (RT) with maize residues (1059.6 kg ha^{-1}) followed by NT with maize residues (954 kg ha^{-1}). Crops performed better with maize residue incorporation under RT/NT in terms of dry matter production and yield attributes (Ansari et al. 2017).

10.3 CA Approaches for Mid-Altitude Region

About 80% of the Meghalaya's population is engaged in agricultural activities for their livelihood. There is a very good scope for promotion of CA in the state in rice- and maize-based system for conserving natural resources and increasing productivity and profitability (Das et al. 2018). Several field studies have been conducted on various aspects of CA in mid-altitude of Meghalaya to standardize package of practices for crop production using various RCTs (Das et al. 2018; Kuotsu et al. 2014; Ghosh et al. 2010). The average grain yield of rice was significantly higher under NT (4.79 Mg ha^{-1}) than that of minimum tillage (MT) (4.49 Mg ha^{-1}) and CT (4.44 Mg ha^{-1}) from a 6-year study at Umiam, Meghalaya. The residual effect of tillage and nutrient management (NM) practices applied to rice had a significant effect on green pod yield of succeeding pea grown under NT system. The pooled green pod yield of pea was highest under MT (8.13 Mg ha^{-1}) followed by CT (7.45 Mg ha^{-1}), and the lowest was under NT (6.40 Mg ha^{-1}). In comparison with the initial baseline, there was a marked improvement in physicochemical and biological properties of soil after 3 years (after harvest of pea crop). The bulk density (ρb) under CT (1.04 Mg m^{-3}) was at par with MT (0.99 Mg m^{-3}) but was significantly higher than those recorded under NT (0.96 Mg m^{-3}). Soil under NT had significantly higher available nutrients (N, P_2O_5, K_2O), SOC, and soil microbial biomass carbon (SMBC) concentration than those under CT. The available N, SOC, and SMBC of soils were recorded to be significantly higher under 50% NPK + GLM as compared to 50% NPK alone at 0–15-cm soil depth (Das et al. 2017a, b). Ghosh et al. (2010) reported that double NT practice in rice-based system was cost-effective, restored SOC, favored biological activity, conserved water, and produced better yield, which were 70.7%, 46.7%, and 49% higher compared to CT. NT along with the retention of maize stalks and application of *Ambrosia* spp. mulch 5 Mg ha^{-1} resulted in maximum improvement in soil quality parameters and enhanced yield of rapeseed in maize-rapeseed cropping system in eastern Himalayas (Das et al. 2017b). Grain yields of maize and rapeseed under CT were similar to those under NT. Mulching had a significant effect on the productivity of maize and rapeseed (Das et al. 2017b). There was a marked increase in SOC concentration (8.4%), water stable aggregates (9.3%), mean weight diameter of aggregates (42.6%), and soil microbial biomass carbon (66.8%) under NT with respect to CT (Das et al. 2017b). The infiltration rate and hydraulic conductivity under raised bed (RB) with residue + hedge leaves along with NT were 108% and 46% higher, respectively, as compared to FP after two cropping cycle. The SMBC was 67% higher under RB with residue + hedge leaves incorporation (381μg g^{-1} soil and 276μg g^{-1} soil) compared to FP, while dehydrogenase activity was 135% higher in RB with residue + hedge leaves under NT (57.8μg TPF g^{-1} soil 24 h^{-1}) after groundnut harvest in the second year (Kuotsu et al. 2014).

Monocropping of rice is a prevalent practice in Mizoram in wet terraces and lowlands. To reduce the cost of cultivation, cultivation of short-duration *rabi* crops (pea, toria, and niger) under NT was tested in rice fallows for the utilization of residual soil moisture efficiently. Conventionally after the *kharif* rice, fields remain fallow in lowland, mainly due to excess moisture owing to seepage from surrounding hillocks. Draining excess water from rice fields at physiological maturity creates favorable condition for successful cultivation of *rabi* pulse (pea (Arkel variety)) and oilseeds, viz., mustard (pusa mustard 991), toria (M-27), and niger (Ratna Suryamukhi). Adaptation of simple drainage technology around the rice fields/plots with appropriate base flow outlets creates favorable rhizosphere environment to grow second crop in the rice fallows. All the combination showed the increase in net system productivity except rice fallow treatment. The highest rice yield, rice equivalent yield, and total system production were obtained with rice-pea system, followed by rice-mustard and rice-niger systems (Singh et al. 2016). Therefore, pea and oilseed inclusion in rice fallows under NT increased the net system productivity and farm income. These combinations doubled the cropping intensity (200%) and improved the soil fertility status related to monocropped rice (Singh et al. 2016). Thus, with the adoption of NT practice and selection of appropriate legumes, the system productivity and farmers income can be enhanced substantially.

10.4 CA Approaches for High Altitude Region

High-altitude hills of eastern Himalayas include the state of Arunachal Pradesh, Nagaland, and Sikkim of the NEH region of India. In Arunachal Pradesh, shifting cultivation is a most common practice, and attempt has been taken to replace it with other sustainable land uses. With burgeoning human population and subsequent increase in pressure on land, fallow periods have been reducing continuously, which led to the reduction in overall farm productivity of the system (Ramakrishnan 1992). Nagaland has an agrarian economy. About 70% of the total population of the state depends on farming. Agriculture has traditionally been and continues to be the mainstay of Naga life; the numerous festivals are centered on agriculture and have their roots in cultivation practices. The main crops grown in the state include rice, millet, maize, and pulses. Although majority of the population is engaged with cultivation, still Nagaland depends on the import of food supplies from other states. Sikkim is a small hilly state having only 12% of the area under cultivation of the total geographical area (7096 sq. km). The ecosystem of the state are from tropical (300 m) to the trans-Himalayan region (5000 m) divided into five categories. Out of the total population of 607,688 (Census 2011) about 65% is still dependent on agriculture for their livelihood. Agriculture is mainly rainfed and mixed type and still at the subsistence level rather than commercial level with irrigated area around 11% only. Farming in Sikkim is done on terraces due to its hilly topography. So, farming is a very big challenge in Sikkim due to its hilly geographical structure and different climatic zones in different districts. Hence, CA can also support the underlying biodiversity and may improve the productivity for Sikkim, Arunachal, and Nagaland. In Arunachal, the maize grain and stover yields under NT lowered by 7% and 4.9%, respectively, than those under CT. However, placement of paddy straw at 4 Mg ha^{-1} had 11.1% and 6.5% higher grain and stover yield over no-mulch. It was also reported that CT plots conserved soil moisture only during the early stage, whereas in the long run, better profile recharge was observed under NT. It was mainly due to placement of residues and very little disturbance of soils which encouraged the infiltration rate (Choudhary et al. 2013). While under NT, a majority of roots were noticed on the soil surface (<20 cm) and were more fibrous, whereas, at deeper soil, lesser root fractions were observed. Placement of paddy straw mulch at 4 Mg ha^{-1}in maize recorded 19% longer, 15.7% more roots, 16.3% more volume, 32.6% better root dry biomass, and 14.1% better root density recorded over without mulch. Soil organic matter on top 10 cm was higher in NT; it decreases the organic carbon oxidation to CO_2 by avoiding soil aeration and maximum aggregate-protected organic matter which slowly decomposed, enriching the SOC on top of the soil and helping in sequestering atmospheric carbon over CT. Green pod and stover yield of pea was 11.1% and 10.0%, respectively, higher in CT over NT (Choudhary 2015). In the hills of Nagaland, the application of mulches made significant improvement in yield attributes (cob length, number of rows/cob, number of grain/row, number of grain/cob, and 1000-grain weight), yields (grain, stover, and biological), economics (gross, net returns, and benefit:cost ratio), and quality attributes (carbohydrate, starch, and sugar) of maize than those under no mulch in both the years. The straw mulching recorded 15.9% and 16.5% increase in grain yield and 20.4% and 22.2% in stover yield over no mulch, respectively (Kumar 2015).

In Sikkim, under different tillage practices, it was observed that planting of vegetable pea under NT immediately after rice harvesting enhances green pod yield (5.89 Mg ha^{-1}) over RT and CT. In the same case, significantly higher net returns (96.1×10^3 Rs ha^{-1}) and B:C ratio (3.27) were recorded with NT over RT and CT. Energy use efficiency was also significantly higher with NT (6.29%) over RT (4.29%) and CT (3.12%). NT had required 44% and 28.3% less energy as compared to CT and RT, respectively (Singh et al. 2015). After two cropping cycles of rice-vegetable pea, SOC content was improved in NT (2.22%) over CT (2.05%) and RT (2.10%). SMBC value was also higher under NT (145 mg g^{-1} soil) over CT and RT (Singh et al. 2015). NT technology also conserves soil moisture as compared to CT and RT. During the study about 18–20% higher soil moisture was noticed under double no-till practice as compared to CT. However, NT and/or RT technology makes cultivation more farmer friendly and saves time and input as well as produces healthy crops (Babu et al. 2015). Hence, to reduce the labor cost and time for the preparation of land for sowing after the harvest of maize, NT techniques for sowing of black gram and rajmash immediately after harvesting of maize has been standardized (Babu et al. 2014). The application of FYM or mixed compost at 5 Mg ha^{-1} has been recommended prior to sowing followed by goat manure/poultry manure at 1–2 Mg ha^{-1} as basal dose to overcome micronutrient deficiencies. Sowing is done by opening a narrow slit (5–8-cm depth) for the placement of seed at 30–40-cm row-to-row and 10–15-cm plant-to-plant distance. The results of the study recorded 17.8% higher rajmash yield under NT practice over CT. Similarly, the black gram yield was also was higher under NT planting (0.98 Mg ha^{-1}) over CT (Babu et al. 2016). The impact of CA practices on soil properties under different altitudes of NER are presented in Table 10.1.

10.5 Adoption Constraints of CA in the Eastern Himalayan Region

The lack of appropriate seeders/equipment/machineries especially for small- and medium-scale farmers and hill farmers are the major bottlenecks for promotion of CA. Significant efforts have been made in developing and promoting machinery for seeding wheat in NT systems, but hill region-specific mechanization is still lacking

Table 10.1 Impact of CA practices on soil properties in different altitudes of the NEH region of India

Altitude/CA practices	Study duration (Year)	SOC (mg kg^{-1})	BD (Mg m^{-3})	References
Low altitude (Lembucherra, Tripura)				
No-till + residue retention in rice-rapeseed system (0–10 cm)	4	7.4	1.42	Yadav et al. (2019)
Conventional tillage + residue incorporation in rice-rapeseed system (0–10 cm)	4	6.6	1.41	
Mid-altitude (Umiam, Meghalaya)				
Retention of maize stalk cover + *Ambrosia* sp. mulch at 5 Mg ha^{-1} in maize-rapeseed system (0–15 cm)	4	25.6	1.13	Das et al. (2017a, b)
No mulch in maize-rapeseed system	4	20.8	1.20	
High altitude (Tadong, Sikkim)				
Maize stalk mulch + weed biomass mulch in maize based cropping system (0–15 cm)	4	13.4	1.30	Singh et al. (2019)
No-mulch in maize-based cropping system	4	12.7	1.34	

to implement the CA in hill areas especially in hill agriculture. There is an urgent need for developing light weeding and seeding machineries for hill ecosystem and development of ecofriendly and efficient weed management practices for the promotion of CA in the hill ecosystem (Das et al. 2018). Farmers prefer burning of crop residues for timely sowing of the next crop and other reasons. It is estimated that out of 628.31 Mg $annum^{-1}$ paddy straw production, approximately 463.7 Mg is burnt per annum (295.10 and 168.6 thousand Mg from valley and hill, respectively) in Manipur (Ansari et al. 2018). The lack of knowledge about the potential benefits of CA to agriculture leaders, extension functionaries, NGOs, FPOs, farmers club and farmers is another major hardles for promotion of CA in the region. Biomass burning in the NEH region under *jhum* farming (10 Mg ha^{-1}) is a prevalent practice, and major challenge is to convince the farmers to recycle biomass and CA (Das et al. 2011). The competing demand for crop residues for other sectors such as fodder, biofuel, etc. also is a challenge for residue retention. With the promotion of organic farming and farmers' reluctance of using herbicide, weed management is a real challenge in organic farming. Inadequate availability of manual labor and involvement of high costs further exacerbate the situation. Lack of adequate skill and training is another important constraint for popularization of CA in the NEH Region.

10.6 Conclusions

The hill and mountain ecosystems of the NER need to be protected, rehabilitated, and developed with much more emphasis than any other ecosystem or economy as the health of the hill will decide the health of the plains. It is proven that several improved conservation effective techniques, viz., minimum disturbance of soil through the use of MT and/or NT practices for winter crops, crop diversification, cover crop, in situ moisture conservation practices using locally available biomass, and substitution of bulky organic nutrient sources by at least 30–40% of the crop residues or weed biomass may be the solution for sustainable soil health management for the resource-poor farmers of the region. The NT along with retention of maize stalks and application of *Ambrosia* spp. mulch 5 Mg ha^{-1} improved soil quality parameters especially SOC, SOC pools, bulk density, infiltration rate, water holding capacity, plant available water, soil microbial biomass carbon, and enzymatic activities. Similarly, the inclusion of short-duration crops in cereal-based cropping system is also recommended for the region to sustain the soil health and enhance cropping intensity. For the promotion of CA practices across diverse agro-ecologies of eastern Himalayas, appropriate policy and institutional and technological support would be a prerequisite.

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11 Impact of Conservation Agriculture and Residue Management on Soil Properties Under Sugarcane-Based Cropping Systems

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Abstract

Sugarcane (*Saccharum officinarum* L.) is an important agro-industrial crop of tropical and sub-tropical regions of the world. It is one of the important cash crops in India, playing a pivotal role in the Indian economy as it contributes about 7.0% of the total annual agricultural revenue and also provides livelihood for 7.5 million sugarcane growers and their families. However, sugarcane productivity has been stagnant over the last two decades, ranging between 54 and 72 t/ha. In the present scenario, stagnation in cane productivity and deterioration in soil health are the major concern for its sustainability. The major reasons for its unsustainability are continuous mono-cropping, excessive use of fertilizers, intensive tillage, and depletion of soil biodiversity. Furthermore, open field burning of trash is also a common practice that results in the loss of organic carbon (SOC), plant nutrients, and soil biota, besides the environmental and health hazards due to the release of soot particles and smoke and greenhouse gas (GHG) emissions. Alternatively, the retention of sugarcane trash in the field and placement of fertilizers in soil can improve the nutrient use efficiency, cane productivity, and soil quality in addition to reducing environmental pollution. Therefore, a multidimensional approach, i.e., Conservation Agriculture (CA), is essential to sustain sugarcane productivity with improvement in soil health and environment. The CA technologies involve minimum/zero tillage, crop residue retention on soil surface, and crop rotations, and it is useful to recuperate

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degraded soils and improve productivity. These technologies also provide opportunities to reduce the cost of production, save water and nutrients, increase yields and the efficient use of resources, and benefit the environment. In the last decades, many researches across the world have recommended the CA as a solution to overcome the adverse effects of conventional practices on soil physical, chemical, and biological health in sugarcane-based cropping systems. The present chapter deals with CA technologies that have potential to improve soil health and related processes, especially soil aggregation, soil moisture, soil infiltration, hydraulic conductivity, organic matter, nutrient availability, cation exchange capacity, and biochemical and enzymatic properties. The CA practices have the potential to improve soil health and cane productivity as well as reduce environmental pollution, and thus, it could be recommended for long-term sustainability of the sugarcane-based cropping systems.

Keywords

Conservation agriculture · Crop-residue · Soil health · Sugarcane

11.1 Introduction

Sugarcane (*Saccharum officinarum* L.) is widely grown in tropical and subtropical regions of the world and is one of the most important cash crops in India. India is one of the largest producers of sugar and is in neck-to-neck race with Brazil for first position. It plays an important role in both agricultural and industrial economies of the country. The Indian share in sugar production is about 17.4% of the world in 2018–2019 (USDA 2020). The sugarcane crop occupies field for as long as 15–-18 months, and its productivity in India is relatively low and gives a net profit of only a few thousand rupees. The major reasons for decrease in crop productivity are continuous mono-cropping system, excess use of inorganic fertilizer, intensive farming, intensive tillage, and depletion of soil nutrient and microbe level (Shukla et al. 2017, 2018). The depletion of nutrient and microbes occurred due to voracious feeding of newly developing varieties, excess use of synthetic chemicals, changes in physical structure of soil, and trash burning. Nambiar and Ghosh (1989) reported that the excess use of inorganic fertilizer damages soil health. Most of the experimental evidences reported that prolonged use of chemical fertilizers and pesticides affects the structural and functional properties of microbial communities in soil (Nicholson and Hirsch 1998; Bohme et al. 2005) and at the same time creates nutrient-imbalance in agricultural soils. Dengia and Lantinga (2018) noted that sugarcane trash burning determines losses in soil organic matter (SOM) and nitrogen (N) as well as change in soil pH and electrical conductivity (EC).

In sugarcane-based cropping system, trash burning either before or after harvest is a common practice worldwide. In Indian agriculture, most of the farmers burnt the sugarcane trash that creates environmental pollution. Trash burning directly reduces the amount of surface organic matter, soil organic carbon (SOC), essential nutrients, and microbial count. The burning practices pollute the surrounding neighborhood with smoke, ash, and gaseous (CH_4, CO_2, NO, NO_2, and N_2O) emissions to the atmosphere that may contribute to the "greenhouse effect," and the associated global warming where the emission of CH_4 and N_2O for the year 2010–2011 was calculated as 115.12 and 26.48 Gg carbon equivalents, respectively (Lenka et al. 2014). During burning, large amounts of C, N, and S present in the plant residues are lost via volatilization. Consequently, a change from burning to retaining sugarcane residues will likely alter the cycling of C and N in the soil. For recovery of the original position, several years may be required before changes are evident. For example, Galdos et al. (2009) noted that after 8 years total soil carbon (C) was 30% lesser in burned treatment compared to an unburned in the first 10 cm of a clayey Oxisol, but no difference was detected in soil C after the first ratoon in the upper 7.5 cm of a Spodosol (Ball-Coelho et al. 1993).

Another important reason for reducing crop productivity and increasing cost is the persistent use of traditional production practices. The costs of inputs such as improved varieties and fertilizers continue to increase, and farmers make inefficient use of them. To overcome these problems, farmers have to understand that agriculture should not only be high yielding but also sustainable in the long term. Therefore, eliminating unsustainable parts of traditional agriculture (i.e., monoculture, intensive tillage practices, imbalanced and excess use of inorganic fertilizers) is essential for gains in future productivity while sustaining the natural resources.

Due to the change in climate, area and production of sugarcane are highly unstable and fluctuate immensely every year. Now it has become a routine feature in the tropical and subtropical climatic zones (Department of Agriculture Cooperation, and Farmers Welfare, Government of India 2019). Srivastava and Rai (2012) reported that sugarcane is very sensitive to temperature, rainfall, and solar radiation; therefore, a negative effect on its production and sugar yield is expected in the future. That is why a multidimensional approach is essential for sustaining sugarcane production with improving soil health, environment, economic viability, and welfare of the society. Therefore, a sustainable agricultural system that responds to the climate change effects efficiently and smartly is conservation agriculture. Conservation agriculture (CA) practices can also contribute to making agricultural systems more resilient to climate change. In many cases, CA has been proven to reduce greenhouse gas emissions (GHG) in different cropping systems and enhance their role as C sinks.

CA technologies involve no or minimum soil tillage, soil cover through crop residues, and crop rotations for achieving higher productivity. In Asia, CA area is mainly located in China (65.4% of the total Asian CA area) followed by Kazakhstan (19%) and India (around 15%) (FAO 2017). CA is practiced to use available resources with minimizing external inputs and soil degradation (Fereres et al. 2014). Sugarcane residues comprising tops and leaves generate about 17% of the crop residues in India (Jain et al. 2014). Sugarcane tops are either used for feeding of dairy animals or burnt on-farm for growing a ratoon crop in most parts of the country. Hence, there is a need to assess the effects of CA practices and crop residue management on soil properties in order to better understand their potentials to optimize soil functions and to provide evidence to support more sustainable outcomes. Recently, reported benefits of CA are improved soil fertility, crop growth, better water infiltration, increased biological activity, decreased soil erosion and reduced labor, machinery use, and fuel costs. This chapter majorly focuses on improving soil health properties in sugarcane-based cropping system through CA practices and crop residue management.

11.2 Sugarcane Statistics: Conservation Agriculture Perspective

Sugarcane is a tropical plant and grown as cash crop in the world. Sugarcane is grown on around 2.8% of gross cropped area of India. The largest sugarcane producing state of India is Uttar Pradesh, next to Maharashtra on the second position and Karnataka on the third. Other main sugarcane-producing states of India include Bihar, Assam, Haryana, Gujarat, Andhra Pradesh, and Tamil Nadu. In India sugarcane crop covers 47.74 lakh ha area and gives 355.10 million ton production with an average productivity of 74.37 ton/ha (Department of Agriculture Cooperation, and Farmers Welfare, Government of India 2018). The statewise area, production, and productivity of sugarcane in the 2017–2018 season are mentioned in Table 11.1.

Table 11.1 State wise area, production and productivity of sugarcane in season 2017–2018

Sr. no.	State	Area (lakh ha)	Production (lakh tons)	Productivity (tons/ha)
1	Andhra Pradesh	0.99	79.48	80.3
2	Assam	0.30	11.15	37.2
3	Bihar	2.43	165.11	67.9
4	Chhattisgarh	0.30	12.47	41.6
5	Gujarat	1.84	122.34	66.5
6	Haryana	1.14	87.29	76.6
7	Jharkhand	0.07	5.23	69.8
8	Karnataka	3.70	299.02	80.8
9	Kerala	0.01	1.22	116.2
10	Madhya Pradesh	0.98	54.30	55.4
11	Maharashtra	9.02	726.37	80.5
12	Odisha	0.05	3.41	64.4
13	Punjab	0.93	75.33	81.0
14	Rajasthan	0.05	4.04	74.5
15	Tamil Nadu	1.83	165.62	90.1
16	Telangana	0.35	22.17	63.3
17	Uttar Pradesh	22.34	1623.38	72.7
18	Uttarakhand	1.02	71.42	70.0
19	West Bengal	0.17	12.94	76.1
20	Others	0.19	8.68	45.7
Grand total		47.74	3550.90	74.4

3rd advance estimates for sugar season 2017–2018. March 2018; Vol. 49, No.7; Issued by Department of Agriculture Cooperation & Farmers Welfare

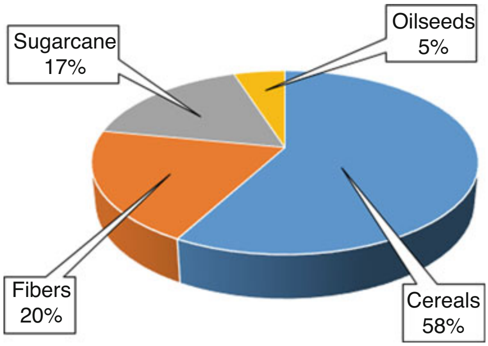

Fig. 11.1 Contribution of different crop categories in residue generation (Jain et al. 2014)

Generally, sugarcane crop occupies the field more than 2 years with different types of inter- or/and sequential cropping systems and generates large quantities of agricultural wastes (i.e., trash). The amount of trash will increase in the future with an increase in area, production, and productivity. The sugarcane residues are left in the field after harvesting of the economic components, i.e., sugarcane stack. Most of the farmers used these residues as animal feed and thatching for rural homes. These residues are also collected by sugarcane and paper industry as industrial fuel and raw material, respectively (Dotaniya et al. 2016). But, a large portion of the crop residues is not utilized and left in the fields. The disposal of such a large amount of crop residues is a major challenge for farmers. To clear the fields rapidly, farmers used to practice in situ crop residue burning, because it is a quick and the easiest way to manage the large quantities of crop residues and prepare the field for the next crop well in time. This is the prime factor in reducing sugarcane crop productivity and affects soil health.

Among the different crop categories, 361.85 million tons of residues were generated by cereal crops followed by fiber crops (122.4 million tons) and sugarcane (107.5 million tons) (Jain et al. 2014). In fact, sugarcane residues contribute to 17% of the total crop residues (Fig. 11.1). There was a large variation in sugarcane trash generation across different states of India depending on the crops grown in the states and their cropping intensity and productivity. Uttar Pradesh contributed maximum to the generation of residue of sugarcane (41.13 million tons/year) next to that Maharashtra (22.87 million tons/year) and Tamil Nadu (12.37 million tons/year) (Jain et al. 2014). The statewise sugarcane trash generation is mentioned in Table 11.2 (Fig. 11.2).

Sugarcane residues burning emit a significant quantity of air pollutants like CO_2 and GHG's. They cause a negative impact on soil health, environment, and ecosystem. In India Uttar Pradesh contributed maximum to the burning of sugarcane trash followed by Karnataka. Mendoza (2014) reported that 12,204 kg/ha CO_2 gas has been emitted from sugarcane trash burning. On the agriculture side, there are many nutrient and moisture lost from the biomass in sugarcane production. Jain et al. (2014) reported that burning of sugarcane trash led to the loss of 0.079, 0.033, and 0.001 million tons/year of nitrogen, phosphorus, and potassium, respectively. Rasse

Table 11.2 Sugarcane crop residues generated in various states of India

States	Crop residues generated (million tons/year)	States	Crop residues generated (million tons/year)
Andhra Pradesh	5.80	Maharashtra	22.87
Arunachal Pradesh	0.01	Manipur	0.01
Assam	0.41	Mizoram	0.01
Bihar	1.87	Nagaland	0.07
Chhattisgarh	0.01	Odisha	0.24
Goa	0.02	Punjab	1.76
Gujarat	5.85	Rajasthan	0.15
Haryana	1.93	Tamil Nadu	12.37
Himachal Pradesh	0.02	Tripura	0.02
Jharkhand	0.13	Uttar Pradesh	41.13
Karnataka	8.80	Uttarakhand	2.11
Kerala	0.10	West Bengal	0.62
Madhya Pradesh	1.12	Pondicherry	0.06

Jain et al. (2014)

et al. (2000) also reported that burning cane trash leads to the loss of 44 kg nitrogen/ha/year and some amount of phosphorus and 70–73% of potassium. Burning decreases soil organic matter (SOM) content and consequently increases bulk density, which decreases water retention (Stoof et al. 2010).

The second important point in declining sugarcane crop productivity is frequent and deep tillage operations. Soil tillage is among the important factors affecting soil properties and crop yields. For newly mechanized farmers, tillage is a way to solve problems. Tillage is usually followed for seedbed preparation, weed management, and incorporating manure and fertilizer into the root zone. The frequent use of tillage operations often negatively impacts soil quality and microbial activity (Choudhary and Behera 2014). They disrupt soil structure, accelerating surface runoff and soil erosion and reducing crop residue. Without crop residue, soil particles easily dislodge and splash away. This process is only the beginning of the problem. The splashed particles clog soil pores, effectively sealing off the soil's surface, resulting in poor water infiltration and root system development. Continuous soil inversion leads to degradation of soil structure, leading to a compacted soil composed of fine particles with low SOM, which led to low crop yields and low water and fertilizer use efficiency (Wang et al. 2007). Rhoton (2000) reported that a plow tillage reduces 10% loss of initial SOM content.

The third important point in the decline of sugarcane crop productivity is mono-cropping system. Mono-cropping in sugarcane reported loss of SOM and soil

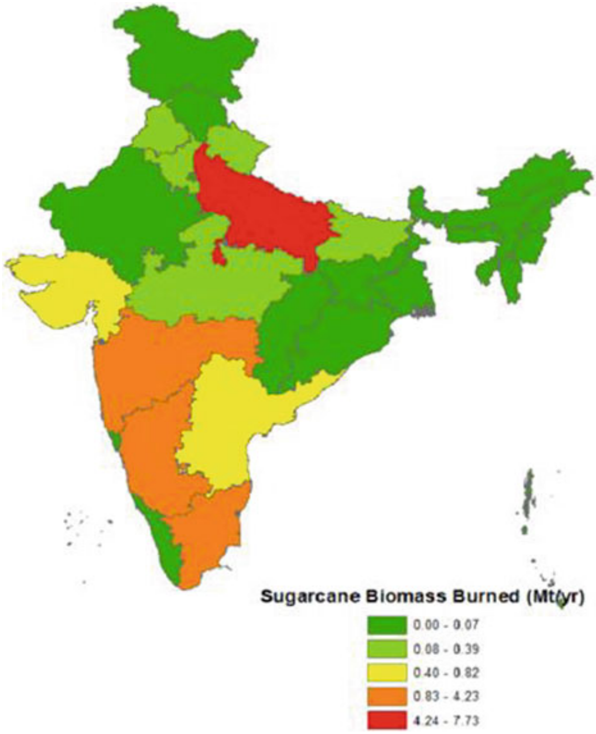

Fig. 11.2 Sugarcane crop residues generated in various states of India (Jain et al. 2014)

degradation (Van Antwerpen and Meyer 1996; Haynes and Hamilton 1999). A loss of SOM has detrimental effects on soil physical, chemical, and biological properties (Stevenson 1994). Those factors directly and indirectly affect sugarcane crop productivity.

To overcome above problems, scientists and policymakers put emphasis to adopt CA-based production systems. Compared to conventional agriculture, there are several benefits from CA such as economic benefits to farmers, cost and time saved, erosion protection, soil and water conservation, increases of soil fertility, and environment safety. The CA practices depend on three basic principles, namely, reduced soil disturbance, permanent soil cover, and crop rotations. According to FAO, CA is a concept for resource-saving agricultural crop production, which is based on enhancing the natural and biological processes above and below the ground. This concept is based on three principles:

1. *Zero/minimum tillage*: It includes less soil disturbances than conventional tillage. Minimum tillage results in good seedbed preparation, rapid seed germination, satisfactory crop stand, favorable growing conditions, and reducing cost of cultivation. Kassam and Friedrich (2009) noted that minimum tillage maintains the optimum proportions of respiration gases in the rooting zone, moderate organic matter oxidation, and porosity for water movement. Minimum- or

no-tillage techniques combined with trash management has shown beneficial results for improving cane yields as well as reducing detrimental environmental impacts and improving SOM (Cheosamutr and Chinawong 1999).

2. *Soil cover through crop residues*: Crop residual cover is an important protective agent against rain, cold, and heat; it also increases soil flora and fauna. It also enhances soil physical and chemical properties associated with long-term sustainable productivity. Graham and Haynes (2005) reported that green cane harvesting with retention of trash mulch increased the size and activity of the microbial community and enzyme activities in soil. In turn it improves soil aggregation and C sequestration (Ghosh et al. 2010). According to the Ramalingaswamy et al. (1998), about 3 tons/ha of trash is utilized for mulching for conserving soil moisture and nutrients.
3. *Crop rotation*: Changing vegetation improves not only soil flora and fauna but also recycled nutrients. Legumes usually accumulate large quantities of N and K, the nutrients which are taken up in the highest amounts by the sugarcane plants. Changing vegetation also improves productivity of the next-generation crop and provides farmers with economically viable options that minimize risk. In some extent crop rotation decreases intensity of disease, weed, and pest. Crop rotation with legume crop disrupts insect life cycle, fixes environmental nitrogen to soil, and enhances biodiversity (Kassam and Friedrich 2009). Additionally, it protects the soil against erosion, prevents weed spreading, and reduces nematode populations (Dinardo-Miranda and Fracasso 2009).

11.3 Conservation Agriculture for Sugarcane-Based Cropping Systems in India

Farmers are facing a serious challenge of residue burning and soil degradation in sugarcane growing areas. These challenges are deteriorating the quality of natural resources, adversely affecting crop yields and increasing cost of production. To conserve soil health and environment and overcome the agriculture challenges, the role of conservation agriculture is well recognized by most of the sugarcane-growing countries including Brazil, Australia, Thailand, etc. In India, conservation agriculture technologies are yet not popularized widely among sugarcane growers. However, efforts to develop and spread conservation agriculture have been made through the combined efforts of several State Agricultural Universities, ICAR institutes, Krishi Vigyan Kendra, and sugarcane factories. Some of the technologies developed by the researchers to promote conservative agriculture in sugarcane-based cropping systems are reported hereunder:

1. *Laser land leveling (LLL)*: The use of laser technology in the precision land leveling is of recent origin in India. The laser land leveling creates a smoother soil surface; increases water use efficiency, uniform germination, and growth of crops; and reduces the use of fertilizer and chemicals. It not only minimizes the cost of leveling but also ensures the degree of precision. Precision land leveling

(PLL) increases water use efficiency and facilitates uniform seed germination, better crop growth, and higher crop yield (Jat et al. 2006). Ren et al. (2003) indicated positive impact of land leveling on water saving and crop and farm productivity. A reduction of 75% in labor requirement for weeding was reported due to LLL. It also saves farm inputs like water and fertilizers, improves crop stand, and encourages uniform germination (El-Behery and El-Khatib 2001). Bhatt and Sharma (2009) estimated that around 25–30% of irrigation water could be saved through this technique without having any adverse effect on the crop yield. Laser land leveling and drip irrigation practices not only saved the irrigation water but also improved the cane yield to the tune of 11% (Choudhary et al. 2019a).

2. *Multipurpose SORF machine*: The sugarcane trash generated after harvest hampers the fertilizer placement and other field operations; therefore, open burning is a common practice in ratoon sugarcane. But its in situ retention could play an important role in replenishing soil quality and reducing environmental pollution. To reduce such losses and improve ratoon yields, a multipurpose machine was developed for stubble shaving, off barring, root pruning, and placement of basal dose of fertilizers (SORF) in soil in a single run (Choudhary et al. 2017a, b, 2018a, Singh et al. 2017). Choudhary et al. (2017c) reported that the use of SORF techniques along with in-situ retention of chopped trash improved the cane yield by up to 30%, NUE by 13%, water productivity by 37%, and net profit by up to ₹50,000 ha^{-1} with 12.6% higher B:C ratio. These techniques facilitate the placement of fertilizers under surface trash retained conditions, promote root growth and new sprouts, reduce tiller mortality, improve nutrient use efficiency, soil health, and cane productivity (Choudhary et al. 2016a, 2017a). Choudhary et al. (2017d, 2018b) reported that the maximum values of millable cane, cane length, cane weight, and juice yield were recorded with chopped trash (CT) + SORF which was significantly higher by 28–60%, 30–47%, 49–76%, and 45–66%, respectively, over the conventional practice and control treatments. Retention of chopped trash on soil surface as mulch and placement of N in soil improved cane yields by 14–57% over the control and conventional practices. However, when stubble shaving, off-barring, and root pruning practices are employed together, cane yield further improved significantly by 17% than that of individual practices of the placement of N.
   Choudhary et al. (2017a) conducted an experiment with SORF machine on ten farmers' fields and revealed that the increase in cane yield averaged 16% and 11% over the trash burning (farmers' practice) and chopping followed by recommended practices of fertilizer application, while the nitrogen uptake efficiency (NUE) improved by 9.9%. Band placement of double the dose of N as basal rather than the recommended two splits as basal and at earthing-up further boosted the initial growth and improved the cane yields and NUE by 22% and 11% over farmer's practice. Finally, they concluded that fine-tuning of this prototype should offer a practical and economic solution of trash burning problem in sugarcane cultivation.

3. *Sugarcane trash management*: Trash management plays an important role in soil and environment health improvement through reduced weed intensity, improving fertilizer use efficiency, increasing water-holding capacity, maintaining the C:N ratio of soil, and reducing emissions of GHGs, smock, and soot particles. Sugarcane trash production depends on the season of planting, climatic condition, variety, intercultural operations, etc. However, on an average it is 12–15% of millable cane yield (Yadav and Srivastava 2005). Basanta et al. (2003) noted that unburned trash remaining as surface mulch resulted in an average N recycling of 105 kg/ha/year which may lead to a more efficient recycling of fertilizer N applied to the system and therefore reduce fertilizer needs. They also reported that the retention of crop residues has been shown to increase soil organic matter and nutrient content in several cropping systems. In situ retention of trash either chopped or unchopped improved the cane yields by about 8–13% over the farmer's practice of trash burning while treating the trash with supernatant of biogas slurry, and *T. viride* further improved the cane yield by about 18% and 23% (Choudhary et al. 2018c). Surface retention of chopped trash and adoption of SORF techniques significantly improved the physicochemical and biological parameters, i.e., bulk density, organic C content, and microbial and enzymatic activities, and also improved crop growth and cane yield significantly over conventional farmers' practices (Choudhary et al. 2018b). According to Yadav and Srivastava (2005), trash mulching over 1 ha of area adds up to 50, 15, and 60 kg of N, P, and K, respectively. Among them 28%, 42%, and 56% of N, P, and K are available to the plants just by leaching. Several researcher showed a positive effect of sugarcane trash mulching, like more nutrient cycling (Oliveira et al. 2002), higher water-holding capacity (Dourado-Neto et al. 1999), higher aggregate stability (Graham et al. 2002), increasing soil organic C (Galdos et al. 2009), reduction of the GHG emissions (Galdos et al. 2010), microbial remobilization, and increasing millable cane and cane yields (Choudhary et al. 2017a). Choudhary et al. (2016b, 2019b) reported that yield improvement with chopping of trash was 7% and 12% when fertilizers were broadcasted and placed with crowbar, respectively. Further, the highest cane yield was recorded with the application of N through fertigation that was 20–45% more over control (N un-fertilized) and broadcast application of fertilizers under trash mulched conditions.
4. *Crop rotation and intercropping system*: Sugarcane is a widely spaced (60–150 cm) crop. At the initial stage of crop growth, sugarcane occupies less canopy; during that period loss of solar radiation energy occurs. According to Ramanujan and Venkataramana (1999), the formative stage of sugarcane noted less than 30% light interception point. The sugarcane rhizosphere occupies less than one third of the soil, remaining interspaces occupies by weeds and affects on crop growth. To avoid those effects and earning more profits through growing of short duration leguminous crops as an intercrops. Leguminous intercrops fix atmospheric nitrogen and thus help sugarcane by enriching the soil with N and organic matter by their residues. Intercrops also improve soil physical and biological properties (Choudhary et al. 2017e, 2018d). Khippal et al. (2016)

observed that the intercropping trials have proved conclusively that crops like pea, chickpea, and lentil can be successfully intercropped with autumn planted sugarcane for higher returns to the farmers with better cane quality, improving soil health for sustainable crop production. Shoko et al. (2007) reported that around 80 kg N/ha could be saved by using soybean as an intercrop in sugarcane. Ladha et al. (1988) reported that 45–60-day-old dhaincha species could fix N equal to 200 kg N/ha. However, covering of soil surface with live mulch of mungbean followed by retention of mungbean residue and trash in the field improved the cane yield on an average by 10% as compared to that without residue (Choudhary et al. 2019a).

Crop rotation improved soil physical environment facilitates, water infiltration, water holding, aeration, and ultimately root growth and plant nutrient uptake. Short crop rotation particularly in areas where continuous mono-cropping is in practice could be an effective means of controlling insects in conservation tillage system. Crop rotation with legumes favors an increase in the amount of nitrogen in the soil. Therefore, it improves the nitrogen nutrition and thus increases the yields of subsequent crops. Sunnhemp rotation with sugarcane will increase soil N availability and reduces response to N fertilization during cane-plant cycle (Otto 2015) and increases sugarcane yield. Senigagliesi and Ferrari (1993) found that crop rotation with crop/pasture increased the organic matter, nitrogen, and phosphorus in soil by 46.7%, 48.3%, and 76.0% with respect to original contents, respectively. Chen (1993) reported that legumes can incorporate 1000 kg of fresh biomass in the soil containing 200 kg dry matter, 5 kg N, 0.4 kg P, and 3.3 kg K. According to Hutchinson et al. (2007), crop rotations improved extensive root systems of crop to increase root C input and give physical protection to soil aggregation.

5. *Raised bed planting system*: This system improves water efficiency with reducing farm inputs like fertilizer, seed, etc. It is also useful for crop residue management, reducing nitrogen losses and increasing rain water conservation. Yadav and Srivastava (2005) conducted an experiment at Indian Institute of Sugarcane Research, Lucknow, and revealed that wheat + sugarcane cropping under furrow irrigated raised bed system (FIRB) system resulted in better utilization of resources and saved 20% water and labor requirements.

11.4 Effects of Conservation Agriculture on Soil Health

Plant growth and development depends on soil quality, and soil quality depends on its physical, chemical, and biological properties. Van Antwerpen and Meyer (1996) reported an adverse effect of sugarcane mono-culture on changes in physical, chemical, and biological properties of soils. Soil quality depends not only on management practices but also on temperature, precipitation, and parental material. In current scenario, soil degradation is the major problem in world, and India is also not an exception. Degradation of soil may occur due to anthropogenic activities. Soil degradation has been defined as a process that leads to decline in the fertility or future productive capacity of soil as a result of human activity (United Nations Environment Programme 1993). The excess use of water combined with higher doses of chemical fertilizers has resulted in enhanced degradation of land and water resources (Pachauri and Sridharan 1998) and declining sugarcane productivity in recent decades (Samui et al. 2005). Jadhav (1995) reported that soil quality decreases with reduced soil organic matter content in India. Qongqo and van Antwerpen (2000) measure the decrease in soil pH, cation exchange capacity, exchangeable cations, organic matter, and aggregate stability, with a corresponding increase in bulk density under continuous sugarcane production.

Conservation agriculture has come up as a new paradigm to achieve the goal of sustainable agricultural production. Conservation agriculture is a widely accepted terminology to denote soil management through crop residue management, minimum tillage, and crop rotation and makes desirable changes in soil properties like increasing biological activity, nutritional values, reducing water run-off, soil loss, and increase in soil water infiltration and decrease in evaporation losses. The beneficial effect of CA on soil properties under sugarcane-based cropping system is explained under here.

11.4.1 Physical Properties of Soil

1. *Soil structure/aggregation*: Soil structure has a strong interrelation with the soil quality. Soil structural stability is the ability of aggregates to remain intact when exposed to different stresses (Kay et al. 1988). Various agents such as soil fauna, roots, inorganic binding agents, and environmental variable (Six et al. 2004) and measures of aggregate stability are useful means for assessing soil structural stability. Soil aggregation and their stability have great influences on water-holding capacity, nutrient dynamics, as well as soil tilth (Hillel 2004); therefore, aggregated soil structure is the most desirable characteristic for higher crop productivity.

   In conventional tillage, better structural distribution occurred but structural component are weaker to resist raindrop splitting than zero tillage or minimum tillage. According to Govaerts et al. (2009), zero tillage improves soil aggregation compared to conventional tillage. Another key factor for soil aggregation and structural stability is improving the level of organic matter by managing previous crop residues. Van Antwerpen and Meyer (1998) observed that burning of sugarcane trash reduces soil organic matter. The remedy for this decline in organic matter may be the retention of crop residues from green cane harvesting. Soil organic matter reduces soil deformation, increases its resistance and resilience (Soane 1990), and improves soil macro-porosity (Carter 1990). Crop residue management decreases the breakdown of aggregates and protects soil from the impact of raindrop, water, and wind erosion (Six et al. 2000). Different types of crop rotation and its crop residues also affect soil aggregation. Six et al. (2004) reported that different types of root system play an important role in soil aggregation and stabilization.

2. *Bulk density*: Bulk density (BD) is the mass of oven-dry soil per unit total volume of dry soil in its natural state. Bulk density is a major factor in soil compaction, and soil compaction occurred due to excessive use of heavy machinery and implements, resulting in increases in bulk density and affecting the transmission of water and air through the soil, changing the heat capacity, and decreasing the amount of nutrients mineralized from the soil, which results in the reduction in crop yield. Compaction creates hardpan below the soil surface and restricted root penetration and soil aeration. Loamy-clay soil compactness, not draining excess irrigation water, causes anaerobic condition and retardation of plant growth. Wang et al. (2014) found that no-tillage and straw cover reduced bulk density in the top soil (0–30 cm) and improved water infiltration. Similarly, Ng Cheong et al. (2009) also reported minimum tillage operation was useful to minimize soil compaction in sugarcane. The beneficial effect of CA-based tillage and residue management in terms of lower bulk density is more subjected to the topsoil (0–15 cm) (Gal et al. 2007; Naresh et al. 2016). Significantly lower values of bulk density recorded under CT + SORF techniques as compared to trash burnt and control treatments in 0–15-cm soil layer (Choudhary et al. 2018b). The crop rotation, tillage operation, and residue managements mainly affect bulk density, but restricted in a topsoil area or plow layer area. Hulugalle et al. (2007) reported that soil compactness increased in dryland Vertisols with cotton-based crop rotations after conversion from conventional- to permanent-raised beds. All the above studies indicated that zero tillage, crop residue management, and crop rotation, i.e., CA, prevent soil compactness in sugarcane-based cropping system.
3. *Soil moisture*: Conservation agriculture can increase infiltration rate and reduce runoff and evaporation rate as compared to conventional tillage. Residue cover is a major factor in determining soil temperature and availability of soil moisture (Beyaert et al. 2002). The crop residual mulching conserves soil moisture and reduces the impact of moisture stress and maintained soil temperature. Low soil temperature reduces evaporation and transpiration losses and helps sugarcane crop to avoid heat stress. The surface retention of chopped trash and the use of SORF techniques improved the root growth and soil moisture content in soil profile that could benefitted the crop to alleviate the short-term drought stress effects in sugarcane (Choudhary et al. 2016a). Peres et al. (2010) observed that sugarcane trash preservation on the field was able to reduce water losses as compared to unmulch. Didier et al. (2018) showed that mulch retains soil moisture and improves cane stalk length and cane yield in rainfed conditions.

   Conservation tillage is recommended to conserve soil and moisture (Magdoff 2007). Brandt (1992) reported that zero tillage increases soil moisture resulted in increased yield with increasing moisture use efficiency. Intercropping, crop rotation, and their residue management increase organic matter content and soil aggregation, which is useful to improve soil moisture and water use efficiency in sugarcane-based cropping system.
4. *Soil hydraulic conductivity*: Hydraulic conductivity is the measure of the ability of a soil to transmit water. From an agricultural point of view, the movement of water through the soil is quite essential for plant growth. Hydraulic conductivity

significantly and positively correlated with the total soil macro-pores, and tillage practices have the potential to alter macro-pores of the soil by affecting the setting and consolidation of soil particles over time (Rasse et al. 2000). The greater number of macro-pores, little disturbance to soil, and presence of litter of well-decomposed residues formed by accumulated organic matter are the main causes of a better hydraulic conductivity under CA practice over CT (Osunbitan et al. 2005). Logsdon et al. (1990) found that long-term no-till increased macro-porosity and saturated hydraulic conductivity. Li et al. (2011) noted that hydraulic conductivity can be improved, and evaporation can be decreased by no-tillage and crop residue cover. According to Kumar and Mall (2012), trash mulch increased hydraulic conductivity from 0.154 to 0.164 cm/h as compared to unmulch.

5. *Soil infiltration*: Infiltration is the process where water enters the soil. In conventional tillage, soil micro-aggregates and the fine ash of crop residue are major factors of soil pores clogging, reducing soil infiltration rate. Under CA, reduced tillage and crop residue management increases the rate of infiltration compared to conventional tillage (CT). CA has been recognized as an advanced agricultural technology that reduced the impact of drought and improved the physical condition of soils worldwide. In CA, the residues left on the topsoil with zero tillage and crop retention act as barriers to reducing surface runoff and increasing water infiltration rate. The maintenance of crop residues that act to cover the soil dissipates the energy of raindrops as well as prevents soil disaggregation and surface sealing, thereby improving the water infiltration capacity (Brady and Weil 2002). Bell et al. (2001) also reported that trash blanketing in sugarcane improves infiltration rate. An increase in water infiltration and a reduction in water and wind erosion could be achieved using no tillage, minimum tillage, and residue cover (Jin et al. 2010).
6. *Soil temperature*: Soil temperature plays a functional role in maintaining the growth and development of plants. The energy available for heating the soil is determined by the balance between the incoming and outgoing radiations. The soil cover is of fundamental importance to the development of the crop, since it affects the radiation balance due to modifications in thermal conductivities and reflection coefficients and, therefore, interferes in all other energy balance components. Soil temperature, being controlled by this balance (Pezzopane et al. 1996), can present significant changes in relation to traditional harvest practices.

   Soil temperature mainly affects the physiological processes of plants. At Coimbatore, Sundara (1998) noted reduced soil temperature by 2.1 °C under trash cover and creating more favorable environment for crop growth. Gascho et al. (1973) observed that the minimum temperature for cane emergence is about 12 °C and that temperature had a marked effect on the number of stalks, growth, and sugar yield. Soil temperature depends on soil composition, bulk density, and water content in the soil (Jury et al. 1991). In tillage operation, soil-drying rate increases because tillage disturbs the soil surface and increases the air spaces in which evaporation occurs (Licht and Al-Kaisi 2005). During the dry season, lower soil temperature and higher soil water content were observed in conservation agriculture compared with conventional tillage (Edralin et al. 2017). Sidiras and Pavan (1986) observed higher temperatures at the 0.03-m depth for soils prepared conventionally, in relation to minimum tillage and permanent soil cover.

The effects of residues on soil temperature are a complex set of processes that result in less evaporation of water from the soil when it is covered with crop residues (Wilhelm et al. 2004). Tayade et al. (2016) observed that in situ trash mulching conserved soil moisture from 0.70% to 5.92% and buffered soil temperature at 25.1–27.2 °C in the top 5 cm layer of soil, whereas in the control, the daily temperature fluctuation was wider (26.9–34.0 °C). Oliveira et al. (2001) studied the effect of soil surface mulching in sugarcane ratoon crops and observed reduced average soil surface layer temperatures by about 7 °C and 2 °C (Moitinho et al. 2013).

11.4.2 Chemical Properties of Soils

1. *Organic matter:* Soil organic matter (SOM) is one of the most important indicators of the soil quality. Small changes in soil organic carbon (SOC) resulting from changes in soil management are often difficult to measure but have pronounced effects on soil behavior and microbial processes. The increase in soil organic matter in the absence of tillage can transform agricultural soils into C sinks. Most of the time, SOM is depleted because of tillage practices, and depletion percentage is about 16% and 77% (Kumar et al. 2017). Increase in tillage reduces the SOC. However, zero tillage improves the stock of SOC and reduces CO_2 emissions (Dimassi et al. 2014). D'Haene et al. (2009) reported that reduced tillage resulted in a higher stratification of SOC in the soil profile than conventional tillage. Halvorson et al. (2002) found that no-till sequestered substantially more C compared to minimum and conventional tillage.
   Choudhary et al. (2018b) reported that there was a build-up in SOC in 0–15-cm soil layer due to trash retention. They further reported that surface retention of chopped trash improved the SOC content by 5–15% over trash burnt and unfertilized and trash burnt practices. Residue management is the precursor of SOM, mainly associated with increases in SOC. The decrease in SOM due to burning process contributes to a decrease in soil organic C because the loss of C input to soil plays a key role in the global C balance and agricultural productivity. Graham et al. (2002) reported that the increased input of organic matter is due to the increased return of crop residue. The recycling of trash in ratoon sugarcane was useful for conserving SOM with improving soil structure and stimulating sugarcane yield (Yadav et al. 1994). In Australia (Robertson and Thorburn 2007) and in Brazil (Galdos et al. 2009), sugarcane trash management increases soil organic matter significantly. Carvalho et al. (2017) reported that sugarcane straw mulching in the field increases soil C content by 0.19 and 0.09 Mg/ha/year at two study sites. Oliveira et al. (2017) also found 0.11 Mg/ha/year C when sugarcane straw was left on the field.

Crop rotation can influence soil organic C by changing the quantity and quality of organic matter input (Govaerts et al. 2009). Sugarcane crop rotated with legumes, improving soil organic matter significantly. Replacement of sugarcane with legume such as soybean and lablab appears to be an improving sugarcane yield (Didier et al. 2018) and organic C (Bowman et al. 1999). Carbon stored in the soil can help improve soil physical properties such as infiltration rate, water-holding capacity, soil structure, soil aeration, and a host of other physical properties. In addition, C storage can contribute significantly to improving soil nutrient pools and other chemical properties.

2. *Nutrient availability:* The nutrient availability of the soil is significantly influenced by crop rotation, crop residue management, and tillage management. Minimum and/or zero tillage practices change the surface layer, affecting soil nutrients at both the surface and subsurface levels. The nutrient cycle and its stratification are mainly affected by the degree of tillage. Greater stratification of soil nutrients was observed in zero and minimum tillage than in the conventional till systems (Lupwayi et al. 2006). Chen (2014) also noted that minimum tillage in clay-loam soils increased mineralization as compared to no-till, which increased available soil N for increased yields when water was not limited. In the 0- to 2-in. soil layer, soil N and K levels were found to be greater under no-till than conventional till, gradually decreasing to similar levels between tillage systems below this layer (Lupwayi et al. 2006). Larger N contents in the uppermost soil layer with minimum tillage were reported from several researchers at various locations (Unger 1991; Salinas-Garcıia et al. 2002). Du Preez et al. (2001) observed increased levels of K in zero tillage compared to conventional tillage. Due to the accumulation of the nutrients N, P, and K in the uppermost soil layer with minimum tillage, a reduction of fertilization adjusted to the crop needs can be deduced (Spiegel et al. 2007). Understanding the effect of minimum or zero tillage on potential soil aggregation, water storage and soil temperature can help producers select management practices that reduce nutrient loss, conserve water, and maximize yield.
   Crop residues are an important source of nutrients for subsequent crops. The minimum tillage with crop residue covering on soil throughout the year helps to decrease the loss of nitrogen nutrient (Spiegel et al. 2002). The decomposition of crop residue depends on composition of residues (Trinsoutrot et al. 2000). Sugarcane is one of the most trash-producing plants and contains 68% organic matter, 0.42% N, 0.15% P, 0.57% K, 0.48% Ca, and 0.12% Mg, besides 25.7, 2045, 236.4, and 16.8 ppm Zn, Fe, Mn, and Ca, respectively (Shrivastava et al. 1992). Trials conducted in Sao Paulo, Brazil, showed recycling of 85–95% of K, 20% N, 40–60% Ca and Mg, and 11% S and a negligible amount of P from trash in a 12-month period (Ridge 2003). The pre-harvest sugarcane crop burning lost 2600 kg C/ha, 17 kg N/ha, and 1 kg P/ha and postharvest burn of the plant crop residue lost 4800 kg C/ha and 42 kg N/ha; P losses were undetectable in the burn (Ball-Coelho et al. 1993). Significant increases in the total nitrogen content have been measured with increasing additions of crop residue (Graham et al. 2002) and soil health in general (Pankhurst et al. 2003). Sugarcane trash contains about

0.41 kg P per ton of trash (Trivelin et al. 2013), which represents 40% of the P up taken by the crop (Oliveira et al. 2010). Ferreira et al. (2016) verified an average N recovery from sugarcane trash after three crop cycles of 7.6 kg/ha or 16% of the initial N content in trash, representing a limited contribution to crop nutrition (2% of the total N needs) in the short term. However, the long-time maintenance of sugarcane trash promotes a gradual increase in the soil N, reducing N fertilization rates in sugarcane crops (Robertson and Thorburn 2007; Ferreira et al. 2016). Finally, the crop residue left on the soil surface, as a result of less tillage, affects nutrient mineralization and increases the efficiency of fertilizer.

Monocropping of the sugarcane crop leads to the depletion of specific nutrients in the soil. Because of this, crop rotation improves soil fertility by controlling deficient or excess nutrients. Legumes are of special interest in organic crop rotations because of their ability to add nutrient to the system and absorb nutrients that are in abundance. Legumes usually accumulate large quantities of N and K, the nutrients which are taken up in the highest amounts by the sugarcane plants. Different types of legumes add or absorb different nutrients to the soil; therefore, it needs a mix up of a variety of legumes to make them more balanced. Generally, sugarcane crop rotated with soybean, green gram, black gram, sunn hemp, turmeric, etc. Residue incorporation studies of legumes using ^{15}N label indicated 5% N recovery from the sunn hemp by sugarcane (Ambrosano et al. 2005) and ranged from 19% to 21% when the recovery was observed from the sunn hemp by two sugarcane harvests (Ambrosano et al. 2011).

3. *pH*: Soil pH is an important aspect of crop health. It is not a nutrient, but it relates to plant nutrition. Soil pH is so important to plant growth because it determines the availability of almost all essential plant nutrients. Different cultural practices positively and negatively affect soil pH. Tillage and straw managements usually had little to no effect on soil pH in any soil layer (Malhi et al. 2011). Kettler et al. (2000) found that the main effect of plowing on soil pH was more significant for 0–7.5-cm soil depth at both no-till and sub-till treatments. Kumar and Yadav (2005) observed a slight decrease in soil pH than initial values in the conventional tillage. Spiegel et al. (2007) investigated that the soil pH in 0–10 cm was lowest in the minimum tillage. Ball-Coelho et al. (1993) reported that the soil pH in the top 7.5 cm layer did not change after the postharvest burn but increased to 1.1 units in the top 1 cm layer. Aquino et al. (2015) did not showed any significant result of straw mulching on soil pH. However, Antwerpen and Meyer (2002) reported acidification due to trashed treatment and lowered soil pH. One possible way of protecting the soil from acidification is by returning the crop residues to the soil (Miyazawa et al. 1993), and pH increased significantly with crop residue application. The lower pH in zero tillage was attributed to the accumulation of organic matter in the upper few centimeters under the soil (Rhoton 2000), causing increases in the concentration of electrolytes and reduction in pH. Crop rotation also affects soil pH; Shoko and Tagwira (2005) noted that soybean crop rotation sustains the ideal soil pH for sugarcane production in Zimbabwe.

4. *Cation exchange capacity*: Cation exchange capacity (CEC) is a useful indicator of soil fertility because it shows the soil's ability to supply important plant nutrients. The highest CEC is observed in legume-based cropping system, because they increase organic matter in the soil. The increases in SOM content in the surface soil results in an increase in CEC and H^+ saturation of exchange complex (Williams 1980). In conservation agriculture the minimum or zero tillage and crop residue management is responsible for the increase in the level of SOM, which ultimately affects the CEC of the soil. Tarkalson et al. (2006) noted 20% higher CEC in the 0- to 5-cm soil depth under no-tillage than in the conventional tillage practices. Similarly, Mohanty et al. (2015) observed that the adoption of minimum tillage enhanced the CEC of soils. However, Govaerts et al. (2007) did not find any effect of tillage practices and crop on CEC.

11.4.3 Biological Properties of Soils

Soil microbes play an important role in sugarcane-based cropping system; they act as safeguard for sugarcane ratoon productivity and soil health under different environments. In conservation agriculture, reduced tillage, crop residue management, and crop rotation practices sustain number and composition of soil fauna and flora (Andersen 1999). Therefore, measuring microbial biomass is a valuable tool for understanding and predicting the long-term effects of the changes in land use and associated soil conditions. Soil microorganisms play an important role in nutrient recycling, organic matter decomposition, and improving soil quality.

In conservation agriculture zero and minimum tillage systems are known to reduce land degradation through arresting soil erosion and enhancing SOC which sustains soil health (Wood and Lenne 1997). In general, microbial biomass and microbial activity in the soil surface under minimum tillage are significantly greater than those in the conventional tillage. The impact of soil tillage on soil biological health mostly depends on the climatic condition and presence of organic matter. Costantini et al. (1996) reported that zero tillage proved to be more efficient in improving SOC and microbial biomass C. Pankhurst et al. (2002) found that zero tillage with crop residue mulching increased the build-up of organic C and soil biota in the surface soil. No-tillage system can effectively improve soil enzyme activity and provide abundant resources for soil microbe's growth and reproduction (Li et al. 2015) and C sequestration (Martinez et al. 2013). Deng and Tabatabai (1997) investigated the effect of tillage and straw management on enzyme activities in soils and found that most of the enzymes studied were present in significantly greater concentrations in zero tillage than in the conventional tillage systems.

The combination of minimum tillage and trash mulching improves the soil organic matter and soil quality, which ultimately affects soil biota favorably. Several studies conducted around the world have shown that the maintenance of sugarcane trash promotes increases in microbial biomass (Graham and Haynes 2006; Paredes Jr et al. 2015) and microbial community diversity (Liao et al. 2014; Rachid et al. 2016), especially in surface soil layers. These management practices also reduce soil temperature in the topsoil, favoring meso- and microflora proliferations (Sanzano et al. 2009; Digonzelli et al. 2011). Sugarcane trash mulching increases the physiochemical activity of the soil rhizosphere and increases organic matter content in the soil. In situ retention of chopped trash as mulch along with SORF techniques improved the MBC, FDA hydrolysis, and DH activities in the soil by 25%, 21%, and 38% over trash burnt and broadcast application of fertilizers and by 41%, 46%, and 59% over trash removal and N-unfertilized plots, respectively (Choudhary et al. 2018b).

Organic matter is a key factor in maintaining the soil fertility as it is the reservoir of nutrients and provides metabolic energy for biological processes which ultimately affects sugarcane yield. Sugarcane crop residues burned not only reduce SOM but also affect the microbial activity and mobilization of nutrients. Rasmussen et al. (1980) indicated that repeated burning decreased the microbial SOM and microbial activity and nitrogen immobilization (Boerner 1982). Successive sugarcane harvests and crop residue burning significantly influence the microbial populations, with harmful consequences to the C, N, and P cycles, which may decrease crop productivity (Pupin and Nahas 2011).

In the sugarcane-based cropping system, crop rotation with legume plants plays a vital role in the soil biota development. Paungfoo-Lonhienne et al. (2017) noted that sugarcane cropping with either legume substantially increased the abundance of soil bacteria and altered the microbial community composition. In the last few years, legume crop rotation during the fallow period between two consecutive sugarcane crop cycles has been reported to improve soil health and fixate biological N_2 in the soil, thus reducing the use of chemical fertilizer. Rhodes et al. (1982) reported legume rotation for soil improvement in the monocropping sugarcane system. Long-term crop rotations also accumulate more soil C and microbial biomass than monocultures (Tiemann et al. 2015; Venter et al. 2016).

11.5 Challenges in the Adoption of CA in Sugarcane-Based Cropping System

1. During the early stage of crop growth, increased pest and fungal incidences are the major issues in the adoption of conservation agriculture by farmers.
2. Rodent problems have also been noted under sugarcane trash mulching.
3. Difficulties in intercultural operations, sowing of inter crops, and application of fertilizers.
4. Lack of knowledge and technological know-how among farmers about CA technologies.

11.6 Future Perspective

It has been widely demonstrated that conservation agriculture (CA) practices have a significant role in the improvement of soil health and prevention of environmental pollution due to residue burning. Worldwide, CA practices have shown its potential of higher productivity and sustainability, but it has not been widely adopted in semi-arid tropics of India due to the limitations posed by the climate, soil, and socioeconomic conditions. Therefore, there is a need to address issues emerging during its implementation on the farmers' field and devise strong policies for farmers for higher adoption of CA practices. A few possible ways for the adoption of CA practices in sugarcane-based cropping system are mentioned below:

1. The state agriculture department and all ICAR institutes should promote the use of multipurpose machine stubble shaver, off-bar, root-pruner-cum-fertilizer drill (SORF) in CA for the trash management in sugarcane for preventing residue burning causing environmental pollution as well as enhancing soil health. The government agencies may provide subsidies on this machine or promote its use on the community level.
2. The farmers should be promoted to adapt CA by providing support and encouragement in terms of financial help or by honoring them through awards for the protection of the environment and promotion of sustainable agriculture.
3. Research must be carried out for fine-tuning the nutrient management practices for better nutrient prescriptions in the sugarcane-based cropping system under varying levels of residues under CA practices in different agro-ecologies of India.

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Can Conservation Agriculture Deliver Its Benefits in Arid Soils?: An Overview

12

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Abstract

To feed around 9.8 billion people by 2050, it is equally important to increase food production while maintaining the sustainability of the environment. Conservation agriculture (CA) is one of the approaches to manage agro-ecosystems in order to improve productivity, increase the profitability and food security and enhance the resource base and environment. Although many researchers have pointed out the prospects and concerns of adopting CA in different climatic conditions, CA in arid regions raises uncertainties due to its extreme climates, most of the soils with low water holding capacity, high potential evapotranspiration, low and non-uniform distribution of rainfall and greater wind erosion. However, CA practices could benefit the arid agriculture through moderation/reducing of evaporation, regulating water and nutrient in soil and reducing wind erosion. Arid soils, largely characterised by low soil organic carbon (SOC), have the greater potential for higher C sequestration with the use of CA practices. Among the key components of CA, no-tillage (NT) coupled with mulching might be effective in

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distribution of the soil moisture at proper stage of the crop growth. The emission of CO_2 flux from soil and soil salinity are reduced with the adoption of CA in arid soils with the use of cover crops. Due to better aeration and nutrient movement in CA land, beneficial bacterial community and diversity are promoted. However, for CA to work effectively in arid regions, the three components of CA such as minimum disturbances of soil through no- and reduced-tillage, permanent soil cover and crop rotation must be critically followed together or simultaneously for improving soil health, crop productivity through high nutrient and water efficiency, carbon sequestration, mitigation of climate change and sustainability.

Keywords

Aridity · Climate change · Cover crops · Dryland · Salinity

12.1 Conservation Agriculture: Principles and Global Distribution

In order to meet the increasing food demands of an estimated 9.8 billion people by 2050, it is the need of the hour to double the agricultural production from the current rate of production (UN/DESA 2017). Concurrently, the agricultural production is also facing several issues such as climate change, shrinking of cultivable land, resource scarcity and economic volatility. Agriculture is one of the anthropogenic activities that significantly contribute to the modification of physical, chemical and biological characteristics of soil (Kladivko 2001). Among the agricultural practices followed, tillage is the fundamental practice that physically disturbs the soil and alters its soil structure and infiltration rate, thus adversely impacting the soil quality (Kladivko 2001). Although conventional tillage (CT) offers some important short-term benefits such as loosening of surface soil (Kay and Vanden Bygaart 2002), better soil aeration (Da Silva et al. 2004), improved soil water infiltration rate (Pagliai et al. 2004), enhanced mineralization of nutrients (Bruce et al. 1999) and proper root growth (Triplett and Dick 2008), the continuous intensive application of CT may expose the top soil to wind and water erosion (Hand et al. 2016) which led to loss of soil organic matter (SOM) and soil nutrients (Idowu and Grover 2014). However, one of the sustainable technologies being studied and adopted to achieve resilient intensification is conservation agriculture (CA). CA revolves around three management principles: (1) direct planting with no-tillage (NT) or minimum tillage, (2) providing permanent soil cover by cover crops or crop residues and (3) crop rotation (Hobbs et al. 2008; FAO 2011) (Fig. 12.1).

Globally around 12.5% of total world's cultivable land (180 M ha) is practising CA during 2015/2016 (Kassam et al. 2018). Since 2008/2009, there has been an increase of 69% CA adoption rate globally. Every year about 10.5 M ha of cultivable land adopts CA on a worldwide basis since 2008/2009. The largest extent of CA adoption is in South and North America followed by Australia and New Zealand (Fig. 12.2). In Asia, the increase of CA adoption since 2008/2009 till 2015/2016 was

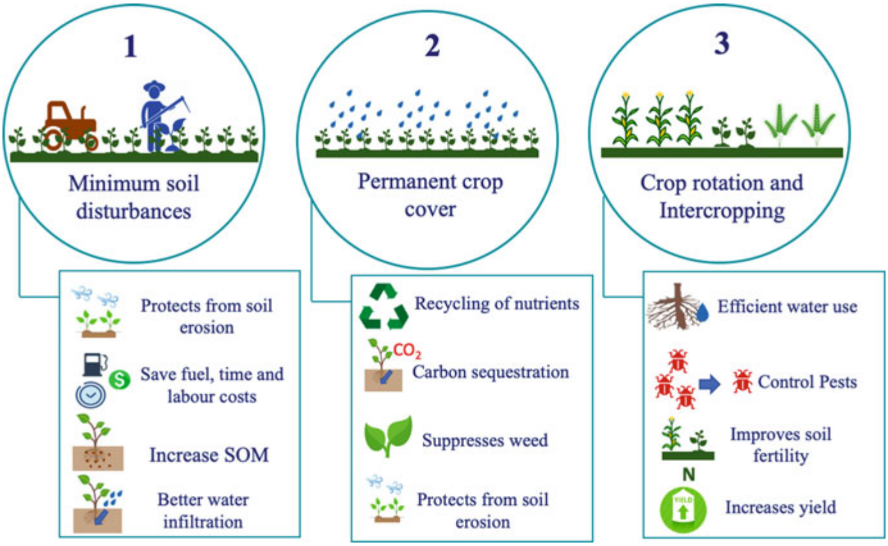

Fig. 12.1 Three management principles of CA. (Graphical diagram constructed from FAO 2011)

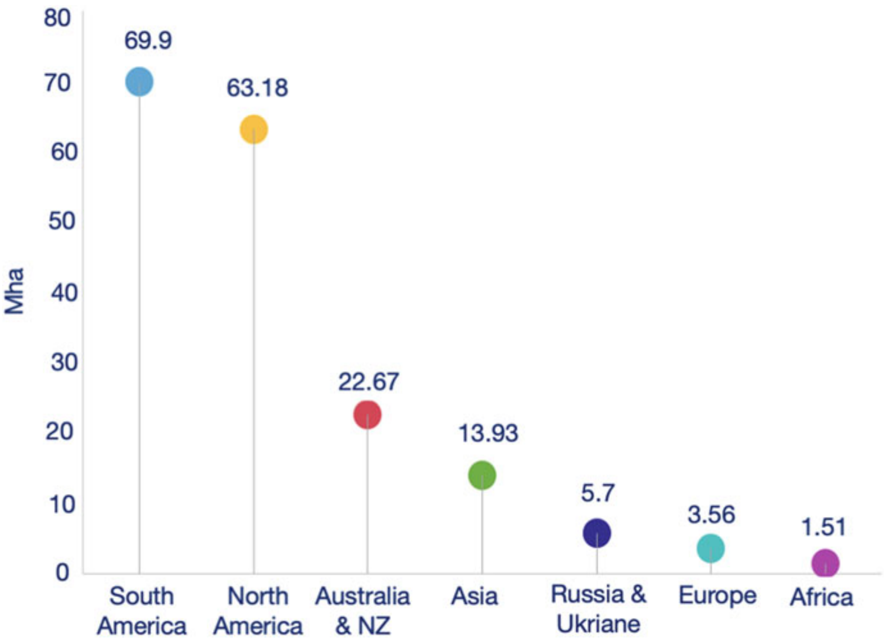

Fig. 12.2 An overview of global distribution of CA practices (the values in M ha represents the total cultivable area under CA in each regions). (Dot plot graph constructed from data given by Kassam et al. 2018)

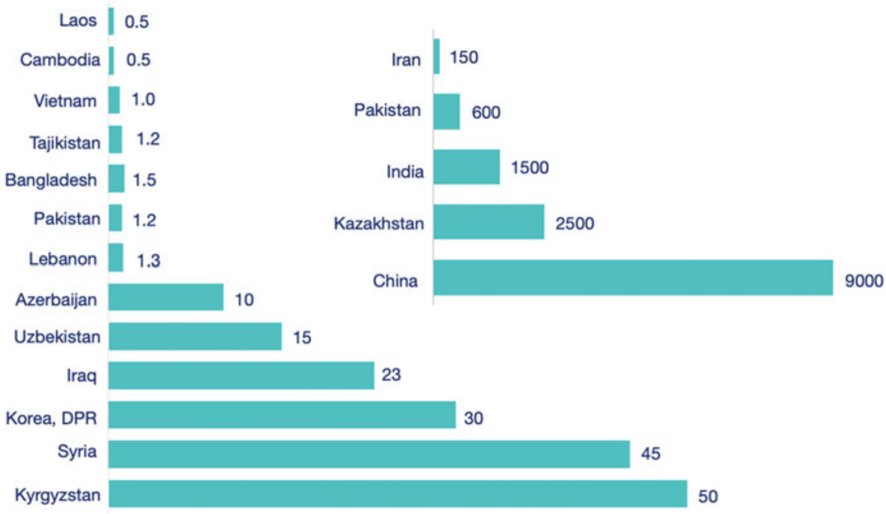

Fig. 12.3 Extent of CA adoption in Asia in 2015/2016 (the values on the right side of each columns represents the area in '000 ha). (Constructed from the data given by Kassam et al. 2018)

more than fourfold (429.7%). Central Asia showed faster development of CA practices in the last decade which has 10.5 M ha of land in Kazakhstan under reduced tillage (Fig. 12.3).

The impacts of NT as a component of CA on crop productivity are often discussed and debated (Hobbs et al. 2008; Giller et al. 2009, 2013; FAO 2011; Rusinamhodzi et al. 2011; Andersson and Giller 2012; Friedrich et al. 2012; Brouder and Gomez-Macpherson 2014; Stevenson et al. 2014). The advantages of adopting CA include improved soil properties, increased yield, conservation of soil and water, reduced weed pressure, reduction in energy consumption and lower production costs as compared to CT (Hobbs et al. 2008; Kassam et al. 2015) (Fig. 12.1). Other researchers have pointed out the possible drawbacks of CA such as yield compromises/penalty at early year's adoption, unavailability of enough crop residues and issues associated with land rights (Erenstein 2002; Giller et al. 2009; Pittelkow et al. 2015). The implementation of various methods of conservation tillage may differ from region to region due to the differences in climate and soil types. However, the main basic goal of such tillage practices is the same which is to reduce the soil disturbance, maintain soil health, provide soil surface cover by crop residue retention/organic mulch and protect from erosion and further degradation.

12.2 Characteristics and Spread of Arid Soils

On the basis of aridity index, four major classes of arid lands are divided, such as hyperarid, arid, semi-arid and dry subhumid (Gaur and Squires 2017). Semi-arid regions are most extensive (15.2% of earth's land surface) followed by arid regions (10.6%), dry subhumid (8.7%) and hyperarid (6.6%) (Fig. 12.4). The challenges frequently faced in arid regions are poor availability of water, limited food, extreme climates, etc. (Gaur and Squires 2017). Therefore, the changing climate will adversely affect both the agriculture and the livelihood sustaining these areas. Arid areas are characterised by high aridity index (more than 70%), extreme temperature and high solar radiation, low and non-uniform distribution of rainfall, low humidity and high wind velocity. Moreover, the soil is sandy type with low water holding capacity, low organic C and deficiency in available nitrogen and phosphorus. Despite these critical points, arid regions play crucial roles in global biophysical processes through reflection and absorption of solar radiation (Ffolliott et al. 2002). These arid areas constitute a large portion of rangeland and cultivable area (Gaur and Squires 2017) (Fig. 12.5). Shortage of water as well as the uneven distribution of available water further restricts the agricultural development in arid regions. Arid regions have limited accumulation of organic C due to hot and arid climate coupled with intensive tillage and irrigation practices. For example, in agricultural soils of California, only 1–1.13% of soil C could be increased from intensive irrigation practices over a time span of 60 years, possibly through the increased crop yield (DeClerck and Singer 2003).

12.3 Prospects of Adopting CA for Grain Production in Arid Land

Sufficient water supply is required for stable production of grain yield. Therefore, water shortage in arid regions threatens the agriculture as the annual precipitation is even lesser than the potential evapotranspiration. For sustainable cereal intensification in arid regions, it is thereby important to improve the water productivity through agronomic management practices. Hence, adoption of NT is a sustainable conservation method that can preserve soil moisture in the profile (Al-Kaisi and Yin 2005; Vita et al. 2007). In 2 years of study (2015–2016) conducted by Guo et al. (2019), over all the growth periods, the average leaf area index (LAI) of wheat was 22.8–28.5% higher in NT with plastic mulching than CT without mulching. Higher LAI was estimated in NT with 20% lesser levels of irrigation and nitrogen than in CT with higher levels of irrigation and nitrogen doses. The LAI of wheat was smaller in the seedling stage than in the jointing stage. During the seedling stage, NT with plastic mulching reduces the soil water evaporation while increasing the soil temperature to optimize the hydrothermal conditions for wheat growth and regulate the crop growth. Both the requirements of water and nutrient resources increase after the jointing stage (Ogola et al. 2002). At this jointing stage, NT improves the availability of soil moisture and nitrogen, thus reducing the negative effects of reduced irrigation

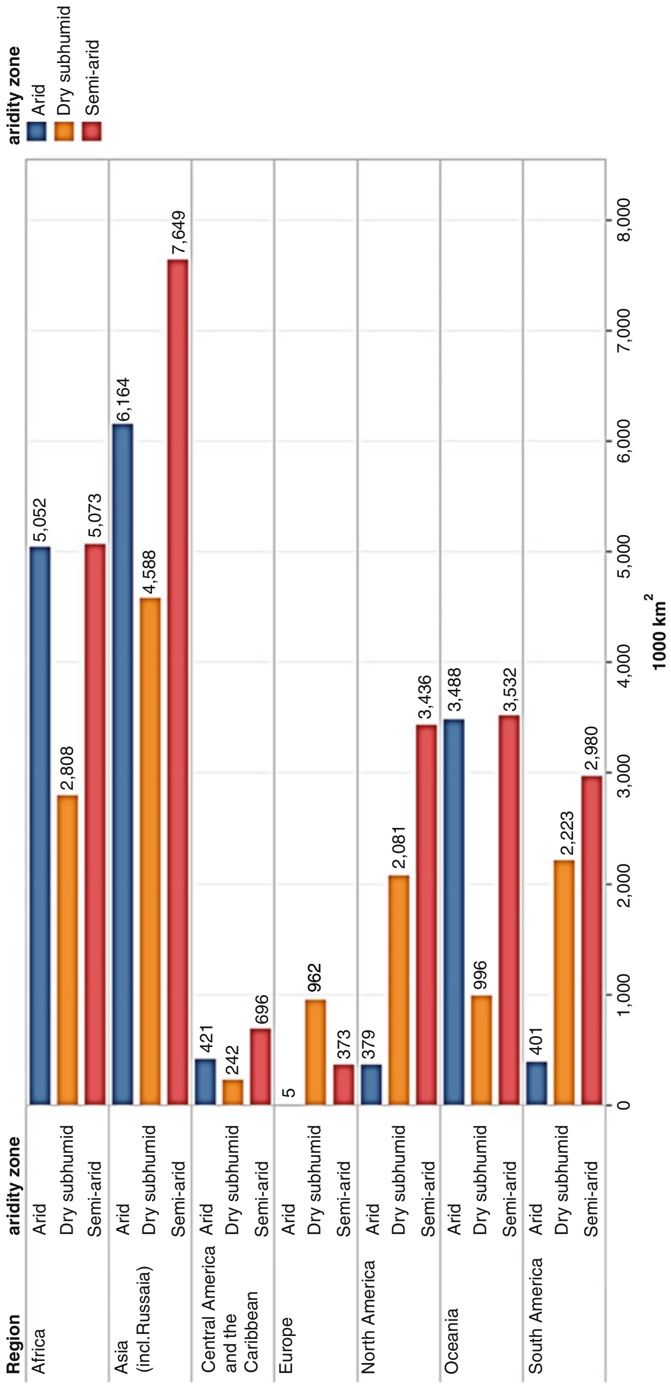

Fig. 12.4 Regional extent of arid soils (the values represent the area under each aridity zone in 1000 km^2). (The bar charts are constructed from the data given by FAO 2008)

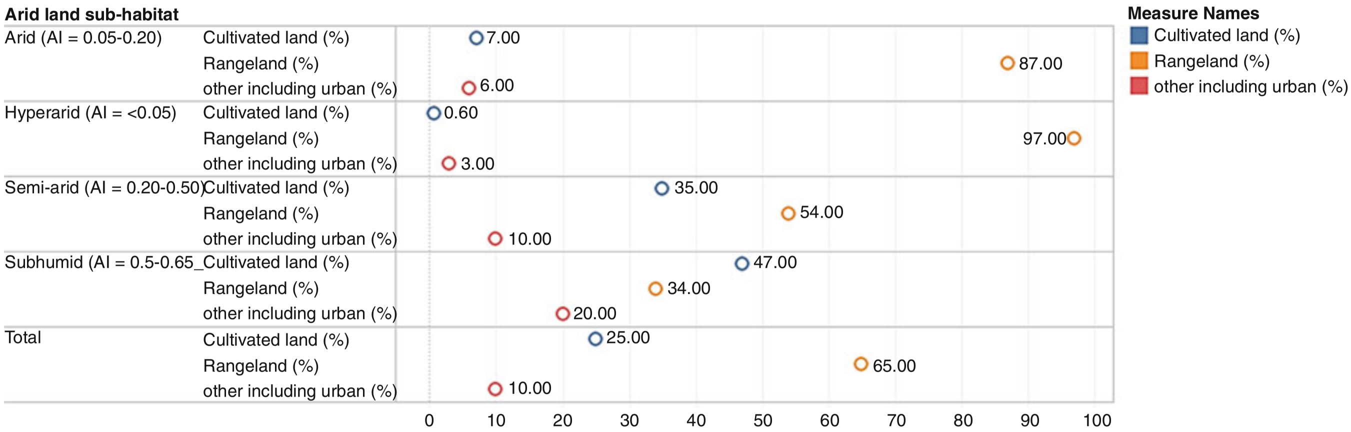

Fig. 12.5 Global distribution of land use systems in different arid regions (data labels are given in percentage; AI refers to aridity index defined by the ratio of precipitation to potential evapotranspiration). (Graph constructed from data given by Safriel and Adeel 2005)

and low N fertilization (Guo et al. 2019). These results indicated that NT not only improved the water use efficiency but also enhanced the nutrient use efficiency in arid soils. Moreover, NT manipulates the crop growing environment to increase grain yield through increase in soil temperature and conservation of soil moisture (Aikins and Afuakwa 2012), thus enhancing crop growth and improving photosynthetic rate.

12.4 Does CA as a Climate Mitigation Strategy Work the Same in Arid Soils?

Soil forms the vital terrestrial pool of C sequestration and can store an estimated global total of 2500 Gt of C which is 3.3 and 4.5 times greater than the C storage capacity of atmosphere and biotic pool, respectively (Lal et al. 2004). However, an estimated total amount of 75 Pg of C is emitted annually to the atmosphere (Andrews 2000) with agriculture contributing a larger portion of CO_2 emission (Lal et al. 2004). One of the common ways of releasing CO_2 from soil to the atmosphere is soil respiration (Raich and Tufekcioglu 2000). The rhizodeposits, crop litter/residue addition, decomposition of soil organic matter and microbial respiration contribute to the CO_2 flux release from soil (Hu et al. 2015). However, soil respiration is an important process in estimating global C cycle and C budget as a small change of soil respiration may significantly affect the CO_2 concentration in the atmosphere (Grace and Rayment 2000; Lal et al. 2004). Continuous tillage practices can cause deterioration of soil structure that affects the stability and further deformation of soil aggregates (Zheng et al. 2018). The excessive soil tillage can accelerate the mineralization rate of SOM that increases CO_2 release into the atmosphere. Increasing CO_2 levels from the agricultural fields not only affect the concentration of greenhouse gases (GHG) in the atmosphere but also have negative impacts on agricultural productivity and sustainability (Quintero and Comerford 2013). Conservation agriculture (CA) is another climate change mitigation strategy that is practised to reduce C emission from agricultural soils to the atmosphere (Gan et al. 2011). Due to the less soil disturbance and improvement of soil organic carbon (SOC) status in CA, it is predicted that lesser CO_2 must be emitted from the soil as compared to the conventional tillage (Boeckx et al. 2011; Fuentes et al. 2011).

In fact, emission of CO_2 from arid soils is dependent on the soil moisture content (Lee et al. 2009). In areas where water availability is extremely low, reduced tillage coupled with residue retention and intercropping could be an effective strategy in conserving soil moisture (Chai et al. 2013; Hu et al. 2015). Crop residue retention on soil surface acts as a barrier against evaporation of soil moisture (Lichter et al. 2008). More C is sequestered in the soil when crop residues are returned to it because crop residues are effective precursors of the SOM pool (Hu et al. 2015). In a field experiment conducted by Hu et al. (2015), reduced tillage (RT) coupled with intercropping and stubble mulching not only increased grain production but also emitted 23% lower CO_2 per hectare per millimetre of water used as compared to CT. An increase of yield of 7.8% in 2011 and 8.1% in 2012 was observed in intercropping under RT with stubble mulching, compared to conventional tillage (CT) (Hu et al. 2015). Similar results were generated in the findings of Fuentes et al. (2011), Shaver et al. (2002) and Ussiri and Lal (2009) where NT with residue retention also stored a greater amount of soil water than CT with or without residue retention.

High levels of CO_2 emissions from CT have been widely reported by several authors (Al-Kaisi and Yin 2005; Bauer et al. 2006; Sainju et al. 2008; Reeves et al. 2019). Alluvione et al. (2009) surveyed the land under tillage and reported 14% higher CO_2 emissions than NT land. Similarly, Ussiri and Lal (2009) calculated 11.3% higher CO_2 emission in CT as compared to NT soils. The differences in CO_2 emission can reach up to 58% higher in CT as recorded by Al-Kaisi and Yin (2005). However, some studies found no significant gap of CO_2 emissions between tilled and NT soil (Aslam et al. 2000; Oorts et al. 2007; Li et al. 2010).

The uncertainties in this aspect are even larger as few studies have depicted higher CO_2 emissions in NT treatments than CT (Hendrix et al. 1988; Oorts et al. 2007; Cheng-Fang et al. 2012). The increase in C emission in conservation tillage practice might be attributed to the increased decomposition of the crop residues on the soil surface (Oorts et al. 2007) which may be higher in arid regions. Another controlling factor of the C efflux difference between tillage and NT is the type of crop and the mode of crop rotation followed in arid areas because differences in root biomass and root respiration also affect CO_2 emission (Amos et al. 2005; Álvaro-Fuentes et al. 2008). Under continuous maize cultivation, the difference in CO_2 output may reach up to 16% between tilled and NT lands (Omonode et al. 2007). On the other hand, under continuous barley and barley-pea rotations, no difference in CO_2 efflux could be found (Sainju et al. 2010). In arid areas, microclimatic parameters such as soil temperature are high and precipitation is less and thus strongly control the response of soil CO_2 release under different tillage practices (Flanagan and Johnson 2005; Oorts et al. 2007).

Abdalla et al. (2016) carried out a meta-analysis study to quantitatively synthesize the findings in respect to CO_2 emissions in CA. The effects of background climate such as arid to humid and different soil textures, crop types, experimental duration, mode of fertilization and crop residue management were considered in the meta-analysis using 174 paired observations around the world (Abdalla et al. 2016). In general, soil CO_2 emissions from conventional tilled (CT) soils (1152 g CO_2-C m^{-2} $year^{-1}$) were higher than no-tilled (NT) soils (916 g C-CO m^{-2} $year^{-1}$), corresponding to 21% difference in CO_2 emissions between the treatments. The maximum value was found in the arid region of the USA with barley under CT soils (Sainju et al. 2008) and the minimum in humid regions of Lithuania with wheat under NT soils (Feiziene et al. 2011).

The increase in aridity might also significantly increase emissions of CO_2 from soils. Under arid climates, CT emitted 27% higher CO_2 than NT, whereas the difference is lesser in humid areas (16% difference) (Abdalla et al. 2016). The response of soils to tillage is significantly affected by climate thresholds (Franzluebbers and Arshad 1996). The smaller difference in soil CO_2 efflux between the CT and NT plots under humid conditions might be due to higher decomposition rates favoured by higher soil moisture content. This also explains the reason for larger gap in arid conditions (Fortin et al. 1996; Feiziene et al. 2011).

12.5 CA in Arid Soil with Limited SOC

Indeed, CT practices have lessened SOC stocks by two-thirds from the pre-deforestation levels (Lal 2003). Due to the soil disturbances and breakdown of soil aggregates, SOC in the soil is exposed to microbial decomposition, and thus C is lost through CO_2 emissions and leaching (Six et al. 2004). It is also known to increase soil compaction and soil erosion and negatively affect the soil microbial activity (Wilson et al. 2004). Tola et al. (2019) conducted a field study using GIS techniques to understand the effects of excessive tillage on the long-term changes in SOC content (1990–2016) in hyper-arid regions of Saudi Arabia. It was proved that the change in SOC content was significantly affected with soil tillage practices. As a result of conventional tillage (CT) practices, 76% of the agricultural fields showed a decrease of SOC content (up to 24 g kg^{-1}) during 1990–2000. On the other hand, conservation tillage increased the SOC content at the rate of 4–55% in about 67% of the studied fields (Tola et al. 2019). Similar reports of improvement in SOC content with the adoption of conservation tillage were shown by Dikgwatlhe et al. (2014), Haddaway et al. (2017), Yeboah et al. (2016), Hernanz et al. (2002) and Choudhury et al. (2014).

12.6 Cover Crops as a Component of CA in Arid Soil

In order to understand the soil quality, estimation of soil C is a crucial part, which can influence a variety of soil functions. The challenges of increasing organic C in arid soils can also be achieved through crop residue inputs, especially from cover crops (Mitchell et al. 2015). Above all, the use of cover crops delivers a myriad of ecosystem services including more productive soil, increased water and nutrient use efficiency, reduced pest infestation and disease occurrence (Follett 2001; Alcantara et al. 2011; Ruiz-Colmenero et al. 2011; Schipanski et al. 2014). Mitchell et al. (2017) studied the effects of NT and cover cropping practices on soil properties in an arid irrigated cropping system in California. After 15 years of establishment of the experiment, both NT and cover cropping practices, which are the important components of CA, significantly improved the soil properties such as soil aggregation, water infiltration rate and organic C and N as well as biological activities. The effects varied with soil depth and seasonal change, with higher values on surface layers (0–15 cm) than deeper layers (15–30 cm) and higher values from the samples collected during the fall than spring season.

The benefits delivered through reduced tillage with cover cropping and their associated costs are agronomic dependent (Schmidt et al. 2018). Cover crops are studied for their benefits in improving crop yield stability (Franzluebbers 2010; Williams et al. 2016), reducing erosion, increasing soil microbial biomass, reducing weed density and preventing excess nutrient leaching into groundwater (Teasdale 2003; Navarro-Noya et al. 2013; Poeplau and Don 2015; Kong et al. 2011). Despite all these ecosystem services, cover crops can also increase the financial and management costs (Giller et al. 2015). It may also lead to the competition of water available for subsequent crops in drier climates where availability of good quality irrigation water is a big challenge (Mitchell et al. 2015). In drier climatic conditions, timely planting of the following crops may be affected if the decomposition of the cover crops are not rapid enough (Mitchell et al. 2017). Similarly, although NT can save the fuel and energy costs, improve soil aggregation, increase SOM, enhance water infiltration and reduce soil erosion (Six et al. 1999; Mitchell et al. 2015; Wang et al. 2016), the need for closer monitoring, heavy use of herbicides for weed management and specialized planting equipment may increase the costs, on the other hand (Buhler 1995; Smith et al. 2011; Kirkegaard et al. 2014; Giller et al. 2015; Pittelkow et al. 2015).

12.7 Effects of Adopting CA on Arid Soil Biology

The soil microbiota that plays prominent roles in the ecological processes are also affected directly or indirectly with the type and intensity of tillage practices, thus influencing the soil productivity and crop growth and development (Roger-Estrade et al. 2010). The direct effect of tillage on soil structure is one of the prime factors that alters the soil microbial diversity and abundance as the difference in soil structure regulates soil air and water movement and content (Brussaard et al. 2007). The question to how does the conservation tillage affects SOC and modifies the soil microbial community and structure (Ceja-Navarro et al. 2010; Pastorelli et al. 2013), are extensively studied. Conservation tillage has a strong correlation with soil clay content through its effect on soil moisture retention (Prakash et al. 2010; Wang et al. 2016). NT systems can significantly increase SOC content through its alteration of soil aggregates mediated by clay-size particles and leading to C sequestration in soil (Neumann et al. 2013). In a 5-year study, Wang et al. (2016) compared the changes in soil microbial diversity and abundance in conservation tillage practices in dryland areas. The Simpson index (a measure of microbial diversity in soil) in conservation tillage treatments was 378% higher than the conventional plots, indicating its positive influence in modification of soil bacterial diversity. In a nutshell, conservation tillage in dryland soils increased the abundance of beneficial functional bacterial species including *Bacillus*. Similarly, the relative increase of *Firmicutes* was also found in conservation tillage practices (Navarro-Noya et al. 2013). The increased abundance of beneficial bacteria in dryland soils under CA may be attributed to better ventilation and nutrient status in conservation tillage plots as compared to the CT practices (Wang et al. 2016). Soil texture is another principal factor that greatly affects the composition of bacterial communities (Bach et al. 2010; Carson et al. 2010). The results of Wang et al. (2016) showed the favourable change in soil texture with the adoption of conservation tillage in dryland soils that positively influence the soil microbial communities such as *Alphaproteo bacteria/Rhizobiales* and *Firmicutes/Bacillus*.

12.8 CA Effects on Soil Salinity

Soil salinity is one of the serious issues in agriculture, affecting around 20% of world's cultivated area and 50% of irrigated croplands (Zhu 2001; Zhang et al. 2007). Arid regions that mostly depend on irrigation for agricultural purposes are most vulnerable to increasing soil salinity (Brady and Weil 2008). Saline soils cover an area of 932.2 M ha (Rengasamy 2006) in at least 100 countries (Qadir et al. 2006), with a high concentration in countries such as Pakistan, China, India, Sudan, Central Asian Countries, etc. (Ghassemi et al. 1995). The losses of agricultural sector could reach as high as 27.3 million US dollars due to increasing salinization and decreasing productivity (Qadir et al. 2006). It is also estimated that every minute about 3 ha area of arable land turns unproductive due to secondary salinization (Bridges and Oldeman 1999).

In arid areas where potential evapotranspiration exceeds precipitation, enough rainfall doesn't exist to leach down the salts formed in the surface, and when it is irrigated with saline water, more salts tend to accumulate in the soil, causing secondary salinization (Devkota et al. 2015). Soil salinity affects the sustainability of arid agriculture (Dong et al. 2008; Cuevas et al. 2019). Devkota et al. (2015) compared the effects of conservation tillage on salinity and CT. Conservation tillage could effectively reduce salinity only when crop residue is retained in the soil. With crop residue retention, salinity could be reduced by 32% in 0–10 cm surface soil (Devkota et al. 2015). Cuevas et al. (2019) conducted a meta-analysis of 128 paired soil quality and yield data and compared the effectiveness of soil improving cropping systems that can cope with increasing salinization. They highlighted that CA can be a promising practice that can achieve higher yields in salt-affected areas.

Maintenance of permanent soil cover in soil surface is one of the primary components of CA, revealing its high importance in arid areas by reducing soil evaporation and loss of soil moisture (Forkutsa et al. 2009). The residue layer in the soil surface is likely to decrease the secondary soil salinization in several areas (Forkutsa et al. 2009). A significant decrease in salt content in 0–40 cm of top soil was observed with the use of straw mulching (Pang et al. 2010) through regulation of salt vertical movement and reducing the salt damage to the crops. NT and use of cover crops in dryland areas could significantly reduce soil salinity even in soils of low hydraulic conductivity (Mendes and Carvalho 2009).

12.9 Suitability and Challenges of CA in Arid Soils

Laborde et al. (2020) applied machine-learning techniques using a collection of published data on CA to create a predictive model of the agronomic outcome of CA as compared to conventional ploughing (CP). It was concluded that precipitation amount or aridity index alone could not predict accurately the increase of yield in CA as compared to CP. Other drivers such as climate, soil types, geographic patterns and management variables might influence the over yielding effect significantly. In addition, with the increase in mean air temperature from 20 °C and long duration of adopting CA up to 13 years, the success probability of CA increased (Laborde et al. 2020). Predictive maps of CA: CP outcomes for rainfed wheat, maize and soybean showed that, given good plant establishment, humid tropics and sub-tropics are the hotspots where the potential of CA to increase system productivity is higher (Laborde et al. 2020).

Through a meta-analysis study conducted by Pittelkow et al. (2015), NT system could negatively reduce crop yields by −5.7% rather than enhancing global crop production. However, in order to implement NT for its benefits, the other management principles of CA also need to be followed to represent a more profitable system. They further determined the maximum decline in crop yield (−29.9%) under NT system without soil cover and crop rotation as compared to CT. However, with the inclusion of other components, the ill effects could be minimized, and the yield gap could be shortened, suggesting that NT must be implemented where crop rotation is followed and permanent soil cover is provided. The meta-analysis study also synthesized that in dry areas, NT significantly increased crop yields (7.3%) under rainfed agriculture when the other two conservation principles are also adopted. This yield benefit of CA in drier climates could be explained by improved water infiltration and greater soil moisture conservation in dry soils (Hobbs et al. 2008; Serraj and Siddique 2012). In irrigated conditions, when water is not a limiting factor, dry areas might exhibit similar crop yields between conservation tillage and CT (Pittelkow et al. 2015). Therefore, CA could be a promising sustainable intensification effort that can provide agronomic benefits to the water-stressed dry regions.

Crop residues are widely used as livestock feed or biofuel production (Wilhelm 2004; Naudin et al. 2012). In arid regions, as the vegetation biomass are relatively lower, the competition of crop residues for use as mulch or livestock feed arises often (Ranaivoson et al. 2017) which might affect the adoption of CA in arid areas.

On the other hand, crop residues when retained as mulch in arid regions could be beneficial as it limits soil water evaporation and soil crusting, increasing soil water infiltration (Scopel et al. 2004; Gangwar et al. 2006). Apart from the conservation of soil moisture, it will also physically protect the soil from water runoff and reduce the risks of wind erosion which is prevalent in arid regions (Bertol et al. 2007; Lal 2009). The decomposition of crop residues will influence the nutrient cycling in soil and increase nutrient availability to the crops grown (Turmel et al. 2014). Other ecosystem services such as carbon storage (Corbeels et al. 2006), reducing greenhouse gas emission, reduction of weed infestation (Teasdale and Mohler 2000) and increase in soil biological activity (Liu et al. 2016) are the advantages of maintaining crop residue in the soil. Swanson and Wilhelm (1996) observed a low rate or delay in germination and reduced crop growth when high quantities of crop residues are retained in the soil under cool and humid climates.

12.10 A Rotation System of Tillage for Arid Soils

CA is a form of sustainable agriculture of great significance. Soil physical properties such as reduction in soil bulk density and high soil porosity could be further improved when regular soil tillage is followed after no tillage (Pierce et al. 1994). Compared with continuous NT and subsoiling, no tillage and subsoiling coupled with rotation tillage were more effective in enhancing soil physical properties (Carter et al. 2002) and chemical properties (López-Fando et al. 2007). In dryland areas, in order to increase the yield and quality of crops, increase the water storage capacity and fertility of soil, it is also important to reduce the threats of wind erosion in the cultivated land (Yin et al. 2000; Lajpat et al. 2006). Conservation tillage is often studied for its higher yield and grain productivity (Liu et al. 2004). However, continuous use of conservation tillage may affect the soil negatively depending on the soils and natural conditions (Liu et al. 2010). The long-term adoption of NT might turn the soil more compact in the surface layer and increase the bulk density, thus affecting the germination of seeds, proliferation of crop root and absorption and movement of soil water and nutrients (Liu et al. 2010). To explore the most suitable long-term tillage practices for the production of maize in arid loess regions of China, Li et al. (2020) conducted an experiment from 2013 to 2018 with different modes of tillage practices. It was found that NT/subsoiling model was the best rotational tillage practice for maize cultivation in arid loess soils. Therefore, in stressed areas like dryland soils, implementation of soil rotation measures such as conventional tillage, NT and subsoiling in a timely manner might be more effective to solve the problems of long-term continuous use of a tillage practice (He et al. 2006; Sun et al. 2010).

12.11 Conclusions

In order to make CA successful in the drier areas, an innovative, multi-stakeholder driven approach must be implemented to adjust to the local conditions. This approach must be sensitive to market opportunities, equipment's availability and farmers' production needs. Reduction in soil disturbance in CA practices along with residue retention increased soil aggregation that further affects the emission of CO_2, soil evaporation, enrichment of SOC, etc. which is relatively more important in arid soils. CA can be a promising system for obtaining higher productivity in arid soils, given the crop residues are available in enough quantity. In the long run, CA, when managed properly with three management principles, can be adapted to a wide range of environments and beneficial in maintaining food security while mitigating the climate change. Further, economic and scientific research can be conducted in rainfed agriculture of arid areas to obtain a vivid picture of suitability of CA in arid areas.

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Conservation Agriculture: Carbon Turnover and Carbon Sequestration for Enhancing Soil Sustainability and Mitigation of Climate Change

13

Somasundaram Jayaraman and Ram C. Dalal

Abstract

Conservation agriculture (CA) practices have emerged as a sustainable production system in improving SOC and soil attributes, reducing soil erosion and also reverting land degradation. Worldwide the area under CA has been rapidly increasing due to its multiple benefits. CA practices, which consist of minimum soil disturbances, crop residue retention and crop diversification, have shown a positive effect on soil properties and crop productivity. However, optimum nitrogen management is found to be a key promising practice in CA to reduce greenhouse gases, especially N_2O emissions, and, therefore, an effective option for climate change mitigation. Similarly, crop rotations/crop diversity in CA system had a significant positive effect on carbon (C) sequestration through greater crop residue retention and root biomass in soil. In this chapter, we address various aspects of no-till practices, crop residue and nutrition management on carbon sequestration and climate change mitigation. We conclude that optimum N management in conservation agriculture is the key to maintaining/increasing SOC stocks, reducing net greenhouse gas emissions and sustaining food production.

Keywords

Conservation agriculture · Soil organic carbon · Carbon turnover · Carbon sequestration · Soil sustainability · Climate change mitigation

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13.1 Introduction

Due to inappropriate management practices such as intensive tillage, residue burning, and low organic input addition to soil has led to decline in soil organic carbon (SOC) and deterioration of soil health. Thus, conservation agriculture (CA) practices have emerged as a sustainable production system, which not only improves SOC and other soil properties but also reverts land degradation (Amundson et al. 2015). The area under CA has rapidly increased from 38 million ha (M ha) during 1996–1997 to 180 M ha during 2017–2018 (Kassam et al. 2018). Conservation agriculture consists of three principal components: minimum or no-till (NT), permanent soil cover with crop/plant residue retention (stubble retention (SR)), and crop rotation and intercropping (FAO 2014; Dalal et al. 2011a). All of these components affect organic carbon (C) turnover and storage in soil since crop/plant residues provide C input, crop rotations affect microbial community structure and C substrates, and no-till minimises soil disturbance, which affects soil organic C (SOC) sequestration (Dalal et al. 2011a; Luo et al. 2010). However, it is essential to provide realistic estimates of SOC sequestration following conservation agricultural (CA) practices (Chenu et al. 2019) since these estimates vary widely in the published literature. Moreover, SOC sequestration does not always lead to mitigation of climate change by adopting CA unless negative greenhouse balance is achieved, and that requires consideration of all major greenhouse gases, CO_2, N_2O and CH_4, as well as energy inputs (fossil fuel, agrochemicals including pesticides, transport), for food production (Wang et al. 2011; Wang and Dalal 2015; Kopittke et al. 2017).

13.2 Soil Organic Carbon Turnover

Of late, climate change has necessitated greater interest and attracted global attention on soil C studies and sequestration of atmospheric CO_2 through agricultural management practices for mitigating climate change and reducing greenhouse gas emissions (Dalal et al. 2003, 2008). Moreover, soil organic C (SOC) turnover is affected by both environmental and edaphic factors (Conrad et al. 2017, 2018). Environmental factors include temperature and precipitation (moisture). Climate change has introduced additional factors such as enhanced CO_2 fertilisation and indirectly increased atmospheric N deposition due mainly to the need for increase in N fertiliser use for increasing food production (Kopittke et al. 2019). These factors affect not only the photosynthate C input but also C turnover in soil. Edaphic factors include soil pH, texture and mineralogy and soil management including N fertilisation.

The rate of soil organic C mineralisation increases by a factor of 2 for every 10 °C increase in temperature (also termed 'Q_{10}'). However, the Q_{10} value varies depending on the decomposability of the organic C. The Q_{10} value is close to two for the labile or easily mineralisable organic C and greater than two, often up to three, for relatively slowly mineralisable, resistant fraction of organic C (Davidson et al. 2006). The NT soil contains more labile organic C than the conventionally tilled (CT) soil (Six et al. 2002); therefore, there is likely to be more organic C mineralisation in soil from the former. However, NT soil is generally cooler than CT soil due to the reflectance of radiation by the surface residues (the albedo effect). On balance, however, organic C mineralisation is similar in the soil under both NT and CT practices (Reeves et al. 2019; Page et al. 2013).

13.3 Carbon Sequestration

13.3.1 Soil Management: No-Till

The effect of no-till on SOC stocks varies from region to region depending on precipitation (Alvarez 2005; Dalal and Chan 2001). Generally, in drier semi-arid regions, the increase in SOC stocks following no-till practice is small. For example, Liebig et al. (2009) reported the effects of NT on soil organic C in dryland cropping systems of the U.S. Great Plains. They found that SOC increases were modest, from -0.05 to 0.12 Mg C ha^{-1} year^{-1}, possibly from low C inputs and productivity due to low precipitation. In sub-humid and humid environments, especially from high productivity and C inputs, SOC increase is generally higher, up to 0.4 Mg C ha^{-1} year^{-1} (Bayer et al. 2006). It has been estimated that adopting NT practice can potentially sequester C at rates of 300–600 kg C ha^{-1} year^{-1} in the USA (Lal et al. 1998). Similarly, Watson et al. (2004) reported the same range of estimate (200–400 kg C ha^{-1} year^{-1}) under CA practices for Australia, the USA and Canada. Soil aggregation offers a great deal of physical protection of soil C (Dalal and Bridge 1996; Somasundaram et al. 2017). The increased or protected SOC is generally located in micro-aggregates occluded within macro-aggregates, primarily due to the avoidance of soil disturbance under NT practice (Six et al. 2000; Du et al. 2015; Conrad et al. 2018). It was also observed that the low positive increase in soil organic C due to NT in other drier areas was possibly due to many factors such as low crop yield, less residue addition due to partial removal of stubble by grazing and high rate of decomposition due to higher temperature (Dalal and Chan 2001). Dalal et al. (1995) reported that the soil organic C level continues to decline even under NT in continuous cropping system in the drier areas.

13.3.2 Crop Residue Management

Various residue management practices such as residue burning, removal and incorporation/retention have significant impact on soil health and soil organic carbon (SOC). Among these practices, residue removal led to a relative C loss from the soil, a decrease in C input, and reduced nutrient availability and microbial activities (Chowdhury et al. 2015). On the other hand, crop residue retention accompanied by NT practice provides C input, protects the soil surface against soil erosion (Anderson 2009) and aggregate disruption, increases infiltration and water storage and creates/maintains favourable microbial habitat, thereby increasing SOC turnover

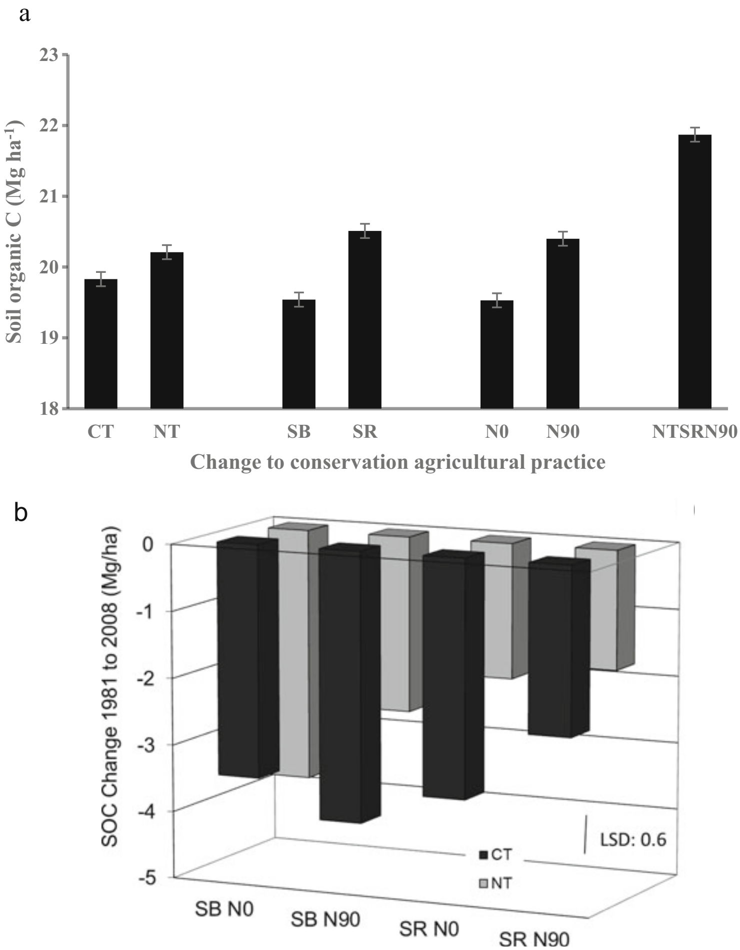

Fig. 13.1 Effect of 40 years (1968–2008) of conservation agricultural practice on soil organic C (SOC) stocks (figure drawn from Dalal et al. 2011a, b) (**a**), and (**b**) changes in SOC stocks from 1981 to 2008 under conservation agricultural practice (from Page et al. 2013). Note the decrease in SOC stocks during this period but less under the NT and stubble retained (SR) than conventional till (CT) and stubble burnt (SB) practice

and potentially SOC stocks in the long term (Dalal et al. 2011a; Page et al. 2019) (Figs. 13.1 and 13.2). Campbell et al. (2001) reported that the increase in SOC stocks was closely related to the amount of crop residue returned to the soil. However, no consistent increase in SOC from crop residue retention under NT practice has been observed in cereal cropping (Page et al. 2013; Ghimire et al. 2017) and sugarcane cropping systems (Page et al. 2013). It appears that the C:N ratio of the added crop residue affects whether the C will be accumulated in SOC or respired to the

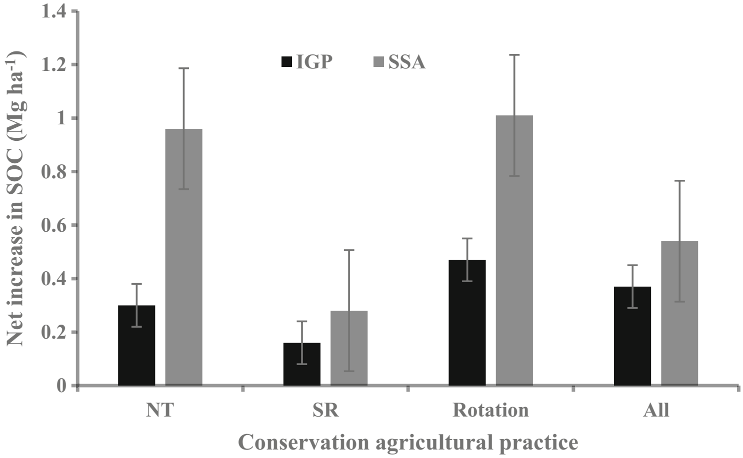

Fig. 13.2 Effect of conservation agricultural practices on the net increase in soil organic C (SOC) after 9–16 years. (Figure drawn from the data of Powlson et al. 2016)

atmosphere (Finn et al. 2016). Finn et al. (2016) found that added N increased the C retention from wheat crop residue into a relatively stable (humus) SOC fraction.

13.3.3 Crop Nutrition Management

13.3.3.1 Fertiliser Management

Nitrogen fertilisation of N-responsive crops grown on soils practising conservation agriculture increases crop yields and potentially increases C inputs to the soils (Paustian et al. 1997; Dalal et al. 2011a) (Fig. 13.1). If the soil is deficient in other nutrients, then the application of balanced fertilisers such as NPK is also required to increase/maintain yields and SOC stocks in soil. For example, Manna et al. (2005) found that SOC stocks in rice-based cropping systems were maintained only when NPK and NPK + FYM were applied although in their field trials >90% of the stubble was removed. The effects of N fertilisation on the increase in SOC stocks are due to the increase in C inputs (stubble and root residue), reduced soil microbial respiration, and reduced positive priming effect. This alters microbial community, creates new sorption sites on mineral surfaces, and stabilises newly formed SOC (Knorr et al. 2005; Ramirez et al. 2010, 2012; Finn et al. 2016; Kopittke et al. 2018; Treseder et al. 2018).

13.3.3.2 Organic Amendments

Organic amendments such as manure application provide stabilised C (and nutrients) to the soil (Rasool et al. 2008). Organic manure provides stabilised C, largely microbial biomass C, because most of the labile C has already been mineralised and lost as CO_2 emission to the atmosphere during the composting process. Most studies show a positive SOC balance after manure application (Zhang et al. 2013; Bhattacharyya et al. 2007) although net SOC sequestration is rarely achieved since it replaces the original plant residues C removed as animal feed or fuel from the soil (Powlson et al. 2011).

13.3.3.3 Soil Amelioration: Salinity, Sodicity and Acidity

Crop production and crop yields are adversely affected by soil salinity, sodicity and acidity. This is due to unfavourable conditions for root growth (e.g. osmotic pressure due to salinity, poor structure due to sodicity, Al toxicity due to acidity and imbalance of essential nutrients due to sodicity and acidity), leading to low crop biomass and hence low C inputs to the affected soil (Sharma and Chaudhari 2012). Moreover, soil microbial biomass is stressed due to adverse conditions, and hence, SOC stocks remain low (Dalal et al. 2011b). As a result, many saline-sodic soils have low SOC stocks (Wong et al. 2010). Remediation of saline-sodic soils using gypsum, organic materials, crop rotation, crop diversity and their combinations results in increased plant productivity (Sharma and Chaudhari 2012) and, therefore, likely leads to increased SOC stocks. Remediation of acidic soils by lime application reduces Al toxicity and increased nutrient availability and increased soil organic matter mineralisation and usually, but not always, results in the net increase of SOC stocks (Paradelo et al. 2015). However, strategic tillage is required in NT system to incorporate soil ameliorants including gypsum, lime and manures to remediate soil constraints due to salinity, sodicity and/or acidity (Dang et al. 2015; Sharma et al. 2009).

13.3.4 Crop Rotation/Diversification/Intensification

Crop rotation, diversification and especially intensification provides crop residues of varying quality as well as increasing C input to the soil. Nitrogen addition through fertilisers and legumes in an intensified cropping system using CA practice creates a favourable condition in terms of C and N substrates for organic matter turnover and C stabilised in SOC, leading to increased amounts of SOC (Halvorson et al. 2002). For example, Samal et al. (2017) observed that crop intensification from rice-wheat to rice-wheat-cowpea increased SOC stock by 0.4 t C ha^{-1} year^{-1} over a period of 7 years. However, further increase in the crop intensification and rice-potato-maize-cowpea for 4 years had similar SOC stock as the rice-wheat cropping system, possibly because of soil disturbance (tillage) during the potato harvest. Similarly, soil organic C at 0–10 cm depth increased by 83% and 72% (from a low base, 0.47%) after 3 years in rice-wheat-mung bean and rice-maize-mung bean farming systems, respectively, under CA than CT due to higher system yields and higher C inputs from the retention of crop residues (Choudhary et al. 2018). Even including a legume as a catch crop (hairy vetch, *Vicia villosa* Roth, for the first 4 years, and red clover, *Trifolium pratense* L., for the next 2 years) in an NT system increased soil organic C from 1.08% to 1.15% in Ap horizon after 6 years in maize-soybean-wheat rotation system (Bhardwaj et al. 2011). Legume cover crops under NT favour the formation of organo-mineral association in micro-aggregates and thereby enhance SOC stocks (Veloso et al. 2019). As observed by Kopittke et al. (2018), microbial N-rich products from the legume crop turnover are sorbed on new mineral sites for further SOC sequestration on these sites.

13.4 Mitigation of Climate Change

For conservation agricultural practices to mitigate climate change from food production, the reduction of net greenhouse gas emissions, including emissions from soil as CO_2 (or net SOC change between the monitoring period), N_2O and CH_4, as well as from energy inputs (CO_2-e) from fossil fuel (diesel, petroleum products, agrochemicals) use, is required. Adopting life-cycle assessment methodology, Wang and Dalal (2015) calculated that annual greenhouse gas emissions were 200 kg CO_2-e ha^{-1} from NT and 364 kg CO_2-e ha^{-1} with 70 kg N ha^{-1} $year^{-1}$ as urea over a period of 40 years of CA in sub-tropical Australia. Therefore, the NT practice resulted in reducing greenhouse gas emissions to the atmosphere, thus reducing the footprint on climate change.

13.5 Perspectives

Powlson et al. (2016) examined the effect of CA practices in the Indo-Ganga Plains and sub-Saharan Africa on C sequestration and concluded that in the experimental plots there was a small increase in soil organic C although it may not be measurable on farmers' fields due to variability in practices, spatial variability and socio-economic constraints. Therefore, climate change mitigation from NT and residue retention is likely to be minor. However, there appears to be a significant interaction between NT, SR and N fertilisation since majority (60–95%) of greenhouse gas emissions (as N_2O) occur from N fertilisation. Therefore, as suggested by Wang and Dalal (2015), optimum nitrogen management is likely to be a more promising practice in CA to reduce greenhouse gases, especially N_2O emissions, and, therefore, an effective option for climate change mitigation. The effect of crop rotations/crop diversity in the CA system on C sequestration is less known although it is expected that the crop rotations that contribute to high C input through crop residue and increased root biomass should lead to an increase in soil organic C and hence C sequestration in soil. However, the overall impact on net greenhouse gas emissions of crop rotations/crop diversity is largely unknown. In conclusion, optimum N management (from synthetic fertilisers, manures and/or N_2-fixed legume N) in conservation agriculture is the key to maintaining/increasing SOC stocks, reducing net greenhouse gas emissions and attaining sustainable food production for long-term food security.

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Soil Carbon Sequestration Through Conservation Tillage and Residue Management

14

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Abstract

To mitigate the changing climate due to the increase concentration of greenhouse gases (GHG) in the atmosphere, studies on carbon (C) sequestration potential of different agricultural management practices are receiving worldwide attention. Conservation agriculture (CA) is highly recommended for its high C sequestration capacity and the productive use of crop residues that are otherwise burnt and pollute the environment. The adoption of CA offers preservation of soil moisture by leaving at least 30% of the soil surface covered with crop stubble/leaf litters, thereby decreasing wind and water erosion. The amount of residue cover left on the field depends on the type of operation, availability of implements and the fragility of the residue. Under CA, if 1 ft of residue is left on the field, an additional amount of 1.6–2.0 t/ha of crop residue is being added in to the field

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compared to farmers' practice that improves soil aggregation, infiltration, organic C status and enhanced biological properties. The C sequestration in CA is accomplished through the addition of carbon through residues, protection of soil organic carbon in soil aggregates under minimum soil disturbance and addition of soil organic carbon (SOC) to deeper soil layer due to the inclusion of legumes in the cropping system. In fact, practising CA can potentially sequester C at rates of 300–600 kg C/ha/year depending on the type of soil and climatic conditions. In addition, CA practices are widely adopted to increase soil productivity, revert soil degradation, improve C sequestration and also increase input use efficiency and crop yields. Therefore, location-specific CA must be developed and advocated. The challenges and bottlenecks in disseminating CA in a large scale must be addressed and overcome by further studies with policy initiatives and interventions.

Keywords

Conservation agriculture · Conservation tillage · Crop residue management · Soil health · Carbon sequestration

14.1 Introduction

Conventional practices comprising repeated intensive tillage operations, residue burning and high- or low-input farming resulted in the decline in crop productivity and deterioration of soil health (Verhulst et al. 2010). It also affects the soil's physical properties, hampers biological degradation and results in stagnancy of crop yields despite increased use of improved varieties, pesticide and fertilizer. These conventional modes of agriculture through intensive farming practices were successful in achieving the goals of production in the short run but simultaneously led to the degradation of the natural resources in the long run (Somasundaram et al. 2020a, b). The growing concerns for sustainable agriculture have been seen as a positive response to the limits of both low-input traditional agriculture and intensive modern agriculture relying on high levels of inputs for crop production. Sustainable agriculture depends on the practices that help to maintain ecological equilibrium and favour natural regenerative processes (Lal 2015), such as nitrogen fixation, nutrient cycling, soil regeneration and protection of natural enemies of pest and diseases as well as the targeted use of inputs (Oliver and Gregory 2015). Agricultural systems relying on sustainability approaches not only support high productivity but also preserve biodiversity and safeguard the environment. Thus, conservation agriculture has come up as a new paradigm to achieve the goal of sustained agricultural production (Abrol and Sanger 2006; Hobbs 2007; Somasundaram et al. 2020b). It is a major step towards the transition to sustainable agriculture. Conservation agriculture (CA), which has its roots in the universal principles of providing permanent soil cover (through crop residues, cover crops and agroforestry), minimum soil disturbance and crop rotations are now considered as the principal route to sustainable agriculture: a way to achieve the goals of higher productivity while protecting natural resources and environment. Rainfed (semi-arid and arid) regions are categorized by highly variable and unpredictable rainfall, structurally unstable soils and low crop productivity. Many research results demonstrated that no/minimum/reduced tillage system without crop residues left on the soil surface can pose a serious threat to soil health as it enhances greater runoff and soil erosion. It indicates that no tillage alone in the absence of soil cover is unlikely to become a favoured practice. Therefore, the minimum soil disturbances in the form of no tillage or minimum tillage coupled with maximum soil cover (at least 30% crop residue cover) and diversified cropping system not only helps to check runoff and soil erosion but also improves soil aggregation and infiltration and enhances carbon sequestration in the long run.

Carbon sequestration is defined as the process of transfer and secure storage of atmospheric CO_2 into other long-lived global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in the atmospheric CO_2. Carbon sequestration may be a natural- or anthropogenic-driven process. The objective of an anthropogenic-driven process is to balance global C budget such that future economic growth is based on a 'C-neutral' strategy of no net gain in atmospheric C pool. A considerable part of the depleted SOC pool can be restored through the conversion of marginal lands into restorative land uses; adoption of conservation tillage with cover crops; crop residue mulch; nutrient recycling; use of compost and efficient use of inputs in agriculture, i.e., nutrient, water and energy. Besides mitigation of climate change, soil carbon sequestration is a win-win situation as it helps in build-up of soil fertility, improves soil quality, improves agronomic productivity, protects soil from compaction and nurtures soil biodiversity.

14.2 Large-Scale On-Farm Residue Burning

Food grain production of the country has reached a record high of 292 million tons during 2019–2020 due to favourable weather conditions and other factors of productivity. Overall, India produces about 600 million tons (Mt) of crop residues annually, of which about 34% (204 Mt) of gross are estimated as surplus. In the Indo-Gangetic Plains, about 95 million tons of rice residues are produced which is about 39% of the total crop residues generated (Sidhu et al. 2015). Rice-wheat cropping system in north-west (NW) states produces about 34 million tons of rice residues of which Punjab alone contributes about 65%. The mechanized harvesting and threshing of rice using combine harvesters is a common practice in NW India. In the process, residues are left behind the combine harvesters in a narrow strip (windrow) in the field. Disposal or utilization of the leftover residue in the short span of 10–20 days for timely sowing of wheat crop is a challenging and difficult task (NAAS 2017). Acute shortage of labour in the peak season resulting in high cost of residue removal/cleaning from the field and increasing use of combines for crop harvest have forced farmers to adopt large-scale on-farm residue burning for timely seeding/planting of succeeding crops. In India, the highest amount of crop residue is burned in Uttar Pradesh (59.97 Mt), Punjab (50.75 Mt), Haryana (27.83 Mt) and

Fig. 14.1 Widespread residue burning in conventional farming practices (left), impediments during field operations

Maharashtra (46.45 Mt) followed by other states and the least in north-eastern part of India such as Mizoram (0.06 Mt) and Sikkim (0.15 Mt) (NPMCR 2014). Most of the crop residues are generated from cereal crops such as rice, wheat, maize and millets, contributing around 70% of the total crop residue generated in the country (NPMCR 2014).

Residue burning is a widespread practice in many parts especially in the rainfed region as it causes a lot of impediment during field operations (Fig. 14.1). It is a quick, labour-saving practice to remove residue that is viewed as a nuisance by farmers. However, residue burning has several adverse environmental and ecological impacts. The burning of dead plant material adds a considerable amount of CO_2 and particulate matter to the atmosphere and can reduce the return of the much needed C and other nutrients to the soil (Prasad et al. 1999). The lack of a soil surface cover may also enhance the loss of soil minerals through surface runoff/soil erosion. Crop residues returned to soil maintain organic matter (SOM) levels, and crop residues also provide substrates for soil microorganisms. As microbes decompose crop residues and soil OM, CO_2 is given off as a by-product of soil respiration. Therefore, it is reasonable to believe that accelerated residue decomposition might affect soil surface CO_2 fluxes.

Worldwide, many farmers resort to burning of field crop residue for a variety of real and perceived benefits, such as timeliness of field operations, reduced cost associated with residue management, increased crop yield and better control of weeds and diseases (Chen et al. 2005). However, it results in a considerable loss of organic C, N and other nutrients by volatilization as well as detrimental effect to soil microorganisms. In comparison to burning, residue retention increases soil carbon and nitrogen stocks, provides organic matter necessary for soil macro-aggregate formation (Six et al. 2000) and fosters cellulose-decomposing fungi and thereby enhances carbon cycling.

Crop residues in general serve a number of beneficial functions, including soil surface protection from erosion, water conservation and maintenance of soil organic matter (OM). Large amounts of residue in the soil surface have traditionally been viewed as a nuisance and have been associated with difficulties such as mechanical planting, poor crop stand establishment, decreased efficacy of herbicides, release of growth-inhibiting allelopathic compounds and, ultimately, yield reductions. Therefore, crop residues, particularly wheat residue, are commonly burned or ploughed followed by discing to prepare a seedbed for double-cropped soybean (Prasad et al. 1999) and rice residues are burnt in the Indo-Gangetic Plains (IGP) for the timely sowing of the succeeding wheat crop in rice-wheat cropping system (Sharma and Mishra 2001; Hobbs et al. 2008; Somasundaram et al. 2020a, b).

14.3 Conservation Tillage Versus Conservation Agriculture

Conservation tillage helps preserve soil moisture by leaving at least 30% of the soil surface covered with crop stubble/leaf litters, thereby decreasing wind and water erosion. The crop stubble layer reduces evaporation in the soil profile by one-half compared to bare soil. Conservation tillage can also reduce pollution caused by runoff and enrich the soil with organic matter. Conservation agriculture (CA) is a slower-evolving agricultural revolution that began at the same time as the Green Revolution and emerged as a new paradigm to achieve the goals of sustainable agricultural production. It is a major transition step towards sustainable agriculture. The concept of CA has emerged from reduced tillage. Concepts for reducing tillage operations and keeping soil covered came up, and the term *conservation tillage* was introduced to reflect such practices aimed at soil protection (FAO 2008; CTIC 1996; Friedrich et al. 2012; Reicosky 2015). Seeding machinery developments were allowed, in the 1940s, to seed directly without any soil tillage/soil disturbances. At the same time, theoretical concepts resembling today's CA principles were elaborated by Edward Faulkner in his book *Ploughman's Folly* (Faulkner 1945) and Masanobu Fukuoka with the *The One-Straw Revolution* (Fukuoka 1975). It wasn't until herbicides became readily available in the late 1950s and early 1960s that the era of conservation tillage could begin.

14.4 Definitions of Conservation Tillage and Conservation Agriculture

Baker et al. (2002) defined conservation tillage as 'Conservation tillage is the collective umbrella term commonly given to no-tillage, direct-drilling, minimum-tillage and/or ridge-tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 30% surface cover by residues characterizes the lower limit of classification for conservation-tillage, but other conservation objectives for the practice include conservation of time, fuel, earthworms, soil water, soil structure and nutrients. Thus residue levels alone do not adequately describe all conservation tillage practices'.

Conservation tillage comprises a wide-ranging set of management practices with an aim to leave some crop residue on the soil's surface to enhance infiltration of water and decrease soil erosion. The several practices termed as 'conservation tillage' have led to terminological confusion. Reicosky (2015) articulates that

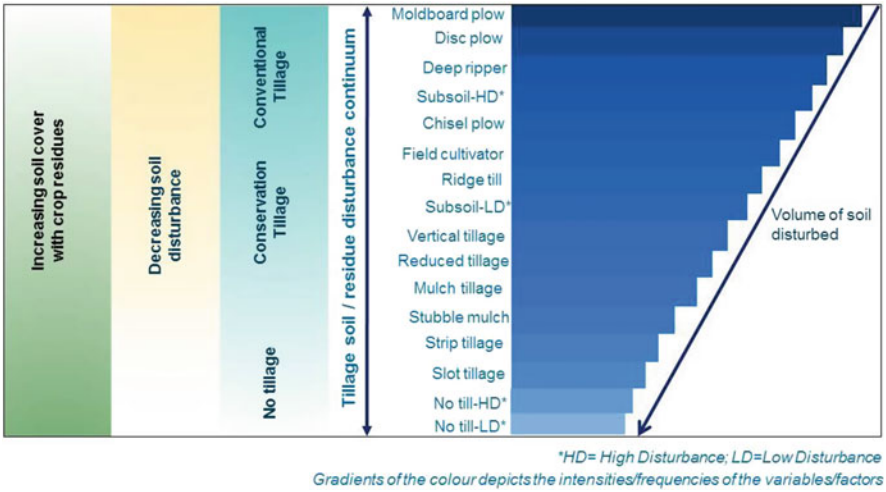

Fig. 14.2 Schematic depiction of different tillage and planting systems. (Adopted and redrawn from Reicosky 2015)

conservation tillage is frequently confused with no-till or options of CT used in vague terms like minimum tillage, mulch tillage, ridge tillage, strip tillage and reduced tillage, where planting is achieved on specially prepared surfaces with various amounts of crop residue cover (Hobbs 2007; Dumanski and Peiretti 2013; Derpsch et al. 2014; Reicosky 2015). For better understanding, different tillage practices and planting system are presented in Fig. 14.2.

'Conservation agriculture (CA) aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. CA system often referred to as resource efficient or resource effective agriculture' (*FAO*, http://www.fao.org/ag/ca/). This includes the sustainable agricultural production need that all humankind obviously wishes to achieve.

Now it is clear that CA does not just mean not tilling the soil and then doing everything else the same. It is a holistic system with interactions among households, crops and livestock since rotations and residues have many uses within households; the result is a sustainable agriculture system that meets the needs of the farmers (Sayre and Hobbs 2004) (Table 14.1).

Somasundaram et al. (2020b)

Table 14.1 Comparison of conventional farming verses conservation agriculture

Particulars	Conventional agriculture	Conservation agriculture	Rationale
Tillage practices	• Farmers follow intensive inversion tillage practices for improving soil structure/tilth of soil and also to control weeds. • Soil tillage operation usually done through rotavators, chisels, moulboard plough, rippers, discs, etc.	• Direct planting/ drilling of seeds without prior inversion of the soil • Planting of seeds by making holes using handheld device or mechanized tools • Use of no-till seeder, strip-till drill, turbo happy seeder (THS) of different variants	• Continuous intensive tillage practices destroy soil structure in the long-term and result in a declining fertility and organic matter levels in soil • CA reduces SOC loss and improves overall soil health
Crop residue management	• Farmers remove or burn residue or mix them into the soil with plough or hoe/tillage implements	• Crop residues are left on the field helps in protecting soil from erosion/degradation • Planting of cover crops	• Crop residue improves soil physical (soil structure, stability, moderation of hydrothermal regimes), biological and chemical properties
Cropping system/ cover crops	• Use of monocropping	• Diversified cropping systems/ rotation • Crop rotation or intercropping of different crops with contrasting rooting pattern • Use of cover crops	• Helps in maintaining soil fertility/health • Breaks pest and disease cycles • Cover crop protects soil from erosion and limit weed growth

14.5 Conservation Agriculture: The Most Promising Alternate Agriculture

Conservation agriculture (CA) technologies involve minimum soil disturbance, maximum soil cover through crop residues or cover crops, and crop rotations for reverting soil degradation and achieving higher productivity and also considered as a sustainable system (Abrol and Sanger 2006; Hobbs 2007) (Fig. 14.3). CA has emerged as an alternative to residue burning, where residue is managed in situ, thereby improving soil organic carbon and sustaining soil health. In comparison to burning, residue retention through conservation agriculture CA increases soil carbon and nitrogen stocks and provides organic matter necessary for the improvement of water availability and nutrient cycling.

The major benefits of CA include (1) reduced costs due to savings in fuel and labour; (2) timely planting of kharif and rabi season crops resulting higher yields;

Fig. 14.3 Crop establishment under residue in CA

(3) saving of irrigation water up to 15–20% and (4) avoidance of the burning of residue, by managing residue in situ helps in nutrient recycling and carbon sequestration in the soil. Though CA technologies have spread extensively in the USA, Brazil, Argentina and Australia covering about 156 M ha (FAO 2015) and 180 M ha (Kassam et al. 2019), the adoption in India is very slow (< 5 m ha) due to poor-availability CA machineries and location-specific technologies particularly for weed management.

The key challenges relate to the development, standardization and adoption of farm machinery for seeding amidst crop residues with minimum soil disturbance; development of crop harvesting and management systems with residues maintained on the soil surface; and development and continuous improvement of site-specific crop, soil, irrigation, nutrients weed and pest management strategies that will optimize the benefits of the new systems.

Minimum and zero-till technologies for wheat have been demonstrated to be beneficial in terms of economics, irrigation water saving and timeliness of sowing in comparison to conventional tillage. However, there are problems with direct drilling of wheat into combine harvested rice/maize fields as loose straw clogs in the seed drill furrow openers (Fig. 14.4), seed metering drive wheel traction is poor due to the presence of loose straw and the depth of seed placement is nonuniform due to frequent lifting of the implement under heavy residue conditions.

These constraints have been resolved by the innovative latest version of the Turbo Happy Seeder (THS) (Fig. 14.5), which is recognized as a significant technological innovation *for* in situ residue management. For efficient sowing of wheat using Turbo Happy Seeder, the loose rice residue needs to be uniformly spread across the field, but the traditional combine harvesters put the loose residues in a narrow swath. Manual spreading of residues is a cumbersome, uneconomical, inefficient and laborious process, compounded by the acute shortage of labour. Therefore, a straw management system (SMS) named Super-SMS has been developed and commercialized by the Punjab Agricultural University, Ludhiana, to equip the combine harvesters with mechanized straw spreaders, which helps in uniformly spreading the rice residue as a part of the process of harvesting rice. Harvesting of

Fig. 14.4 Clogging of loose straw in seed drill

Fig. 14.5 Wheat sowing using Turbo Happy Seeder under residue retention

rice by Super-SMS-fitted combine harvesters allows concurrent sowing of wheat, which saves time, energy and one irrigation by utilizing the residual moisture of rice fields. Most importantly, it dispenses the compulsions for crop residue burning. This combination facilitated easy operation of the Turbo Happy Seeder with about 20–25% increase in its capacity and less wear and tear of cutting flails (NAAS 2017).

14.6 Crop Residue Management

The amount of residue cover left on the field is greatly affected by the type of operation and the implements that have been used. Each implement's design, adjustments, and depth of soil disturbance, and to a lesser extent, its speed and the condition of the residue, will have an effect on the percentage of both fragile and

Fig. 14.6 Crop residue retention in CA plots

non-fragile residue remaining on the soil surface. Other factors that affect residue cover are the type of residue, chopping versus leaving residue unchopped, carryover of residue, degree of grazing after harvest, type of field operations, soil moisture and weather conditions, and timing of field operations. The effect of each of these factors varies considerably. The fragility of the residue is important and will determine the amount of residue that will remain on the soil surface as it interacts with other factors. Valzano et al. (2005) defined the three crop residue management practices, namely residue retention, residue incorporation and residue burning. Residue retention involves leaving stubbles on the soil surface, treated or untreated (Fig. 14.6). The untreated stubble is considered standard harvesting by cutting high or low with no modification of the stubble levels. The treated stubble is considered to have levels reduced by cutting low or by windrowing, baling or removal (chaff carts). This method of stubble management protects the soil surface from wind and water erosion, while retaining carbon at the soil surface. Another option may be in situ or ex situ composting of residues and their application to field. Under residue incorporation method, residues are incorporated to the soil during field preparation. Under residue burning, farmers resort to burning of residues in the field, which damages both the environment and soil biodiversity.

14.7 Residue Addition Under CA

It is estimated that additional amount of about 1.6 t/ha of crop residue is being added in to the field compared to farmers practice, if 1-ft-height residue is left on the field under no-tillage (NT)/reduced tillage (RT). Conservation agricultural practice (CA) added about 1.6 t/ha wheat residues (0.65 t/ha C) to a vertisol compared to 0.7 t/ha (0.30 t/ha C) in farmers' practices, suggesting the addition of C in the soil through CA. Similarly, about 2.6 t/ha residue was added under maize-gram system (Somasundaram et al. 2013, unpublished data) (Table 14.2).

Table 14.2 Residue addition under conservation agriculture practices

Stubble retention	Addition of residue (air-dry weight kg/ha)	
	Soybean-wheat	Maize-gram
Farmers' practice (10–15 cm)	676	1500
Reduced tillage/no-tillage (1 ft)	2283	4100
Difference (CA − farmer's practices)	2283 − 676 = 1607	4100 − 1500 = ~2600

14.8 Conservation Agriculture and Soil Carbon Sequestration

Conservation agricultural systems have been successfully developed for many different regions of the world. These systems, however, have not been widely adopted by farmers for political, social and cultural reasons.

Through greater adoption of conservation agricultural systems, there is enormous potential to sequester soil organic carbon, which would:

1. Help mitigate greenhouse gas emissions contributing to global warming.
2. Improve soil health and productivity and avoid further environmental damage from the unsustainable use of inversion tillage systems, which threaten water quality, reduce soil biodiversity and erode soil around the world.

Adoption of CA practices improves soil carbon sequestration due to the addition of carbon through residues, protection of soil organic carbon in soil aggregates under minimum soil disturbance and addition of soil organic carbon to deeper soil layer due to inclusion of legumes in the cropping system. Further, crop residues retained on the soil surface under conservation agriculture (Fig. 14.6) serve a number of beneficial functions, including soil surface protection from erosion, enhancing infiltration and cutting runoff rate, decreasing surface evaporation losses of water, moderating soil temperature and providing substrate for the activity of soil microorganisms, and a source of SOC. Long-term implementation of conservation agricultural practices also increases the organic matter levels in the soil. Lower soil temperatures and increased soil moisture contributes to slower rates of organic matter oxidation. An increase in organic matter is normally observed within the surface soil (0–10 cm) which helps in better soil aggregation. Carbon turnover rate slows down when soil aggregation increases and soil organic carbon (SOC) is protected within stable aggregates (53–250μm).

The impact of conservation tillage and crop residues combination has shown the remarkable potential in C sequestration in comparison to conservation tillage alone. Conservation agriculture, based on the use of crop residue mulch and no-till farming can sequester more SOC through conserving water, reducing soil erosion, improving soil structure, enhancing SOC concentration and reducing the rate of enrichment of atmospheric CO_2 (Lal 2004). Doraiswamy et al. (2007) found that ridge tillage in combination with fertilizer and crop residue is very effective in SOC sequestration through erosion control. Ghimire et al. (2008) reported that SOC sequestration could be increased with minimum tillage and surface application of crop residue, and SOC sequestration was highest in top 0–5 cm soil depth irrespective of the tillage and crop residue management practices. Suman et al. (2009) reported that changes in residue management and incorporation of organic manures may help in carbon sequestration by restoring soil organic carbon (SOC).

Ghimire et al. (2008) reported that soil (0–50 cm depth) retained 8.24 kg C/m^3 under no-tillage practice, which was significantly higher than 7.86 kg C/m^3 from conventional tillage treatment. Crop residue treatment in no-tillage soils sequestered significantly higher amount of SOC than any other treatments in the top 15 cm soil depths. Thus, it was revealed that SOC sequestration could be increased with minimum tillage and surface application of crop residue. Crop residue served as a source of carbon for these soils especially in the upper soil depths. No-tillage practice minimizes the exposure of SOC from oxidation, ensuring higher SOC sequestration in surface soils of no-tillage with crop residue application.

Minimum tillage practices, including no-till (NT) and reduced tillage (RT), have received attention due to their ability to both reduce soil erosion and increase C sequestration in the agricultural surface soils (Cole et al. 1997) by increasing aggregate stability. Alvarez (2005) reviewed the effect of nitrogen and no-tillage on soil organic carbon (SOC) from 137 sites and concluded that nitrogen fertilizer increased SOC but only when crop residue were retained. Furthermore, nitrogen fertilizer used in tropics resulted in no SOC sequestration, while, in the temperate regions, there was a trend towards an increasing SOC sequestration. In contrast to CA, conventional cultivation generally results in the loss of soil C and nitrogen. However, CA has proven its potential of converting many soils from sources to sinks of atmospheric C, sequestering carbon in soil as organic matter. In general, soil carbon sequestration during the first decade of adoption of the best conservation agricultural practices is 1.8 t C/ha/year. On 5 billion ha of agricultural land, this could represent one-third of the current annual global emission of CO_2 from the burning of fossil fuels (FAO 2008). Lal et al. (1998) estimated that the widespread adoption of conservation tillage on some 400 M ha of crop land by the year 2020 may lead to total C sequestration of 1500–4900 Mg.

A study conducted at IISS, Bhopal, also reveals the effect of tillage systems on SOC was found to be significant only at the surface layer (0–5 cm) and higher SOC value was observed under no-tillage (NT) and reduced tillage (RT) compared to conventional tillage (CT) after 3 years of crop cycles (Fig. 14.7). Further, reduction in tillage operations coupled with residue retention helps in maintaining the soil organic carbon (Somasundaram et al. 2018). Similarly, Bhattacharyya et al. (2012) reported that reduction in tillage intensity led to a significantly larger SOC accumulation in the surface soil layer (0–5 cm), but not in the 5–15-cm soil layer after 6 years of cropping in a sandy-clay-loam soil (Typic Haplaquept) near Almora, India. The year-round NT management practice was very effective for SOC sequestration in a rainfed lentil-finger millet rotation system (net gain in SOC storage was about 0.37 Mg/ha/year in the 0–15-cm soil layer).

Of late, worldwide conservation agriculture (CA)/no-till (NT) farming is considered as a practicable approach to increase or maintain SOC and also improve soil

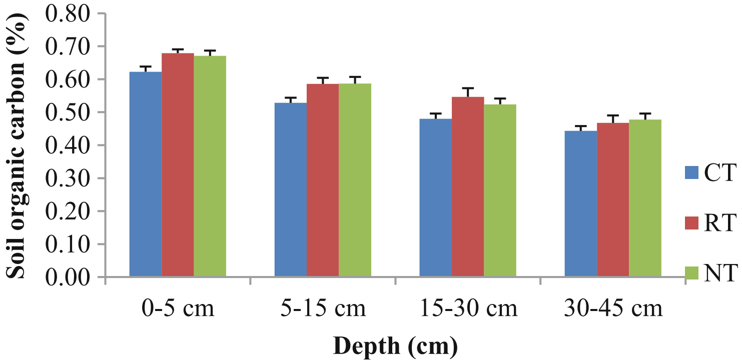

Fig. 14.7 Soil organic carbon (%) under different tillage systems after four crop cycles

aggregation (Powlson et al. 2011; West and Post 2002; Dalal et al. 2011; Palm et al. 2014). It has been estimated that practising NT can potentially sequester C at rates of 300–600 kg C/ha/year in the USA (Lal et al. 1998; West and Marland 2002). Franzluebbers (2005, 2010) reported that NT favoured SOC sequestration rates by approximately 400 kg C/ha/year than conventional tillage (CT). Similarly, Watson et al. (2000) reported that these rates are in the same range as the estimate of 200–400 kg C/ha/year conservation tillage practices for Australia, the USA and Canada. Anger and Ericksen-Hamel (2008) indicated that on an average, there was 4.9 Mg/ha more SOC under NT than CT. However, overall this difference in favour of NT increased significantly but weakly with the duration of the experiment. Dalal et al. (2011) reported that tillage effects were small on SOC and total nitrogen following 40 years of continuous no-tillage in Vertisols of Queensland region. The carbon (C) sequestration potential of different agricultural management practices is presented in Table 14.3.

There have been several meta-analyses and scientific literature reviews on the effects of NT versus CT on SOC in world soils (e.g., West and Post 2002; Alvarez 2005; Baker et al. 2007; Palm et al. 2014). Many of the earlier studies found NT to have significantly higher SOC than mouldboard plough and chisel plough systems when the soils were only sampled to 0.15- or 0.30-m depth (West and Post 2002; Baker et al. 2007). Baker et al. (2007) reported that conservation tillage was recorded to sequester C only to a depth of 30 cm or less. It was observed in few studies that conservation tillage has shown no consistent increase of SOC, where sampling extended beyond 30 cm or deeper. Moreover, many studies reported worldwide indicated higher concentrations near the surface in conservation tillage and higher concentrations in deeper layers under conventional tillage (Alvarez 2005; Baker et al. 2007; VandenBygaart 2016).

Analysis of the results from the long-term experiments demonstrated that a shift from conventional tillage (CT) to no-till (NT) could sequester 57 ± 14 g C/m^2/year (West and Post 2002). Carbon sequestration rates, with a change from CT to NT, can be expected to peak in 5–10 years with SOC reaching a new equilibrium in

Table 14.3 Carbon sequestration potential of different agricultural management practices (* depicts C stock estimated on regional estimates)

Management practices	References	Depth observed	Period of observation	Carbon sequestration rates (t C ha^{-1} yr^{-1})	Average C stock (t C ha^{-1})
No till	Arrouays et al. (2002b)	0–30 cm, Wheat-corn rotation	20 years	0.200	51.6
	Jin et al. (2008);Lu et al. (2009);Wang et al. (2009)	Plough layer	3 to 25 years	0.160	18.3
	Johnson et al. (2005)	0–20 or 0–30 cm	12–34 years	0.400	53.0
	Powlson et al. (2012)	Topsoil	5–23 years	0.310	80.0
No till plus cover crops	Franzluebbers (2010)	0–20 cm	11 ± 1 years	0.450	25.5
No-till	Jin et al. (2008);Lu et al. (2009);Wang et al. (2009)	Plough layer	3 to 25 years	0.510	18.3
Organic amendment	Jin et al. (2008)	Plough layer	3 to 25	0.540	24.4
	Wang et al. (2010)	Plough layer, 0–20 cm fordry cropland and 0–15 cmfor paddy soil	14.4 (on average)	0.620	24.4
Organic amendment combined with inorganic fertilizer	Jin et al. (2008);	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.620	24.4
	Wang et al. (2010)	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.890	24.4
	Zhu et al. (2015);	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	3 to 25	0.690	24.4
Reduced tillage	D'Haene et al. (2009)	0–60 cm	20 years	0.000	21.2
	Sanderman et al. (2010)	0–15 cm	4 to 42 years	0.340	21.2
Reduced use of summer fallow	VandenBygaart et al. (2008)	0–30 cm	20 years	0.300	75.0
Residue incorporation	Raji and Ogunwole (2006)	0–15 cm	*18 years	0.240	20.0
Rice-Rice with NPK	Mandal et al. (2008)	0–20 cm	36 years	0.230	31.3
Rice-Rice with NPK + compost	Mandal et al. (2008)	0–20 cm	36 years	0.410	31.3
Rice-Wheat with NPK	Majumder et al. (2008)	0–60 cm	19 years	0.660	34.4
Rice-Wheat with NPK + Farm yard manure (FYM)	Majumder et al. (2008)	0–60 cm	19 years	0.990	34.4
Rice-Wheat with NPK + Green manuring	Majumder et al. (2008)	0–60 cm	19 years	0.820	34.4
Rice-Wheat with NPK + Paddy straw	Majumder et al. (2008)	0–60 cm	19 years	0.890	34.4
Straw return	Jin et al. (2008);Lu et al. (2009)	Plough layer	*3 to 25 years	1.170	55.2
Straw return with Inorganic fertilizer	Sugiyanta (2015)	0–15 cm, paddy soils	*3 years	0.470	17.9
Stubble retention	Lam et al. (2013)	0–10 cm	4 to 42 years	0.147	18.3
	Sanderman et al. (2010)	0–15 cm	*	0.190	21.2

(continued)

Table 14.3 (continued)

Management practices	References	Depth observed	Period of observation	Carbon sequestration rates (t C ha^{-1} yr^{-1})	Average C stock (t C ha^{-1})
Compost addition	Lee et al. (2013)	0–30 cm paddy soils	42	0.240	40.5
	Wei et al. (2015a); Wei et al. (2015b)	0–15 cm	13–20	0.460	36.0
			13–21	1.000	36.0
Compost addition with inorganic fertilizer	Lee et al. (2013)	0–30 cm, paddy soils	42	0.390	40.5
Compost with inorganic fertilizer	Wei et al. (2015a);Wei et al. (2015b)	0–15 cm	20	1.200	74.8
Conservation tillage	Lam et al. (2013)	0–10 cm	4 to 40 years	0.150	18.3
	Metay et al. (2009)	0–25 cm	28 years	0.100	51.6
Conventional till to no-till	VandenBygaart et al. (2008)	0–30 cm	20 years	0.210	150.0
Conversion of annual cropping to crop+ley rotation Grassland	Dick et al. (1998)	0–30 cm	30 years	0.500	78.0
Conversion to ley farming	Powlson and Johnston (2015)	0–23 cm	30 years	0.200	80.0
Crop rotation	Arrouays et al. (2002a,b)	0–30 cm	20 years	0.160	51.6
	Sanderman et al. (2010)	0–15 cm	4 to 42 years	0.200	21.2
Crop rotation with perennial grasses	Savin et al. (2002)	Plough layer	5 years	0.110	64.6
Farm yard manure (@0.16 Mg C/ha/yr)	Buysse et al. (2013)	0–25 cm	20 years	0.450	50.0
Farm yard manure/crop residue	FAO (2004)	Topsoil	50 years	0.100	33.4
			51 years	0.300	33.4
Inorganic fertilizer	Minasny et al. (2012)	0–15 cm, paddy soils	8 years	0.320	27.3
	Pathak et al. (2011)	0–15 cm	6–32 years	0.160	13.3
Inorganic fertilizer + FYM	Pathak et al. (2011)	0–15 cm	6–32 years	0.330	13.3
Inorganic fertilizer with straw return	Minasny et al. (2012)	0–15 cm, paddy soils	40 years	0.520	17.9

Country
Australia, Canada, England, India, Nigeria, S. Korea, UK
Belgium, China, France, Indonesia, Russia, Taiwan, USA, USA (southeast)

Modified from Minasny et al. (2017)

15–20 years. A meta-analysis of the published data showed that converting from conventional to no-tillage increased SOC storage in over 20 years by 23% in the tropical moist climates as compared to temperate dry climates (10%) (Ogle et al. 2005).

There are several evidences that suggest the existence of a C saturation level based on the physicochemical process that stabilizes or protects organic carbon in the soil. While many long-term field experiments exhibited a proportional relationship between C inputs and soil C content across treatments (Paustian et al. 1997), some experiments in high C soils show little or no increase in soil C with two- or threefold increases in C inputs (Campbell et al. 1991). Alvarez (2005) reported that the build-up of SOC under reduced tillage (RT) and no-tillage (NT) follows an S-shaped time-dependent process, which reached a steady state after 25–30 years. Similarly, Marland et al. (2003) reported that soil organic carbon will gradually approach a new steady state that depends on the new set of practices. Many researchers estimated the time period necessary to reach the new steady state range from 20–40 years (Marland et al. 2003) to 50–100 years (Sauerbeck 2001; Ingram and Fernandes 2001) (Fig. 14.8).

14.9 Conclusions

Overall, several practices termed as 'conservation tillage' have led to terminological confusion. Indeed, conservation tillage (CT) is frequently confused with no-till or options of CT used in vague terms such as minimum tillage, mulch tillage, ridge tillage, strip tillage and reduced tillage, where seeding/planting is accomplished on specially prepared surfaces with varying amounts of crop residue cover. However, conservation agriculture (CA) technologies involve minimum soil disturbance, maximum soil cover through crop residues or cover crops, and crop rotations for reverting soil degradation, achieving higher productivity and also considered as a sustainable system. These CA practices were considered a practicable approach to increase or maintain carbon sequestration in the soil. Sequestering carbon in the soil and biota is a win-win strategy as it can mitigate climate change and also improve soil and crop health. Worldwide, CA practices not only improve soil aggregation, infiltration and reduce soil erosion but also greatly influencing the nutrient availability/recycling in soils as compared to conventional farming practices. Therefore, simultaneous application of location-specific CA principles can increase soil productivity and avoid degradation of soil resource from the unsustainable use of inversion tillage systems, which threaten water quality, reduce soil biodiversity and erode soil at a greater extent. However, site-specific CA technologies should be developed and disseminated for improving crop productivity, soil health, carbon sequestration, and enhancing input use efficiency. The constraints in the way of large-scale adoption of CA practices should be overcome by systematic research and development efforts and policy initiatives. The CA technologies need to be promoted by providing incentives, technological know-how, required resources and policy support to the farmers.

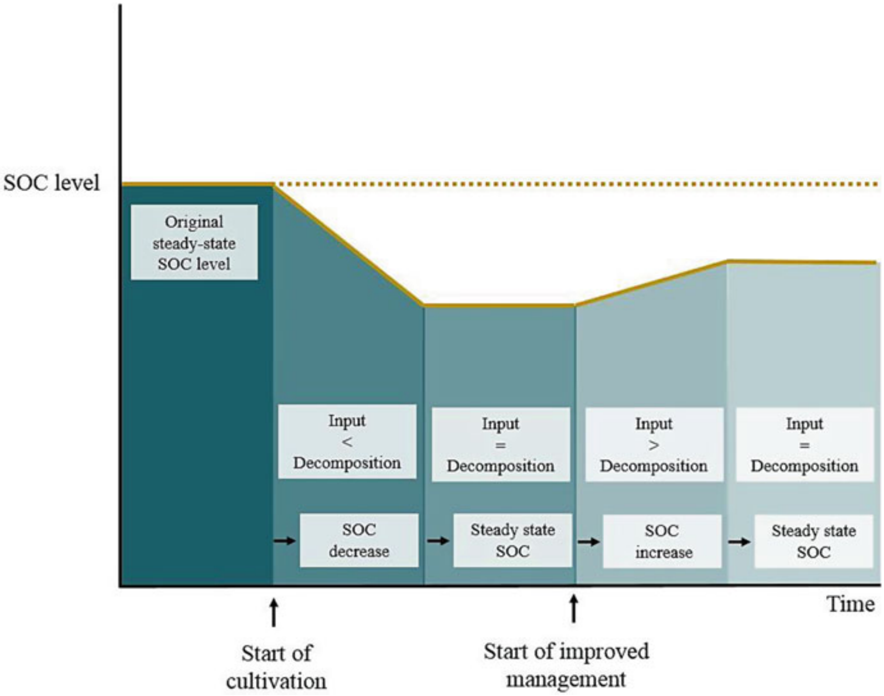

Fig. 14.8 SOC sequestration with time duration. (Source: Modified from Sauerbeck 2001)

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15 Carbon Dynamics Under Conservation Agriculture

G. S. Dheri and N. S. Pasricha

Abstract

Soil organic carbon is the third biggest carbon pool after oceanic and geological pools with estimated quantity of 1550 Pg of C. There is still a tremendous potential to further enhance the capacity of this pool for the safe storage of C in the soil. Climate change and global warming due to anthropogenic release of CO_2 to the atmosphere is the biggest concern. All-out efforts to store and conserve large amounts of C as soil organic matter in the root zone of agricultural soils can help slow down the climate change impact and improve sustainability of production system and environmental safety. Conservation agricultural (CA) practices involving the retention of large amounts of crop residue on the surface and least soil disturbance through minimum tillage are the two important components which greatly help in storing more C in soil as soil organic matter. By restoring soil productivity, these practices help make food production system more sustainable by protecting the environment and making the production system more resilient to climate change. Over years of this practice, CA can ensure the stratification of organic matter near the soil surface, which increases the soil infiltration rate manyfold, resulting in the decrease in runoff losses of water and protecting the soil from erosion losses besides storing more rainwater in the soil profile. The impact of increased frequency of high-intensity rains and decrease in the number of rain days in the future can be greatly overcome with the adoption of CA practices. The importance of CA thus becomes more relevant in the changing climate. In the present chapter, we have discussed the importance of CA practice in relation to climate resilience and efficient agro-ecosystem to ensure global food security and environmental safety.

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Keywords

Conservation agriculture · Tillage · Carbon sequestration · Soil aggregates · Soil carbon fractions

15.1 Introduction

Carbon dioxide (CO_2) contributes about 66% of the radiative forcing caused by long-lived greenhouse gases (GHGs) and responsible for approximately 82% of the increase in radiative forcing over the past decade and over the past 5 years (Butler and Montzka 2018). The atmospheric CO_2 level touched 405.5 $\pm$ 0.1 ppm which is 146% of the pre-industrial level in 2017 (WMO 2018). Among the five principal carbon (C) pools estimated by Lal (2004), the oceanic pool is the most predominant having a value of 38,000 Pg (1 Pg = 10^{15} g) followed by geologic pool (5000 Pg), soil organic carbon (SOC) pool (1550 Pg), the biotic pool (560 Pg) and the atmospheric pool (760 Pg). It is being considered that 110–170 Pg of C (approximately 10% of the Earth's total C) is present in agricultural land (Schlesinger 1984; Paustian et al. 1997).

There are some estimates of the historic loss of C from geologic and terrestrial pools and transfer to the atmospheric pool, i.e., 40 Pg by Houghton (1999), 55 Pg by Schimel (1995) and 60–90 Pg by Lal (1999). On an average, there is a net transfer of 3 $\pm$ 0.1 Pg C year^{-1} to the atmosphere from geologic and terrestrial pools, and there is a potential to put back almost 500 Pg of C into the terrestrial biosphere (Lal 2003). More recently, Le Quéré et al. (2018) estimated that the terrestrial CO_2 sink from the model ensemble was 3.8 $\pm$ 0.8 Gt C in 2017. The conversion of forest land to tillage-intensive agriculture resulted in the depletion of soil C reserves at a rate higher than its replenishment. Conventional tillage (CT) practice involves the intensive soil disturbance for seedbed preparation and other intercultural operations during crop cultivation. CT was considered as an important component of higher agricultural productivity until the soil was recognized as a potential sink of atmospheric C. Improving the C sequestration in soils using management practices becomes the researchable interest of scientific communities. The application of organic manures, crop residues, bio-solids, mulch farming, conversation tillage, agroforestry, diversified cropping systems, and cover crops are the necessary management practices of conservation agriculture (CA) that lead to SOC build-up for partly neutralizing SOC loss and increasing CO_2 concentration of the atmosphere (Lal 2004). All these sustainable practices have the potential to enhance the C sink capability of cultivable soils (Halvorson et al. 2002; Russell et al. 2005; Pasricha 2017).

Conservation agriculture (CA) emphasizes on the main three key farming principles, namely (1) minimum soil disturbance, (2) keeping the soil surface always protected with some kind of organic cover (>30%), and (3) crop diversification. A farming system with minimum soil disturbance includes reduced tillage (RT) and no-tillage (NT) evidently proven as the tillage practices for improving C sink potential of agricultural soils (West and Post 2002; Franzluebbers 2010).

Agricultural productivity under climate change scenarios is uncertain and efforts may be done to make it more sustainable and environmentally stable. CA improves crops and soils productivity that make agriculture climate resilient. It can create favourable conditions for higher rainfall infiltration and soil moisture storage in the soil profile, reducing the negative effects of excessive runoff and soil erosion, moderating soil temperature fluctuations and regulating soil nutrient cycling processes to make system climate resilient (Indoria et al. 2017). Favourable effects of CA on agro-ecosystem may largely be controlled by soil structure and soil organic matter (SOM). A high positive correlation between SOM and crop productivity under intensive cultivation has been recorded by Benbi and Brar (2009). Thus, maintaining SOM above the critical level enables a given soil to sustain higher agronomic productivity under adverse environmental conditions and to minimize environmental degradation (Lal 2010). However, maintaining or improving SOC stock in light-textured soils of arid and semi-arid regions is a major challenge (Lal 2011) specifically under C-exhausted tillage practices which further accelerate its losses.

Kassam et al. (2018) has estimated that the global cropland area under CA has expanded by 69.42 M ha (69.12%) from an area of 106 M ha (7.5% of global cropland) in 2008–2009 to 180 M ha (12.5% of global cropland) in 2015–2016 over the 5-year period. CA is considered as an alternative production system and accepted by more than 40 countries with a massive adoption in few regions (Ekboir 2002; Derpsch et al. 2010). CA has benefits of enhanced biodiversity, climate resilience, mitigation of climate, normalization of nutrient cycles, low soil erosion, and improved pest/disease management. Indeed, CA will make improvements with respect to groundwater resources, soil resources, biodiversity and climate change mitigation (Haugen-Kozyra and Goddard 2009). CA may ensure sustainable production under climate change scenarios of elevated temperature, erratic and intense rainfalls, accelerated soil erosion, sever runoff, droughts and flash floods (Trenberth 2011). Runoff-mediated soil erosion is one of the major factors of SOC loss and enrichment of soil with SOC through the best management practice (BMP) adoption of conservation-effective measures (i.e., CA on cropland) can avoid the emission of 1.1 Pg C year^{-1} caused by erosion-induced mineralization of SOC (Lal 2003). The adoption of CA is more relevant in achieving the aspirational goal of "4 per mille," set at COP21 (Conference of the parties to the United Nations Framework Convention on Climate Change in Paris) as a compensation for the global emissions of GHG by anthropogenic sources (Minsany et al. 2017).

Sustainable intensification is another important component of CA which is defined as the increase in crop productivity with minimum damage to environment and build-up of resilience and flow of ecosystem services (Kassam et al. 2014). Sustainable intensification conditions as per the definition are said to being met with the widespread adoption of the CA practices. Such a system has been successfully implemented in Europe, where application rates of chemical fertilizers and pesticides have been significantly decreased without any loss in the crop yield; rather there is an overall increase in the crop yield (Kertasz and Madarasz 2014). In the coming decades, resource constraints over soil, water and biodiversity will dominantly influence agricultural systems and crop productivity. Sustainable agroecosystems are those tending to have a positive effect on natural, social and human capital, while unsustainable systems feedback to deplete these assets, leaving fewer for the future. Thus, the adoption of sustainable intensification practices increases agricultural yields without adverse environmental impact and without the conversion of additional nonagricultural land (Pretty and Bharucha 2014). They concluded from a review paper that with sustainable intensification, both yield and natural capital dividends can occur as observed by several researchers both in developing and industrialized countries. The long-term impact of sustainable intensification, as compared to usual agricultural practices typical of the affluent economies of the world, was analyzed by Pretty and Bharucha (2014).

Nitrogen in soil is closely linked with C in SOM. Several factors which affect C and N cycles in the soil are influenced by agronomic practices. CA practices regulate these cycles similar to stable natural ecosystems as it qualifies the conditions of minimum soil disturbance, permanent soil organic cover, and species diversification. In this context, CA maximizes the productive transformation of C and N in an agro-ecosystem by plugging the unwanted gaseous losses through C and N. Ortiz et al. (2008) estimated that the increase in temperature by 0.8 °C over the next 50 years has a potential to negatively impact the wheat production in India unless some preventive measures such as CA and BMP may be adopted. Thus, understanding the vulnerability of the conventional agriculture system to futuristic adverse climatic conditions, the importance of CA becomes more relevant in the climate change scenario and provides climate-resilient C efficient agro-ecosystem to ensure global food and environmental security.

15.2 Importance of CA Under Climate Change

Agriculture and climate change are closely interlinked. The impact of climate change can be evidenced by unprecedented occurrence of climatic extremes, and its effects on agriculture sector are prominently visible now in many ways. The increased atmospheric CO_2 concentration and the concomitant increase in temperature have a profound effect on the global agricultural production. The analysis of the recorded observations indicated that the doubling of atmospheric CO_2 concentration probably increases crop yields by 33% (Kimball 1983) that may be attributed to more efficient photosynthetic process (Newton 1991). However, there is a prediction that doubling of atmospheric CO_2 concentration will increase the Earth's temperature by 2–3 °C, which could negate the positive effect of CO_2 fertilization and adversely impact agricultural production (Kimball and Idso 1983). Agricultural production of the regions having limited resources will be most vulnerable to climate change conditions, and this will be the situation in the developing world of South Asia and Africa where food demand will be highest because of population growth.

Food production in many African (Below et al. 2010) and South Asian (Pasricha 2017) countries is projected to be severely affected by climate change. Therefore, adaptation to climate change will be a key element to resolve the projected acuteness of climate change impacts on food production (Lobell et al. 2008). The potential benefits of CA to shift agriculture to climate-smart agriculture through adaptation and mitigation have been widely published (Kassam et al. 2018; Thierfelder and Wall 2010; Lanckriet et al. 2012; Pasricha 2017). Thierfelder et al. (2015) reported that the overall yield response of maize- to CA-based cropping system in Southern Africa showed a greater yield response (80%) than on conventional tillage treatments across all sites and seasons.

Conservation agriculture proved to be of great benefit for reducing soil erosion, improving soil structure and water infiltration for better water conservation and decreasing greenhouse gas emissions by stocking of C in soil as organic matter. In a nutshell, with CA practices, there can be a significant improvement in biodiversity and ecosystem services of land in the given area. Greater soil erosion and carbon loss due to erratic and intense rainfall events coupled with tillage-intensive agriculture may not be able to sustain the current productivity level under climate change conditions. Furthermore, conventional tillage (CT) involves frequent soil disturbance which contributes to soil erosion and soil heating, thus reducing water productivity (Rockström et al. 2010). Thus, there exists a high opportunity to increase land productivity under water-limited condition by adopting CA (Su et al. 2007). The higher exposure of the soil to atmospheric conditions under conventional tillage practice due to frequent soil disturbance makes the SOC vulnerable to biotic and abiotic processes which results in greater C loss. Lower C accumulation due to high oxidation rate in CT is a condition favourable for the GHG emissions to the atmosphere.

Thus, the benefits of CA become more crucial in adapting and mitigating the adverse effects of climate change on agriculture and the environment (Trenberth 2011). The build-up in soil organic C is the key benefit of CA which makes the soil relatively more self-sustainable. For a visible change in SOC and satisfactory effects on productivity, CA needs suitable time for SOC build-up; therefore, the benefits of CA may not be realized immediately (Chivenge et al. 2007; Thierfelder and Wall 2009). Enhanced soil quality and better nutrient cycling will enable crops more resilience and adaptable to regional climate changes by improving the efficiency of crops to face severe drought conditions in some area (Hobbs and Govaerts 2010). CA is more beneficial in areas where soil moisture and organic matter is a limiting factor (Thierfelder and Wall 2009).

Schlaepfer et al. (2017) forecasted that, over the twenty-first century, the temperate of drylands may shrink to subtropical drylands and that deep soil layers may become increasingly drier during the growing season, resulting in a major shift in vegetation and ecosystem service delivery. Climate change effects are not limited to dryland areas only; the scarcity of fresh water availability may drastically hit some irrigated regions as well. This could compel conversion of 20–60 M ha of cropland from irrigated to rainfed management and a further loss of 600–2900 Pcal (Elliott et al. 2014). Further, they estimated that maize, soybean, wheat, and rice may involve losses of 1400–2600 Pcal (24–43% of the present-day total) when CO_2 fertilization effects are accounted due to the direct impact of climate. In this context, therefore, uncertainty in the performance of irrigated agriculture exacerbated the threat to food and fibre services. In general, CT which is a common farming practice of irrigated agriculture will necessitate the adoption of CA under such climate-impacted regions. Thus, to make agriculture resilient to climate change, CA could be an alternate for reconciling agriculture to climate-smart agriculture to face the detrimental effects of climate change (Ghosh et al. 2010).

15.3 Tillage Effects on Carbon Stocks and Sequestration

Anthropogenic emissions of greenhouse gases could be compensated by increasing global soil organic matter stocks by 4 per 1000 (or 0.4%) per year, i.e., an inspirational value of 4 per mille (Lal 2016). The feasibility of achieving the 4-per-mille initiative was assessed by Minsany et al. (2017). They concluded that high C sequestration rates (up to 10 per mille) can be achieved for soils with low initial SOC stock (topsoil less than 30 t C ha^{-1}) within the first 20 years after the implementation of best management practices. Traditional agricultural practices and intensive tillage have caused a decrease in soil C of between approximately 30% and 50% due to the fact that many soils were brought into cultivation more than a 100 years ago (Schlesinger 1986). Soil organic matter (SOM) is an important determinant of soil fertility, productivity, and sustainability and is a useful indicator of soil quality in tropical and subtropical regions of the world (Chivenge et al. 2007). Residue retention and reduced tillage are both CA management options that may enhance soil organic carbon (SOC) stabilization in tropical soils (Chivenge et al. 2007). CA can, potentially, be used as an alternative farming system for locking atmospheric CO_2 in the soil to mitigate the adverse effect of climate change and global warming caused by energy-intensive conventional soil cultivation methods (COP22 2016; Gupta and Seth 2007). Lal (2003) estimated that there is a greater potential to put back almost 500 Pg of C into the terrestrial biosphere.

The favourable effects of CA on SOC have been long recognized and well accepted by the scientific community. The adoption of the first principal of CA, i.e., zero and reduced tillage practices, accumulated more SOM compared with the conventional tillage practices such as mouldboard and chisel plough by reducing soil disturbance required for enhanced SOM depletion. The magnitude of soil C stocking under different CA practice depends upon the tillage depth. For example, no-till was 14% better than minimum tillage system in improving SOC after a period of 20 years (Hernanz et al. 2009). The positive effect of conservation tillage can be observed within a short period when zero tillage after four cropping cycles could improve SOC at a rate of 1.17 and 1.14 t ha^{-1} $year^{-1}$ under wheat-*dhaincha*-rice and wheat-*mungbean*-rice, respectively, while SOC in conventional tillage and deep tillage under wheat-fallow-rice were almost unchanged (Khairul et al. 2016).

Studies have also identified tillage-induced soil erosion as the major cause of severe soil carbon loss and soil translocation on convex upper slope positions of cultivated, upland landscapes (Lobb et al. 1995; Lobb and Lindstrom 1999; Reicosky et al. 2005). The tillage systems influence carbon distribution in the soil profile and higher carbon stratification was observed under conventional tillage compared to traditional tillage (Moreno et al. 2006).

Sequestration of SOC as a result of minimum tillage is a reversible process, and any short-term shift in tillage practice may not yield a long-term objectives of significant improvement in SOC accrual (Jarecki and Lal 2003; Al-Kaisi 2008). In fact, single-tillage event is enough to damage the soil aggregates and carbon stocks, resulting in the loss of sequestered soil carbon and years of soil restoration (Grandy et al. 2006). Therefore, once shifted to CA practices, the agronomic managements particularly the concept of minimum soil disturbance should be followed on a permanent basis. It was estimated that soil under long-term no-tillage (NT) expected the drop of 20–40% of their original C after shuffling to conventional tillage (Davidson and Ackerman 1993). However, one-time ploughing of soil under long-term NT practice could not affect total organic C (Malhi et al. 2018). They expected improvement in the total organic carbon as a result of one-time ploughing of NT attributed to more crop residue C input due to its immediate beneficial effects on crop productivity.

Stoking of C in undisturbed soil may be influenced by a change in soil biodiversity due to modified soil microbial flora and fauna and biochemical characteristics compared to tilled soils. Better fungal hyphae network promotes soil aggregation; better SOC protection from decomposition may be one of the reasons of C accumulation in soils under CA. Greater fungal matrix was reported in the soil of NT as compared to conventional tillage (White and Rice 2009). That NT practice benefits on C stocking almost confined to surface layer (0–15 or 0–20 cm) is confirmed by recent global meta-analyses. Nonetheless, its effect on SOC stocks in the subsurface layer (>30 cm) was minor to negligible (Angers and Eriksen-Hamel 2008; Haddaway et al. 2017; Luo et al. 2010; Meurer et al. 2018). For example, during a meta-analysis of paired experiments on tillage, Luo et al. (2010) reported that conversion from CT to NT had a significant impact on the distribution of soil C confined to the soil depth up to 40 cm; in deeper soil layers (>40 cm), soil C was not affected significantly by tillage practices.

With stratification of C stocking, there is an accumulation of organic C but little changes in the whole profile. Regional climate may also regulate the direction of NT effect on C accumulation (Dimassi et al. 2014). For example, the effect of tillage was restricted to 15 cm depth under sub-humid to semi-humid climate of western Canada, whereas, no significant effect of tillage systems was recorded under humid climate of eastern Canada when soil was sampled to 60 cm depth (VandenBygaart et al. 2010). The theory of physical protection of SOC from mineralization under NT practice stands relevant at very fine spatial scales (<100μm) (Juarez et al. 2013). Thus, the build-up of SOC after NT implementation may partially be attributed to C input changes under such conditions (Virto et al. 2012).

15.4 Tillage Effects on Soil Aggregates and Associated Carbon

The disintegration of soil aggregates by tillage practices is considered to be the most undesirable action responsible for unstable soil aggregation. Stable-aggregated soils have a higher potential of C protection against abiotic and biotic agents of degradation compared to weak-aggregated soils. Further, aggregate classes differ in their capacity to protect C; tillage may affect the proportion of aggregate fractions. Six et al. (2000) postulated that it's the differences in aggregate turnover which is partially responsible for the reduced C sequestration in conventional tillage (CT) compared with no-tillage (NT). They reported that the formation of micro-aggregates within macro-aggregates was negatively affected in CT compared to NT due to a faster turnover rate of macro-aggregates and lesser stabilization of newly formed SOM in free micro-aggregates under CT. Enrichment of SOC in NT may partially be explained by interpreting the linkages between macro-aggregate turnover, micro-aggregate formation, and C stabilization within micro-aggregates (Six et al. 2000). It has been observed that the stability of macro-aggregates (>250μm) under CT were lower compared to NT. The distribution of C among the aggregate size fractions may be influenced under NT, whereas in CT, the C accumulation was similar among size classes (Beare et al. 1994a). The relative protection potential of aggregate size classes was assessed by Beare et al. (1994b) and classified as unprotected, protected, and resistant C pool. According to them, surface soil under NT had 21% to 65% higher aggregate-unprotected pools of SOM than that of CT, and mineralization rate of SOM resulting in the disruption of macro-aggregates was higher under former. However, CT soil has high rates of mineralization from protected and unprotected pools of C.

No-tillage soils, dominated by 2:1 clay mineralogy in temperate region, decreased macro-aggregate turnover by enhancing the stabilization of C and formation of micro-aggregates (Denef et al. 2004). They identified and isolated a fraction that explains almost the entire difference in the total SOC between NT and CT across soils characterized by drastically different clay mineralogy. The difference in SOC between NT and CT could be more than 90% as explained by micro-aggregate-associated C which may constitute only 50% of the total SOC under NT. Bossuyt et al. (2002) used ^{14}C-labeled plant residue as a tracer to explain the mechanisms of C protection under NT practice. The results indicate that the depth of C accumulation influences its stability depending upon tillage practices. The subsurface soil of CT stocked younger C (^{14}C) compared to NT; however, the long-term sustainability of this C was low. Whereas NT accumulated higher and stabilized C in the surface layer compared to CT, both on a short- and long-term basis, this C stabilization occurs mainly at the micro-aggregate level. The soil under NT had 137% and 204% higher mean weight diameter (MWD) compared to CT in 0–15 and 15–30 cm depth, respectively (Acar et al. 2018). The loss of aggregate-associated C in CT soils may be due to the distortion of macro-aggregates to micro-aggregates resulting in an increased surface area for microbial activities responsible for the oxidation of C present in the macro-aggregates. Further, the addition of more crop residues under

NT than the conventional practices and the rate of mineralization influence the stability of aggregates (Blanco-Canqui and Lal 2004).

15.5 Tillage Effects on Soil Carbon Stratification

Since CT differs in the depth of soil disturbance, the adoption of NT altered the SOM stratification pattern of the soil profile. Enrichment of soil C under NT is more confined to the surface soil compared to CT; this difference may become narrow in the deeper layer along the soil profile. Therefore, assessment on changes in C stocks of subsurface layers of soil profile is necessary for concluding the overall benefits of conservation tillage. Luo et al. (2010) based on the meta-analysis of global data from 69 paired experiments studied tillage impact extended deeper than 40 cm concluded that shifting from CT to NT influenced the distribution of C in the soil profile significantly but without increasing the total SOC except where double cropping systems were implemented. Considering profile stocks, the adoption of NT has no C-enrichment benefits when soil C increased by 3.15 ± 2.42 t ha^{-1} in the surface layer (0–10 cm) and decreased by 3.30 ± 1.61 t ha^{-1} in deep soil layers (20–40).

The effect of NT in C increments in the surface layer could be seen after a shorter period of the initial 10 years of study (Mazzoncini et al. 2016). Continuing the NT practice in the same experiment for 28 years accumulated negligible SOC in deep soil layers (10–60 cm).

Higher SOC stratification ratio (>2) obtained under NT soils with low in native organic C indicated the benefits of NT to soil quality in semi-arid regions (Lopez-Fando and Pardo 2011). Fernández-Romero et al. (2016) highlighted the limitations of using stratification ratio (SR) for soil quality indexing influenced by different management practices in an olive grove in Mediterranean areas (Andalusia, southern Spain). He suggested that SR does not analyze the behavior of the variable over time and using a single variable could lead to an oversimplification of the assessment of the soil quality. However, notwithstanding the limitations, the addition of organic material improves soil quality under NT practice.

15.6 Tillage Effects on Carbon Fractions

No-tillage (NT) certainly has some advantage over conventional tillage (CT) in maintaining or improving SOC, with profound increment in surface soil layers. The quality of the stocked C could be judged by examining the relative proportions of different C fractions and their structural arrangement responsible for recalcitrant nature and resilient toward climate change and management practices. The separation of SOC into soil C fractions more responsive to tillage practice is necessary to study the C stabilization in the soil (Parton and Rasmussen 1994). Therefore, both quantitative and qualitative analyses of SOM is required to study the effects of tillage in reducing the CO_2 load of the atmosphere. Shrestha et al. (2015) examined the quality of SOM in surface soil using ^{13}C solid-state NMR spectroscopy. The effect of NT on SOC stock could be visible after 26 years of the experiment, where a 56-year application of fertilizer has no significant impact on C stock, emphasizing more efficiency of NT tillage in managing SOC stock compared to fertilizer application. The quality of SOM was influenced by tillage type, fertilizer dose and crop rotation. The advanced stage of SOM decomposition under CT could be indicated by the enrichment in alkyl C, while O-alkyl C was more in NT. The aromaticity of the C fractions may also be affected by soil depth. For example, the aromaticity of the dissolved organic carbon (DOC) and hydrophilic DOC (Hy-DOC) as detected by specific ultraviolet absorbance (SUVA) under reduced tillage was more in subsurface soil than surface soil (Bongiorno et al. 2019).

The assessment of labile fractions of SOC such as particulate organic carbon (POC), microbial biomass carbon (MBC) and permanganate oxidizable carbon ($KMnO_4$-C) was assumed to be a good indicator to study the management influence on SOC at the early stages of experimentation. The implementation of minimum tillage in an Alfisol for 10 years enhanced the total organic carbon by 27% over CT, and the corresponding increase in POC, MBC, and $KMnO_4$-C under MT were 47%, 16%, and 43% higher, respectively, in comparison to CT in the 0–20-cm soil layer (Prasad et al. 2016).

Mangalassery et al. (2015) investigated the functional chemistry of the SOM accrual intemperate well-drained soils under zero tillage practice for 7 years. Carbon assimilated under ZT was predominated by aromatic functional groups, an indicator of more stable and recalcitrant C compared to tilled soils. The effect of land use systems on SOM can't be explained using a single soil C pool; rather the use of other indicators such as labile C, $KMnO_4$-oxidizable C, nonlabile and recalcitrant C, mineralizable C, basal soil respiration and dehydrogenase activity could distinguish the impact of different land use systems effectively (Benbi et al. 2015).

15.7 Tillage Effects on Soil Respiration and CO_2 Emissions

The atmosphere is being enriched at the rate of 100 Pg C year^{-1} by the release of CO_2 during soil respiration; thus, necessitating the implementation of mitigation measures can regulate soil respiration to suppress the CO_2 emissions, hence the potential effects of the climate change (Liu et al. 2015). Recently, Tubiello (2019) estimated the greenhouse gas emissions (GHGs) from agriculture and reported that global GHG emissions from agriculture increased from 2752 to 5294 Mt CO_2-eq year^{-1} from 1961 to 2016. Therefore, efforts have been initiated to identify the controlling factors to minimize CO_2 losses through soil respiration (Reynolds et al. 2015). Tillage frequency increased soil CO_2 flux dynamism, high soil temperature and moisture conditions are most conducive for CO_2 production; hence, CO_2 flux was higher in the wet-hot season compared to the dry season (Xiao et al. 2019). In this context, NT or MT has more relevance in reducing CO_2 flux in the regions experiencing such climate conditions. The study indicated that the annual cumulative CO_2 fluxes were directly affected by the changes in SOC, whereas tillage has indirect effects on CO_2 production through the breakdown of macro-aggregates and changes in microbial biomass. Silva et al. (2019) determined the temporal variation in CO_2 emissions and the soil's physical attributes in response to the process of soil particle rearrangement after soil tillage operations. It was observed that CO_2 emissions were 87% higher under intensive tillage (3.86μmol m^{-2} s^{-1}) than reduced tillage (2.06μmol m^{-2} s^{-1}) on the first day after tillage and 147% higher compared to NT (1.56μmol m^{-2} s^{-1}). Intensive tillage disintegrates soil aggregates, resulting in a higher number of macropores, improving soil aeration compared to the higher number of micropores and higher soil water retention under NT, and causing more CO_2 emission in the earlier than the latter tillage practice.

The comparison of NT and manual tillage in two upland rice soils (Lixisols and GleyicLuvisols) in northern Benin in West Africa indicated that NT combined with nitrogen fertilizer could be used by smallholder farmers to achieve higher grain yield and lower soil carbon emission in upland rice fields in northern Benin (Dossou-Yovo et al. 2016). Abdalla et al. (2016) conducted a meta-analysis to compare CO_2 emissions over entire seasons or years from tilled and untilled soils across different climates, crop types and soil conditions using a total of 46 peer-reviewed publications. It was summarized that on an average, soils under tillage emit 21% (1152 g CO_2 cm^{-2} $year^{-1}$) more CO_2 compared to no-tillage soils (916 g CO_2 cm^{-2} $year^{-1}$). This difference in sandy soils low in SOC ($\leq$1%) and low soil moisture under arid climates increased to 29%. However, the effect of tillage on CO_2 fluxes in clayey soils with high SOC (>3%) was not significant. They suggested that NT could be a more effective measure to mitigate CO_2 emissions in soils of arid conditions. Lower respiration rates in NT compared to CT may also depend on the hydraulic characteristics of NT soils which may restrict the diffusion of gas flow in high moist soils due to water-blocking of the meso- and macropores (Schwen et al. 2015). Soil respiration in NT soils was spatially less homogeneously distributed, resulting in the occurrence of CO_2 "hotspots."

15.8 Tillage Effects on Carbon Footprints

The term "carbon footprints" (CF) refers to the amount of GHGs expressed in terms of CO_2 equivalents, released into the atmosphere by an entity, organization, process, product or event from within a specified boundary (Pandey et al. 2011). The agricultural CF is measured as the effect of different agricultural activities on the environment in terms of GHGs produced, measured in CO_2 equivalents (Maheswarappa et al. 2011). Assessing CF of different farm activities can assist in developing sustainable agriculture, which will not only meet our present and future needs for food, fibre, and ecological services but also consolidate sustainability of energy use (Tilman et al. 2002).

The practice of NT with residue retention (NT-RR) was efficient in reducing the energy consumption (16,727 MJ ha^{-1}) and the cost of production (INR 54,271 ha^{-1}, 1 US$ = 64.46 INR) compared with those under CT with residue incorporation (CR-RI) (27,630 MJ ha^{-1} and INR 76,903 ha^{-1}, respectively). Consequently, NT residue retention had high energy use efficiency (EUE), energy productivity (EP), and net returns, but lower CF (14.6%) of the system compared with those under CT-RI (Yadav et al. 2018). Less number of tillage and low GHG emissions associated with machinery could be the possible season for low CF in NT practice.

Tillage practices influence SOC sequestration and direct and indirect emissions of GHGs, hence differ in their CF. Zhang et al. (2016) reported that the CF including SOC sequestration was significantly lower than that when SOC sequestration was excluded among the treatments. For example, yield-scaled CFs of winter wheat under NT was 0.431 kg CO_2-eq kg^{-1} year^{-1} excluding and 0.286 kg CO_2-eq kg^{-1} year^{-1} including SOC sequestration. This further suggested that for lower CFs, NT could be a preferred "climate-resilient" technology for the winter wheat-summer maize system.

The application of chemical fertilizer contributes a major portion of C emissions; thus, high amounts of chemical fertilizers accounted for high CFs for both NT and CT practices. It's the positive changes in SOC and low direct emissions of GHGs which lower the C feedback of untilled soils compared to tilled soils. The contribution of chemical fertilizers in the total C emissions under NT and CT varied from 73.3% to 77.1% and has become the main C source under such practices (Zhang et al. 2015). Further, NT had higher total CO_2 flux of soil respiration than that under CT, but considering a carbon balance analysis indicated that NT was a C sink, whereas CT acted as C source.

Contrary to the evidence of low CFs in NT practice, Wang et al. (2016) reported lower CFs and highest grain yield among the different tillage treatments. Furthermore, the application of N (180 kg ha^{-1}), irrigation of 150 mm, and conventional tillage proved to be the best management practices for lower CFs and high system productivity. Therefore, while computing the CFs of the systems under different tillage practices, changes in SOC in response to these practices may not be ignored.

15.9 Conclusions

Conservation agriculture emphasizes minimum soil disturbance, organic cover of soil, and crop diversification. CA improves crops and soil productivity that make agriculture climate resilient. It improves the soil's physical, chemical, and biological properties, resulting in a higher water infiltration and storage, nutrient cycling, and gaseous exchange for better carbon storage. CA has been adopted by more than 40 countries with a massive adoption in few regions. There exists a high opportunity to increase land productivity under water-limited condition by adopting CA. The adoption of CA for a short term may not yield long-term objectives of significant improvement in SOC accrual. Comprehensive soil profile studies are needed to evaluate the overall effect of CA on soil C storage. Thus, the benefits of CA become more crucial in adapting and mitigating the adverse effects of climate change on agriculture and the environment.

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16

Impact of Conservation Agriculture on Greenhouse Gas Emission and Its Implications

Pratap Bhattacharyya, P. K. Dash, and S. R. Padhy

Abstract

Conservation agriculture (CA) is being practiced globally approximately in 125 M ha of land. However, in India it is adopted only about 1.5 M ha. The CA is recommended for its beneficial effects like protection from soil degradation, mitigation of greenhouse gas (GHG) emission, and restoration of soil health. It is an approach often considered as one of the resource conservation technologies (RCTs), which aims to utilize natural resources including soil, water, and nutrient. The CA approach includes residue retention/management, reduced tillage practices, and crop diversification. This chapter reviews impact of CA on GHG emission and carbon sequestration on prevalent cropping systems by comparing the effect of cropping system, residue management, integrated nutrient management, etc. with conventional agricultural practice. The conservation tillage system stabilizes soil carbon but may contribute more to GHG emissions as compared to conventional practice. The retention of crop residues and crop diversification affects nitrous oxide (N_2O) emission from agriculture by altering the availability of nitrate (NO_3^-) and decomposability of carbon substrates. However, legume residues resulted in higher N_2O-N losses compared to nonlegume. Hence, for a better understanding of the GHG emissions under CA practices, it is necessary to know the relative importance of its (CA's) components, such as zero tillage, residue retention, and crop rotations on emissions and carbon sequestration. Whether conversion of conventional to conservation system can mitigate GHG emission is still a debatable issue; however, it definitely sequesters more carbon in the soil. Therefore, intensive research is needed, particularly on different tillage practices and cropping systems in combination with nutrient management on long-term CA systems.

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Keywords

Conservation agriculture · Residue management · Crop diversification · Greenhouse emission · Carbon sequestration

16.1 Introduction

Conservation agriculture (CA) is a unique approach to improve, conserve, and efficiently use natural resources through effective management of soil, water, and biota. It is a package of practices that reduce soil erosion, improve soil and water productivity, reduce production costs, and provide affordable services to farmers (Dash et al. 2019; Govaerts et al. 2007). In a broader perspective, CA includes those practices which help in conserving the agricultural land as well as ecosystem along with optimizing the crop yield. Primary components of CA include zero tillage or minimal tillage, crop residue retention over the soil surface, and crop diversification (selection of suitable cropping sequence). The primary objective of CA is to minimize disturbance of soil surface and promote natural microbial activities and at the same time provide a sufficient amount of organic substance in the form of crop residue and manures to soil in order to sustain soil health for a longer time (Dalal and Nandkar 2011; Xue et al. 2018). Apart from that, it also aims to mitigate greenhouse gas (GHG) emissions from agriculture (Bhattacharyya et al. 2012).

Conservation agriculture (CA) is also often described as one of the resource conservation technologies (RCTs) having three compact components of RCTs (zero tillage, crop residue retention, crop diversification) (Hobbs and Gupta 2003). Reports confirmed that the adoption of RCTs in several countries in rice production systems helped to reduce GHG emissions (Gupta and Seth 2007). Majority of the RCTs in rice were also aimed to higher utilization efficiency of resources (soil, water, and nutrient) by adopting residue management, reduced tillage practices, and crop diversification and cutting down the GHG emissions (Busari et al. 2015). The application of suitable RCTs could also retain more carbon (C) in soil, which is useful for C sequestration.

Global warming is a major issue primarily caused by the increased concentration of greenhouse gases (GHGs) in the atmosphere, which have direct or indirect effects on agriculture. The agriculture sector is estimated to account for 10–20% of anthropogenic GHG emissions worldwide (Smith and Olesen 2010). The major GHGs associated with agriculture are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Agriculture is responsible for 5%, 47%, and 84% of the global CO_2, CH_4, and N_2O emissions to the atmosphere, respectively. These gases contribute differently towards global warming such as CH_4, 20–25%; CO_2, 40–50%; N_2O, 5–10% with the present rate of increase per year: 0.41%, 0.42%, and 0.25%, respectively (IPCC 2014). Carbon dioxide is emitted through decomposition of soil organic carbon (SOC), CH_4 from enteric fermentation and from flooded rice fields, and N_2O primarily through application of different nitrogen fertilizer (IPCC 2014).

16.1.1 Conservation Agriculture and GHG Emission

Conservation agriculture (CA) plays an important role in GHG mitigation and could help for SOC sequestration. Particularly, in rice-based systems, zero-tillage (ZT) systems combined with proper water management could considerably reduce GHG emissions (Dash et al. 2019). Residue management and crop rotation affect N_2O emissions from agriculture by altering the availability of NO_3^- in the soil and the decomposability of C substrates. The retention of crop residues and higher C and NO_3^- in surface soils lower N_2O emissions (Senbayram et al. 2012). On the other hand, applications of N fertilizers increase N_2O emissions due to higher N availability in the soil (Davidson 2009). The quantity and quality of residues in CA systems could also affect N_2O emissions. Legume residues resulted in higher N_2O-N losses (Millar et al. 2004) compared to nonlegume (low N) residues (Yao et al. 2009). However, low soil temperatures and better soil structure under ZT reduce emissions of N_2O.

Methane has a global warming potential 28 times more than that of CO_2 (in 100 years' timescale; IPCC 2014). Agricultural soils contribute to CH_4 emissions due to methanogenic processes in anaerobic conditions, which are usually associated with lowland rice cultivation and enteric fermentation of rumens. Flooded rice production system contributes 15% of total global CH_4 emissions (IPCC 2014). Methane emission is significantly influenced by water management with the addition of mineral and organic fertilizers. Addition of organic manure has the potential to increase CH_4 emissions by 40–45% relative to nonorganic fertilizers (Yao et al. 2009). In contrast to N_2O, CH_4 could be easily oxidized by microbial activity in soil and sink in the soil system (Dalal et al. 2008). The effect of tillage practices on the rate of CH_4 consumption, in general, depends on the changes in gas diffusion characteristics in soil (Gregorich et al. 2006); however, CH_4 oxidation rate has not been significantly affected by tillage (Smith et al. 2012). However, the decrease in CH_4 oxidation or an increase in CH_4 emissions with the retention of crop residue under CA is more conclusive. Residue retention provides a source of readily available C, which enhances CH_4 production in rice paddies which are generally cultivated under anaerobic conditions (Zou et al. 2005). Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on the C/N ratio of residues; a high C/N ratio has little effect on oxidation, while residues with a narrow C/N ratio seem to inhibit oxidation (Hiitsch 2011). Reduced tillage (RT) or zero tillage (ZT) is currently promoted in the Indo-Gangetic Plains (IGP) under CA in rice-wheat systems (Gathala et al. 2013). In this system, direct drill-seeded rice does not require puddling and continuous soil submergence, and thereby could reduce CH_4 emissions from rice as it grows like aerobic crops (Pathak 2009).

16.2 Conservation Agriculture: Potential and Challenges

16.2.1 Area Under Conservation Agriculture

Conservation agriculture (CA) practices have been adopted in the tropical/subtropical and temperate regions of the world under both *rainfed* and irrigated cropping systems. Thus, CA is an innovative and adaptive process; however, it throws a challenge the avenues to develop suitable and compatible farm implements and production technologies to make it more acceptable to various stakeholders.

The CA is being practiced globally approximately in 125 M ha of land. The USA is the pioneer, and the CA is being practiced in maximum area in that country. Other countries in which CA practices are widely accepted include Australia, Argentina, Brazil, and Canada with an area of 17.0, 25.5, 25.5, and 13.5 M ha, respectively (Fig. 16.1). However, in India, CA adoption is still in the initial phase, and only in the last 10–15 years, it is slowly accepted by the farmers. The zero tillage and RCTs/CA practices have covered about 1.5 M ha in India (Jat et al. 2012; effort towards rice-wheat consortium in IGP), and through National Agricultural Research Systems (NARS) of different countries such as India, Nepal, Pakistan, and Bangladesh, it is spreading at a higher rate.

16.2.2 Options Available Under RCTs

There are several options available in RCTs; those are not always fully satisfying the three principles of CA. However, we have listed some of those to understand the development of CA over the last two to three decades. Some of the RCTs in irrigated rice production systems are as follows:

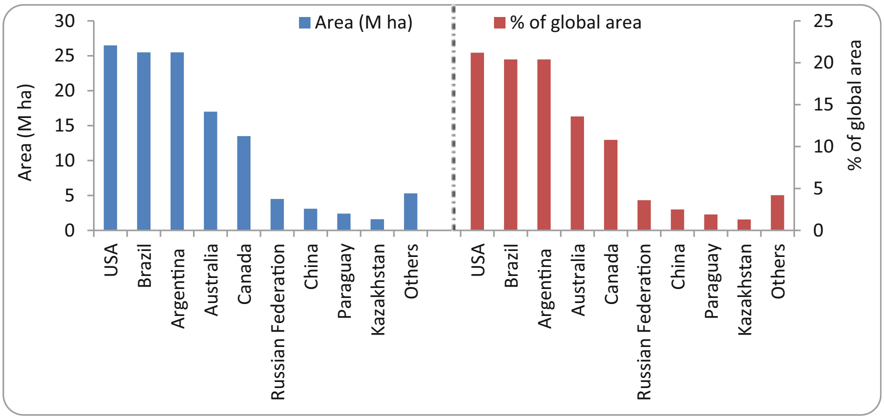

Fig. 16.1 Adoption of conservation agriculture in different countries. (Source: Bhan and Behera 2014)

1. Residue management practices
2. Crop diversification
3. Reduced or zero tillage practices
4. Nutrient conservation techniques (green manuring, brown manuring, INM, etc.)
5. Water conservation techniques (direct seeding, bed planting, aerobic rice, etc.)
6. Energy, labor-saving technologies by farm mechanization

16.2.3 Rice-Based Production System and RCT/CA

Rice is a staple food crop for approximately 50% of the world's population, and it provides 50% of total calorie intake in most of the Asian countries (Ghimire et al. 2017). It is grown under upland as well as lowland ecologies and covers more than 57 M ha area in South Asia. Mostly, rice-based cropping systems include lowland rice, rice-wheat, maize-rice, and upland rice-winter crop systems (Hossain et al. 2016). In irrigated conventional rice production system, rice is either transplanted or direct seeded and heavily supplied with nitrogen fertilizers that contribute to approximately 76% of the global rice production (Fageria et al. 2011). Rice-wheat rotation is a common cropping system in South Asia with 13.5 M ha representing a prime agricultural region of India, Pakistan, Bangladesh, and Nepal (Ladha et al. 2003). The rice-based cropping systems involve puddling (wet plowing) of rice fields followed by tillage for other crops in the rotation (Hobbs et al. 2008). In recent years, there is a growing interest among the farmers for zero tillage (ZT) in the rice and wheat cultivation in some parts of South Asia (Erenstein and Laxmi 2008).

16.2.4 Limitations of Conservation Agriculture

The main constraint of wider adaptability of CA is the mindset. Change of farmers' minds by adopting a routine practice of soil-degrading tillage operations is the main issue. However, the technicians and researchers should take a next step towards conservation agriculture (Derpsch 2001). In most of the cases, it may be difficult to convince the farmers about CA beyond its potential to reduce production costs, by reducing tillage. But the CA is now considered a route to sustainable agriculture. Spread of CA, therefore, will call for scientific research linked to development efforts. Apart from the common mindset problem, few other limitations also exist in the adoption of CA on large scale, which are:

- Lack of appropriate seed-drill machines mainly for small- and medium-scale farmers.
- Other alternative uses of crop residues, such as animal feed and fuel.
- Burning of crop residues (mostly rice straw burning).
- Lack of knowledge and coordination among agriculture officers, agents, and farmers about the potential and benefits of CA.
- Skilled and scientific manpower for handling CA machineries.

16.2.5 Advantages of Conservation Agriculture

There are several advantages of the adoption of CA over the conventional method of cultivation. Those are:

1. Higher ability of the soil to sequester carbon.
2. Soil organic matter buildup, which is an important strategy to mitigate GHG emissions.
3. Better soil water infiltration, thereby reducing soil and water erosion and nitrate runoff.
4. Stabilization of soil surface, which reduces wind erosion.
5. Avoiding residue burning and reduced loss of nutrients and environmental pollution, which reduces a serious health hazard.
6. Reduction of nutrients leaching.
7. Slowing down of evaporation losses and increase in moisture conservation, which could increase yields in drought years/ordinary land.
8. Water savings up to 15–50%; however, greater savings are possible when crops are planted on beds.

In spite of considerable advantages, CA has few concerns. Those are, more herbicide and pesticide requirements, altered distribution of SOC and nutrient stratification in soil profiles in temperate regions, etc.

16.3 Conservation Agriculture and GHG Emission: Cropping System-Based Analysis

16.3.1 Rice-Wheat

A study was carried out in rice-wheat cropping sequence on tillage and nutrient management to estimate global warming potential (GWP) of the system. The GWP was significantly higher under conventional tillage (1914 kg CO_2-eq ha^{-1}) as compared to zero tillage (395 kg CO_2-eq ha^{-1}) (Jat et al. 2014). Similarly, the impacts of four tillage practices, such as (1) conventional tilling (CT) as well as puddling before rice transplanting and conventional tilling before wheat sowing (RCT-WCT), (2) conventional tilling and puddling before rice transplanting and no tilling (NT) before wheat sowing (RCT-WNT), (3) no tillage before rice sowing and conventional tilling before wheat sowing (RNT-WCT), and (4) no tilling before sowing of both rice and wheat (RNT-WNT) on fluxes of GHGs and crop yield, were assessed in IGP of India (Pandey et al. 2012). All the treatments comprised of NT significantly reduced the CH_4 and N_2O emissions but increased CO_2 fluxes than conventional tillage. They also concluded that the NT practices in rice were more effective to reduce CH_4 and N_2O emissions than NT in wheat (Fig. 16.2 and Table 16.1).

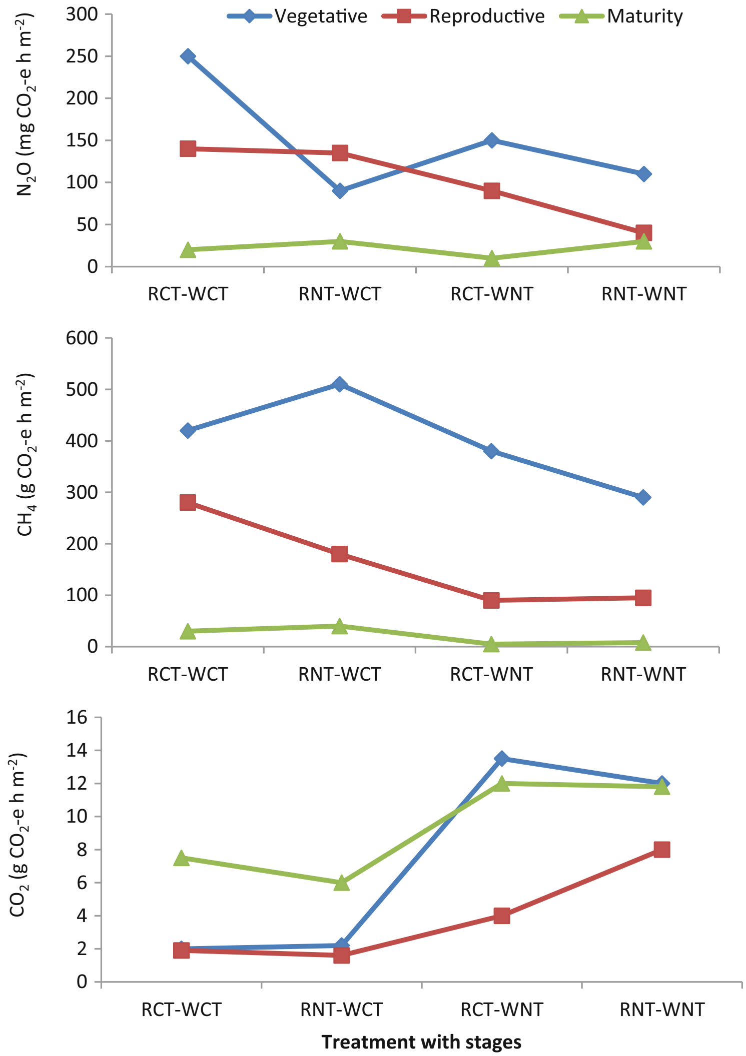

Fig. 16.2 Impact of tillage practices on GHG fluxes in rice-wheat system. (Source: Pandey et al. 2012)

16.3.2 Rice-Based Cropping Systems (Other than Rice-Wheat)

Datta and his team (2011) estimated the GHG emission from different rice-based (other than rice-wheat) systems. The study included (1) rice-potato (*Solanum tuberosum*)-sesame (*Sesame indicum*) (R-Po-S), (2) rice-maize (*Zea mays*)-pigeonpea (*Cajanus cajan*) (R-M-Pi), (3) rice-sunflower (*Helianthus annuus*)-cowpea (*Vigna unguiculata*) (R-S-C), (4) rice-chickpea (*Cicer arietinum*)-green gram (*Vigna radiate*) (R-C-G), and (5) rice-rice (R-R) (*Oryza sativa*). Methane flux was

Table 16.1 Different conservation agriculture practiced under rice-based cropping system

S. N.	Cropping system	Location	Soil type	Type of CA practice treatments	References
1	Rice-wheat	Chitwan, Nepal	Sandy loam	Conventional tillage, no tillage, crop residue retention	Paudel et al. (2014); Ghimire et al. (2012)
2	Rice-wheat	Parwanipur, Nepal	Sandy	Control/no fertilizer FYM, chopped wheat straw added	Gami et al. (2001)
3	Rice-wheat	Uttranchal, India	Sandy clay loam	Conventional tillage, no tillage	Bhattacharyya et al. (2012)
4	Rice-wheat	West Bengal, India	Sandy loam	Control NPK + FYM, straw and green manure	Majumder et al. (2008)
5	Rice-wheat	New Delhi, India	Sandy clay loam	No crop residue, crop residue retention	Sharma et al. (2010)
6	Rice-wheat	Ludhiana, India	Sandy loam	No fertilizer and FYM NPK, FYM	Bhandari et al. (2002), Rasool et al. (2007)
7	Rice-wheat	Palampur, India	Silty clay loam	Control, organic residue addition	Sharma and Bhushan (2001)
8	Rice-rice-wheat	Bhairahawa, Nepal	Silty loam	No fertilizer FYM	Regmi et al. (2002)
9	Wheat-mung bean-rice	Gazipur, Rajshahi, Bangladesh	Grey Terrace soils/ clay loam	Conventional till, deep tillage, no-tillage, crop residue retention	Alam et al. (2014)
10	Rice-based rotations Rice-wheat-fallow	Rajshahi, Bangladesh	Silty loam	Farmers practice on fertility management, legume integration, integrated nutrient management	Hossain et al. (2016)
11	Rice-wheat-jute	Barrackpore, India	Sandy loam	Unfertilized NPK, and NPK + FYM	Manna et al. (2005)

Source: Ghimire et al. (2017)

the highest in the rice-rice system, whereas annual N_2O flux was significantly lower (3.42 kg ha^{-1}) in the rice-rice system and the highest (6.19 kg ha^{-1}) was from rice-chickpea-green gram rotation. Similarly, the GWP was significantly higher under the rice-rice system (8.62 Mg CO_2 ha^{-1}) than other systems. Annual CH_4 flux (kg ha^{-1}) was in the order R-R (304.25) > R-Po-S (23.42) > R-C-G (16.33) > R-M-Pi (16.32) > R-S-C (15.55) (Fig. 16.3). Similarly, annual N_2O flux (kg ha^{-1}) from different cropping systems followed the order R-C-G (6.19) > R-Po-S (5.56) > R-S-C (4.68) > R-M-Pi (4.46) > R-R (3.42) (Fig. 16.3).

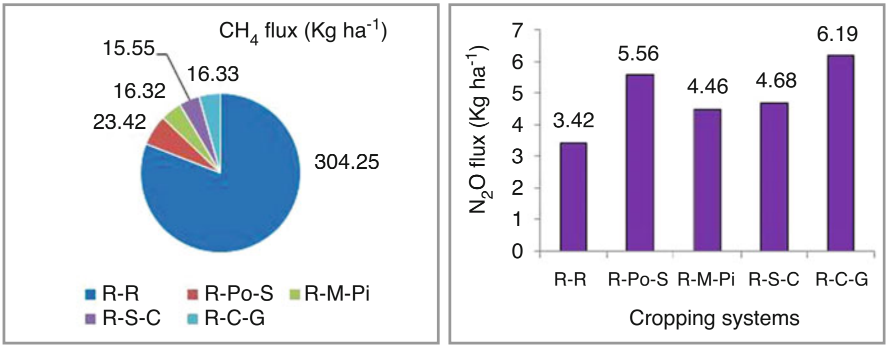

Fig. 16.3 Comparison of annual CH_4 and N_2O flux from irrigated rice-based cropping systems (*R-R* rice-rice, *R-Po-S* rice-potato-sesame, *R-M-Pi* rice-maize-pigeonpea, *R-S-C* rice-sunflower-cowpea, *R-C-G* rice-chickpea-green gram)). (Source: Datta et al. 2011)

Table 16.2 The GWP in rice production system with different technological options in upper and lower IGP

Technology	GWP in upper IGP (kg ha^{-1})	GWP in lower IGP (kg ha^{-1})
Conventional transplanting	3957	2934
Direct seeded rice	2623	979
Zero till	637	346
Crop diversification	2118	529

Another study in Japan was conducted to investigate the impact of no-tillage practices on GHG emission under conventional puddling (CP) and no tilling (NT) under rice (*Oryza sativa* L.). The average CH_4 emissions for the consecutive years were 179 and 102 kg ha^{-1} for the CP and NT fields, respectively. Similarly, the cumulative N_2O emissions from the puddling, no-tilling, and no-puddling fields were 0.16, 0.26, and 0.28 kg N_2O ha^{-1}, respectively. The cumulative CH_4 emissions from the NT cultivation were 43% lower than those from CP cultivation. However, N_2O emissions were not significantly differed among the cultivation scenarios.

In a separate study from India, Pathak and co-workers (2011) compared different RCTs and their performance to assess the GWP of the technologies in upper and lower IGP with stimulation models (Table 16.2) (Pathak et al. 2011).

16.3.2.1 Rice-Pulse/Oil Seed

Nitrous oxide emission from rice-based CA systems could be affected by crop diversification. Higher N_2O–N emission was noticed from legume rotation (Millar et al. 2004) as compared to nonlegume rotation (Yao et al. 2009). On the other hand, low-quality cereal crop residues (C:N ratio generally greater than 25) in CA systems could result in immobilization of N and ultimately decreased N_2O production compared to conventional systems. The N_2O emissions under CA mainly depend on the crop rotation and the types and quantity of residues/fertilizers used in CA systems compared to conventional practices.

16.3.3 Maize-Based Conservation Agriculture

An experiment in the *rainfed* area of Mexican highlands was carried out to investigate CA as a sustainable alternative for conventional maize production practices. It was reported that the soil quality increased under CA as compared to CT but GHG emission was enhanced. However, the cumulative GHGs emitted were similar for CA and CT, but the C content in the 0–60 cm layer was higher in CA (117.7 Mg C ha^{-1}) than in CT (69.7 Mg C ha^{-1}) (Dendooven et al. 2012).

16.4 Impact of Components of CA on GHG Emission

Agricultural soils contribute to CH_4 emissions as a result of methanogenic processes in anaerobic conditions that are usually associated with rice production. Flooded rice production contributes 15–18% of total global CH_4 emissions (IPCC 2014). Methane has a lifetime of 12 years and a global warming potential 28 times than that of carbon dioxide (CO_2) over a 100-year time horizon (IPCC 2014). However, N_2O is a potent and long-lived GHG, having a global warming potential 298 times that of CO_2 and remaining in the atmosphere for up to 114 years. The N_2O is produced by a cycle of nitrification and denitrification process in soil. Nitrification is the oxidation of ammonium to nitrate, which is an aerobic process, while denitrification is the reduction of nitrate (NO_3^-) to N_2O/N_2, which takes place in anaerobic conditions (Bhattacharyya et al. 2016).

16.4.1 Conservation Agriculture: Tillage and GHG Emission

Soil disturbance increases C loss in soil by altering the rate of soil respiration and CO_2 emission. Minimum soil disturbance (minimum/zero tillage) facilitates soil C storage compared with CT (Mishra et al. 2010). Tillage significantly affects the soil C storage. However, in the majority of studies, soil C stock is reported based on fixed soil depth layer, and bulk density is not included in the calculation. The studies used fixed depth rather than equivalent soil mass (ESM) to report changes in soil C stocks. Therefore, those were confounded by management-induced changes in bulk density rather than outright changes in stock (Palm et al. 2014). At deeper soil layers (>10 cm), soil C level in CA might be equal to or less than that in CT system (Blanco-Canqui and Lal 2008). Similarly, Franzluebbers (2008) compared 100 studies about soil organic carbon (SOC) in Canada and the USA, Brazil, Australia, Mexico, Switzerland, China, and Spain. Out of those, in 54 cases, SOC was more in NT. However, in 39 cases, the difference was not significant between NT and CT. And in the rest cases, SOC storage was lower in the NT system.

The N_2O emission response to NT in CA systems compared to CT is not clear (Snyder et al. 2009; Pelster et al. 2011). However, majority of the researchers reported higher N_2O emissions under NT as compared with CT (Baggs et al. 2003; Ussiri et al. 2009; Abdalla et al. 2014). Few other studies, however, reported lower N_2O emissions under NT or minimal tillage as compared to conventional tillage (Almaraz et al. 2009; Ussiri et al. 2009; Wang et al. 2011). Six et al. (2004) reported that the N_2O emissions in NT treatment were decreased with time, which is consistent with the report of Rochette (2008), who observed that N_2O emission is significantly increased only in poorly aerated soils under NT practices. Soil factors which are directly related to soil structure such as bulk density, soil C stock, and aggregate formation are influenced by soil disturbance and tillage. Soil aggregate formation under the NT system is higher than conventional practice due to higher soil organic input. For example, when the water-filled pore space (WFPS) is less (40%), that triggers N_2O emission by 65–70% (Dalal et al. 2003). Higher soil moisture and C input under CA practices also increase N_2O emission (Regina and Alakukku 2010). Other evidences showed wetter soil conditions combined with higher C availability under NT increase N_2O emissions (Liu et al. 2006; Regina and Alakukku 2010; Venterea et al. 2005; Yao et al. 2009). Rochette (2008) after assessing various related studies with tillage and N_2O emission concluded that NT only increased N_2O emissions in poorly aerated soils. Interestingly, many of the studies showed no difference in N_2O emission under different tillage practices, which include a high proportion of long-term trials, where CA practices have been imposed for a considerable period of time.

Tillage practices decreased the CH_4 oxidation efficiency of methanotrophs by six to eight times as compared to undisturbed soils (Hütsch et al. 1994). Maxfield and his team (2011) suggested that tillage can reduce methanotrophic biomass and activity significantly. The effect of tillage practices on the rate of CH_4 consumption, in general, depends on the changes in gas diffusion characteristics in soil (Gregorich et al. 2006). A decrease in CH_4 consumption and a potential net emission of CH_4 could be expected with ZT or NT due to increased bulk density as well as water pore spaces. Yet, no significant tillage effects on CH_4 oxidation rates have been detected (Smith et al. 2012). We know that the flooded rice (with the practice of puddling the soil) is a large contributor of CH_4 emissions from agriculture. Therefore, reduced or NT is currently being promoted in the Indo-Gangetic Plains (IGP) in rice-wheat systems to mitigate CH_4 emission (Gathala et al. 2013). Grace et al. (2012) reported there would be only 3% reduction of GHG emissions in CA compared to conventional practices in rice-wheat systems across the IGP, India.

16.4.2 Conservation Agriculture: Residue Management and GHG Emission

Plant residues' influence on soil carbon and CO_2 emission are not consistent. Crop residue removal may not alter CO_2 emissions, compared to crop residue retention as expected (Johnson and Barbour 2010). However, a USDA project in the USA indicated that 4% CO_2 emissions decreased by the removal of corn stover, relative to no removal (Jin et al. 2014). Paul et al. (2013) observed that a limited amount of crop residues has less effect on soil C storage. Moreover, rather than the amount of crop residues, the C:N ratio affects the soil C dynamic and storage. Residues with high C:N ratio reduce available N in soils, and it may lead to lower crop production, and materials with low C:N ratio as in the case of legume increase available N and facilitate microbial processes and soil respiration, which consequently leads to higher CO_2 emission (Palm et al. 2001).

Crop residue retention leads to higher SOM content on the surface soil. Consequently, easily decomposable organic matter releases soluble NO_3^-, which undergoes denitrification resulting in N_2O emissions (Dalal et al. 2003). Largely, there are three main reasons for getting inconsistent results on the effect of CA on N_2O emission. Those are: (a) the majority of studies measure N_2O fluxes (seasonal or annual), (b) variation in N_2O emissions (high temporal and spatial), and (c) methodological limitation on field measurements. For example, sampling intervals vary (i.e., from days to several weeks) in different studies. However, seasonal and annual patterns of emissions could be captured precisely in static chamber-based methods by high-frequency measurement (Palm et al. 2014).

The frequency and magnitude of N_2O emissions are closely linked to soil structure, which is a function of bulk density, soil C, and aggregation, all influenced by tillage practices and residue inputs. Nitrification is the main substrate of N_2O production at low water-filled pore space (WFPS; below 40%) (Dalal et al. 2003). In contrast, the contribution from denitrification increases in the condition where the WFPS is above 65–75%. The N_2/N_2O ratio increases with little N_2O produced at WFPS above 80–90% (Dalal et al. 2003). The soil bulk density is generally higher with NT compared to CT practices; therefore, WFPS is higher in NT/ZT; so anaerobic conditions and denitrification are potentially induced sooner at the same water content with NT. Residue management and crop rotations can significantly affect N_2O emissions by regulating the soluble/labile C and NO_3^- availability in soil (Firestone and Davidson 1989). The reduction of N_2O to N_2 is inhibited when NO_3^- and labile C concentrations are higher (Senbayram et al. 2012). The retention of crop residues and higher soil C in surface soils in CA play major roles in those processes. Under anaerobic conditions associated with soil water saturation, high contents of soluble C or readily decomposable organic matter could significantly boost denitrification (Dalal et al. 2003).

Soil moisture regulates CH_4 transport from soil to atmosphere by controlling air diffusion into the soil (Thierfelder and Wall 2010; Liu et al. 2013). However, the optimal range of soil-water content primarily depends on land use. For example, in grassy soils, maximum CH_4 oxidation occurred in soil having 18–33% of moisture content, and in forest soils, moisture varied in the range of 30% and 51% (Czepiel et al. 1995), which reduces CH_4 oxidation. Soil granules are generally formed when the pore volume increases, which could alter the CH_4 availability to the methanotrophs for oxidation (Czepiel et al. 1995). Therefore, evidence supporting a decrease in CH_4 oxidation or an increase in CH_4 emissions with crop residue retention under CA is more conclusive than for N_2O. Residue retention provides a source of readily available C, which enhances CH_4 emissions from rice paddies under anaerobic conditions (Zou et al. 2005; Bhattacharyya et al. 2012, 2014, 2016). Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on their C/N ratio; residues with a high C/N ratio have little effect on oxidation, while residues with a narrow C/N ratio seem to inhibit oxidation (Hiitsch 2011). Some studies investigated the orientation and stability of soil structure to understand lower CH_4 flux in pastures than forest soils (Abichou et al. 2011; Hiltbrunner et al. 2012). It was rightly stated that the soil aggregates play an important role in soil structure and function. It also affects water, nutrient availability, pore size distribution, movement of water, and GHG exchanges (Kasper et al. 2009). More organic C through residue retention increases the soil aggregate formation by increasing the binding agent. Binding agents include organic matter (humified), polysaccharides (microbial and plant-derived), fungal hyphae, and roots.

16.4.3 Conservation Agriculture: Crop Diversification and GHG Emission

The effects of NT with four different crop rotation practices such as continuous wheat, continuous sorghum, wheat/fallow, and wheat/fallow/sorghum/fallow were evaluated in southern Great Plains in the USA (Potter et al. 1997). The study concluded that continuous crops under NT management practices stored more C in soils and in fallow crop rotation limited carbon was accumulated. Obviously, higher biomass production and having diversifying root systems in crop rotation could affect the soil C storage. Actually, in several studies, the effects of crop rotation and tillage are combined, which makes it difficult to understand the effects of crop rotation alone. West and Post (2002) observed that corn-soybean crop rotations stored higher C as compared to monoculture (maize) under NT. Franzluebbers et al. (1995) observed that 65–98% of the variation in CO_2 flux could be accounted for by crop rotation, tillage, temperature, and soil moisture. While temperature increases soil CO_2 efflux, the effect on net ecosystem C balance primarily depends on productivity. Crop rotation effects on soil C stock are linked with above- and below-ground biomass production (West and Marland 2005). However, there are limited studies that explain the soil C input by plant root biomass as affected by crop rotation. Boddey et al. (2010) showed that legume intercrops in the rotation increased soil C stock in NT treatment due to higher production and residues inputs. They concluded that low mineral nitrogen in NT treatment led to slower decomposition rates and CO_2 efflux.

Crop rotation could alter N_2O emission by changing soil NO_3^- availability, which originated from soil organic matter decompositions (Jackson et al. 1989). The quantity and quality of crop residues (derived from different crop rotation) could alter N_2O emissions. Legume residues contain low C:N ratio and results in higher N_2O emissions (Millar et al. 2004). Similarly, crop residues with high C:N ratio lead to N immobilization and result in a less amount of N_2O emission. Therefore, N_2O emission in CA systems significantly depends on crop rotation as well as the quality and quantity of crop residues (Palm et al. 2014).

Different kinds of crops can have distinct CH_4 balances. According to Hütsch (1996), lower CH_4 oxidizing activity was observed in intact “soil cores” of continuous maize field than continuous rye plot. The CH_4 oxidation was decreased under the crops with low C:N ratios by converting ammonium (NH_4^+) or nitrate (NO_3^-) concentrations. Ammonium inhibited the methanotrophic activity in the field (Steudler et al. 1989). This is because structural similarities between "CH_4" and "NH_3" molecules permit both the compounds to compete with each other for methane monooxygenase enzyme (MMO) (Dunfield and Knowles 1995). However, Hütsch et al. (1993) observed that no significant effect of nitrogen application on CH_4 oxidation might be due to the tolerance of methanotrophs towards excess NH_4^+, or other soil properties such as N immobilization and pH protection them.

16.4.4 Interaction of Tillage, Crop Rotation, and Crop Residues on GHG Emission

It is important to study interaction effects among the components of CA (minimum soil disturbance, crop rotation, and organic soil cover) in order to understand the different processes involved in GHG fluxes in agroecosystems. In general, when the crop residues are limited in CA practice, it may not increase soil C stock. Hence, adequate crop residues in the field are essential for increasing C storage (Somasundaram et al. 2017). According to Dendooven et al. (2012), soil tillage had no significant effect on CO_2 emission under crop residue management. However, removal of crop residue significantly reduced soil respiration rate and also CO_2 fluxes. Residue management improves soil C stock and also provides C substrate for soil microorganisms and thereby may reduce soil CO_2flux. However, actually, the interactions between crop residue and other soil parameters such as soil moisture, temperature, and texture can determine the rate of respiration rate and CO_2 fluxes from soil to atmosphere. Therefore, the network of multiple interactions that alter soil C stock makes it difficult to identify the fixed guideline for CA practices which could reduce GHG emissions from agricultural fields. Models could be used to simulate interaction effects between CA components at different levels to evaluate the contribution of different practices in C sequestration and GHG emission. Few studies have tried to simulate C sequestration and reported relatively small C stock improvement (compared to observed valve) in soils under NT system (Leite et al. 2004; Apezteguía et al. 2009). However, during simulations, it should be taken into consideration that models have to be validated in site-specific conditions to accommodate soil, climate, and crop types in order to identify the response of CA practices precisely (Palm et al. 2014) (Fig. 16.4).

16.5 Conclusion

Understanding the impacts of CA practices on soil C sequestration requires an integrated approach of soil C decomposition, mineralization rate, crop productivity, and microbial activity in relation to C input in soil. Additionally, effects of climate change, soil type, crop residue added, and crop rotation followed must be addressed simultaneously to quantify C stock in a particular ecosystem. The effects of CA on

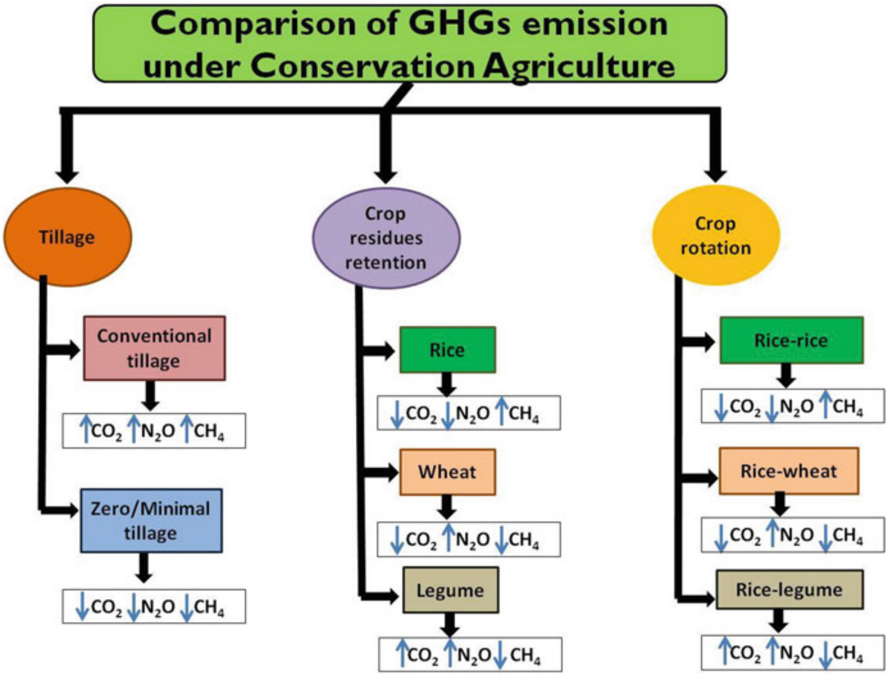

Fig. 16.4 Comparison of GHG emission under conservation agriculture and conventional practices

GHG emission underline mechanism and processes need to be studied along with final output. Available customized process-based simulation soil-C models may be a helpful tool for that. Equivalent soil mass (ESM)-based C stock assessment should be done along with real-time estimation of soil-atmosphere GHG fluxes.

On the other hand, conservation agriculture (CA) facilitates soil conditions that result in reduced erosion and runoff and improved water quality compared to conventional practices. Likewise, water holding capacity and storage are enhanced with CA providing some buffer to crop production during drought conditions. The SOM is invariably higher in the surface soil with CA practices compared to conventional practices and influences many other soil properties and processes involved in the delivery of ecosystem services. Some localized differences may be due to the duration of experiments or the experimental designs with some comparing NT, residue retention, or a combination of the two. There is a need that ecologists should study the site-specific soil biodiversity in different CA practices and connect them to C sequestration, GHG emission, and ecosystem services. In other words, to better assess the CA practices, it is necessary to know the relative importance of its components such as tillage, residue management, crop rotations, and their combination on production, C sequestration, and GHG emission.

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17 Responses of Soil Carbon Storage, Compaction, and Biological Properties Under No-Till and Conventional-Till Systems

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Abstract

Conventional-till (CT) practices can reduce soil organic matter (SOM) and microbial activity and increase soil erosion and compaction. In contrast, no-till (NT) has emerged as a viable option for protecting the soil surface against erosion and degradation. The NT has a lot of advantages such as reduced equipment costs, runoff, and erosion, increased drought resistance of crops, and higher SOM and microbial activity compared to the CT systems. Under the NT system, maintenance of high surface soil cover has resulted in a significant change in soil properties such as bulk density, soil water retention, pore size distribution, infiltration, soil organic C, enzyme activity, and microbial communities. Soil microbial communities are the drivers of SOM decomposition and nutrient cycling including the most limited nutrients for crop growth, N and phosphorus. This chapter mainly focuses on the impact of NT on soil C storage, compaction, and biochemical and microbial activity as compared to the CT systems.

Keywords

Soil carbon · No-till · Conventional till · Soil organic matter · Nutrient cycling

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17.1 Introduction

Tillage is defined as the mechanical manipulation of the soil for the purpose of better crop establishment and production. The impacts of tillage are conspicuous on soil physical, chemical, and biological properties and have a major influence on soil productivity and sustainability (Busari et al. 2015). Intensive tillage operations with either residue removal or burning, popularly known as conventional tillage (CT) practices, may adversely affect the long-term productivity of the soil due to higher loss of soil organic matter (SOM) and erosion (Feng and Balkcom 2017). Tillage activities can cause changes in soil physical properties such as bulk density (BD), aggregation, and water holding capacity. Such changes in physical properties can alter the habitats for microorganisms and eventually influence soil microbial community structure and its composition (Helgason et al. 2009). The no-till (NT) practices, for instance, can improve soil properties such as aggregate stability, nutrient availability, and the diversity of microbial populations while reducing soil disturbance (Heidari et al. 2016; Helgason et al. 2009). NT has emerged as a viable option compared to CT to ensure sustainable soil productivity and food production and maintain environmental integrity and ecosystem services (Corsi et al. 2012; Mathew et al. 2012). Conservation tillage, including NT, is an ecological approach with the principle of covering soil surface through the retention of crop residues (>30%) available from the previous crop (Corsi et al. 2012).

The major components of conservation tillage are reducing or minimizing tillage events to reduce soil degradation, conserve soil moisture, save crop production costs, and reduce the propensity for problems such as soil erosion, temperature fluctuations, weed control, and buildup of SOM (Busari et al. 2015; Hillel and Hatfield 2005; Mathew et al. 2012). Under the NT system, maintenance of high surface soil cover has resulted in a significant change in soil properties, especially in the topsoils (Anikwe and Ubochi 2007). Soil management such as NT is aimed at the maintenance of optimal soil conditions (physical properties) for crop production. Soil properties such as bulk density (BD), pore size distribution (PSD), penetration resistance (PR), soil water retention (SWR), and infiltration characteristics play a significant role in determining soil suitability for crop production (Bauer and Black 1994). For example, crop growth is profoundly impacted by SWR, which is directly influenced by other physical properties such as BD and PSD (Hubbard et al. 2013). Physical properties also influence the soil chemical composition and biological properties such as microbial activities and compositions. Conservation tillage systems increase the SWR and water infiltration and decrease soil erosion. Soil physical and chemical properties are generally more favorable with NT than with the CT-based systems (Busari and Salako 2012; Lal 1997). Studies conducted under a wide range of soil types, climate conditions, and crop rotation systems showed that soils under NT and reduced till have significantly higher SOM, labile carbon (C) and nitrogen (N) pools, and available nutrients compared with those under CT (Alvarez 2005; Awale et al. 2017; Kabiri et al. 2016; Schmidt et al. 2018). Thus, altered soil physical and chemical properties under NT create a more suitable soil environment for microbial community structure and biochemical activities (García-Orenes et al. 2013).

Soil microbial communities and enzyme activities are directly related to soil biogeochemical processes and play a prominent role in soil nutrient cycling and turnover (Sekaran et al. 2018) and other soil ecosystem services such as plant productivity and greenhouse gas (GHG) emissions (Finn et al. 2017). All these microbial functions drive sustainable soil health and, ultimately, impact crop productivity. The CT activities favor aerobic microorganisms to dominate in the soil microbial communities, while conservation tillage practices such as NT increase microbial population diversity and activity as well as microbial biomass (Balota et al. 2003). Therefore, microbial and enzyme activities have often shown to be important components and indicators of soil health (Nogueira et al. 2006). Soil microbes play a key role in the decomposition of organic matter via a variety of soil enzymes. The latter impact soil functions by catalyzing the cycling of fundamental plant nutrients such as C, N, phosphorus (P), and sulfur (S) and the ability to regulate SOM dynamics. Their activities have been suggested as potential indicators of soil quality (Saviozzi et al. 2001) because of their rapid response to changes in soil management practices (Kandeler et al. 1999). Soil enzyme data can be used as an early alert to the change in soil metabolic capacity after disturbances that occur following specific agriculture practices (Acosta-Martinez et al. 2007; Calderon et al. 2016). The long-term use of NT systems can provide higher SOM and enhance soil health by improving the biological status of the soil, which usually implies an increase in microbial and enzyme activities (García-Orenes et al. 2010, 2016; Mathew et al. 2012). Microbial diversity and biochemical activities are widely recognized as key factors in driving ecological functions in soil (Kabiri et al. 2016; Mohammadi et al. 2013; Sekaran et al. 2018). Thus, it is essential to understand the causes of tillage activities on soil microbial activity and biochemical properties (Tian et al. 2017).

17.2 Impact of NT on Soil C Storage

Soil C is important for sustaining soil health, protecting the global environment, and promoting sustainable crop production due to its impact on nutrient and water retention, nutrient cycling, soil aeration, and root growth and development (Ontl and Schulte 2012). The C in soils is presented in two distinct components: (1) soil organic C (SOC), composed of plant and animals' residues at various stages of breakdown (decomposition) of SOM and (2) the microbial biomass and their derivatives (cells and tissues of organisms). SOM acts as a major source and sink of soil C (Ontl and Schulte 2012). SOC is a heterogeneous mixture of organic materials such as carbohydrates, sugars, fresh residue, complex organic compounds, and pyrogenic compounds. Loss of C to the atmosphere as a gas (carbon dioxide, CO_2) due to agricultural management activities can contribute to global warming (Lal 2004). However, soil can act as a sink for sequestering C in the soil by retaining the crop residues on the soil surface and thus reducing the atmospheric CO_2 levels.

The C storage in soil is a natural process (Lal 2008). Plowing the soil brings organic materials such as plant roots and microorganisms to the soil surface. Tillage activity removes any plant residues covering the soil and loosens the soil by disintegrating the soil aggregates and leaving the soil bare (Günal et al. 2015). Soils with no residue on the surface are usually low in organic matter and more prone to erosion by water and wind. When these organic materials are exposed to oxygen in the atmosphere, it transforms into CO_2, contributing to the greenhouse gas (GHG) emissions that warm the earth. The CT systems accelerate the disruption of soil aggregates and SOC losses (Six et al. 2000).

Due to decreased soil disturbance under the NT system, C and other soil organic materials are retained better in the soil. NT systems protect soil, conserve energy, and improve soil health by improving SOM (0.17–0.23 ton C acre^{-1} year^{-1} increase with NT) (Al-Kaisi 2018). The C storage enriches soil biodiversity, reducing the need for inorganic fertilizers that emit GHGs and also additional costs for crop production. The major potential benefits of NT include an increase in SOM content, C sequestration, soil aggregation, and an increase in the intensification of crop sequence (Brouder and Gomez-Macpherson 2014; Rusinamhodzi 2015). To mitigate the C emissions that induce global warming, conservation agricultural (CA) practices such as NT are recommended to potentially sequester the C in agricultural soils. Compared to other tillage systems, the NT system has shown to increase the soil C stocks, thereby reducing the emission of CO_2. Through the adoption of conservation practices, globally, agricultural soils are estimated to sequester 0.4–0.8 Pg C per year. Among conservation practices, NT was one potential strategy for sequestering C in the soil with the rate of 100–1000 kg ha^{-1} (Lal 2004). It has been well documented that long-term implementation of conservation soil and crop management practices can increase soil C storage (Al-Kaisi and Yin 2005). Sithole et al. (2019) observed higher particulate organic C (POC) under the long-term NT system as compared to the CT system. Choudhury et al. (2014) stated that CA systems such as NT proved to be a good alternative to conventional agricultural systems in the maintenance of SOC and sustainable agricultural production. The NT system reduces the process of oxidation and loss of soil C and nutrients. The addition of crop residues under NT acts as a barrier between soil and the environment, which may have greater potential in reducing soil erosion and improving soil quality (Sithole et al. 2019). Soil physical, chemical, and biological properties, especially those related to sequestering C in the soil, are highly influenced by tillage practices (Indoria et al. 2017; Jat et al. 2018). Jat et al. (2019) observed considerable increase in oxidizable organic C, total organic C (TOC), and macroaggregates associated C at the soil surface layer under CA compared to the CT system. This may be due to the addition of huge quantities of crop residues coupled with NT, further easing the stabilization of organic C as SOM (Choudhury et al. 2014; Lorenz and Lal 2005) (Table 17.1). Increased TOC content over the years under CA practices might be due to the decomposition of added crop residues with time (Nachimuthu and Hulugalle 2016). Six et al. (2000) reported that under the CT system, a considerable amount of SOC was lost due to the disruptive effect and increased respiration of soil microbes. Higher C input in the soil through huge

Table 17.1 Impact of the no-tillage system on soil carbon (C)

Duration (years)	Cropping sequence/ system	Soil type	C type	NT vs. CT	Location	References
13	Continuous maize	Haplic Ferralsols (clay loam)	POC	25.3 and 20.7 t ha^{-1}	KwaZulu-Natal Province, South Africa	Sithole et al. (2019)
6	Rice-wheat-mungbean	Fine-loamy mixed hyperthermic family of Typic Natrustalf	Oxidizable organic C	8.1 and 4.9 g kg^{-1}	Haryana, India	Jat et al. (2019)
			TOC	11.4 and 8.7 g kg^{-1}		
	Maize-wheat-mungbean		Oxidizable organic C	8.2 and 4.9 g kg^{-1}		
			TOC	11.0 and 8.7 g kg^{-1}		
6	Rice-wheat/ maize	Fluvisol (silty clay)	TOC	7.25 and 6.38 g kg^{-1}	Bihar, India	Nandan et al. (2019)
5	Maize-soybean-wheat-cowpea	Silt loam	TC	16.9 and 11.8 g kg^{-1}	South-Central Ohio, USA	Aziz et al. (2013)
			AC	730.1 and 656.1 mg kg^{-1}		
7	Rice-wheat/ chickpea-mungbean	Typic Ustochrept (sandy loam)	AC	2.35 and 1.72 g kg^{-1}	Uttar Pradesh, India	Kumar and Nath (2019)
			SOC	3.40 and 2.56 g kg^{-1}		
3	Maize-soybean	Canisteo and clarion soil series	TOC	17.0 and 11.4 Mg ha^{-1}	Iowa, USA	Al-Kaisi and Yin (2005)
10	Cotton/rye-cotton-maize/ rye	Decatur silt loam (clayey, kaolinitic, thermic, Typic Paleudults)	SOC	40.1 and 37.4 Mg ha^{-1}	Alabama, USA	Sainju et al. (2008)

(continued)

Table 17.1 (continued)

Duration (years)	Cropping sequence/ system	Soil type	C type	NT vs. CT	Location	References
3	Sorghum/rye	Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults)	SOC	41.6 and 40.6 Mg ha^{-1}	Georgia, USA	Franzluebbers and Stuedemann (2008)
25	Cotton-wheat/ soybean-cotton	Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults)	SOC	20.3 and 10.1 Mg ha^{-1}	South Carolina, USA	Bauer et al. (2006)
24	Cotton-wheat/ soybean-cotton	Norfolk loamy sand	SOC	31.4 and 20.6 Mg ha^{-1}	South Carolina, USA	Novak et al. (2007)
20	Sorghum-wheat/soybean	Westwood silty clay loam (fine-silty, mixed, superactive, thermic Udifluventic Haplustept)	SOC	49.2 and 35.4 Mg ha^{-1}	Central Texas, USA	Dou and Hons (2006)
11	Cotton-wheat/ soybean	Bojac (coarse-loamy, mixed, semiactive, thermic Typic Hapludults)	SOC	29.9 and 20.2 Mg ha^{-1}	Virginia, USA	Spargo et al. (2008)
13	Cotton/wheat-soybean	Ultisols	SOC	31.4 and 20.4 Mg ha^{-1}	USA	Causarano et al. (2008)

POC particulate organic carbon, *TOC* total organic C, *TC* total C, *AC* active C, *SOC* soil organic C quantities of crop residues under the NT system resulted in the formation of higher POC (Six et al. 2000). In soil, the particulate organic matter (POM) decomposition process led to soil aggregation (Torres-Sallan et al. 2017). Soil microbes, especially bacteria, produce mucilage during the mineralization of POM, which serves as an adhesive between the POM and soil mineral particles. Through the binding of POM with soil mineral matter, SOC is enclosed into large and small macroaggregates (Torres-Sallan et al. 2017). Soils managed with NT systems can be benefited in increasing SOC content and improving soil aggregation. Protecting the SOC within soil aggregates can protect the SOC from the microbial attack and increases the C sequestration or storage for a long period. The impact of NT has significant effects on soil health by sequestering more C and improving soil aggregation when systematically followed for longer durations.

17.3 Impact of NT on Soil Compaction

In mechanized agriculture, soil compaction has been recognized as a severe problem and has an impact on many soil physical, chemical, and biological properties and also on crop yield (Etana et al. 2013). Soil compaction in agricultural soil is caused by the compression of soil particles from heavy machinery traffic or livestock trampling (Chamen et al. 2015). Compacted soil has low porosity and air permeability, reduced water infiltration and drainage, and increased traction power in seedbed preparation. Soil compaction also leads to increased emission of GHGs (CO_2, CH_4, and N_2O) and contributes to global warming (Horn et al. 1995). At the soil surface or subsurface, soil compaction can occur in the form of soil crusting. Soil compaction can be caused by various farming practices and occur at different times of the year: (1) Soil tillage activity removes the protective crop residues from the surface soil, leaves the soil surface prone to excessive tillage or natural environmental forces (rain and wind), which causes soil aggregate breakdown, and can lead to soil crusting (Aikins and Afuakwa 2012); (2) when soils are wet, soil tillage equipment can induce compaction just below the depth of tillage (So et al. 2009); and (3) the heavy machinery used in agriculture systems (tractors, seed carts, combines, trucks, manure spreaders) to provide an optimum condition for all processes relevant to crop production (Aikins and Afuakwa 2012) can cause compaction through wheel traffic to a considerable depth within the root zone (Defossez and Richard 2002). As the moisture content of the soil increases, the depth of soil compaction also increases (Fig. 17.1). Soil compaction will restrict root growth and penetration into the subsoil (Badalíková 2010). This can lead to restricted water and nutrient uptake and stunted and drought-stressed plants, which results in reduced crop yields. In high-moisture conditions, soil compaction can reduce soil aeration and lead to anaerobic conditions (soil pores are mostly filled with water) (Badalíková 2010). Under anaerobic conditions, loss of nitrate-N (NO_3-N) increased through the denitrification process, which is the conversion of available NO_3-N into gaseous N forms, which are then lost to the atmosphere (Skiba 2008). Reduced soil aeration can also lead to restricted

Fig. 17.1 Visible wheel traffic compaction on soil surface under conventional till system compared to no-till. (Photo: Peter Sexton)

root growth and function and increase the risk of crop disease. All these factors can result in reduced crop yield and increased crop stress.

Living roots under the NT system increase soil pore space for increased soil permeability, infiltration, and water holding capacity. In a natural system, the land is not tilled extensively, and the presence of living cover protects the soil from the impact of a raindrop (Hoorman et al. 2009; Schnepf and Cox 2006). Growing cover crops in the winter season adds C inputs into the soil and keeps nutrients within the system. Organic matter retention under the NT system retains more soil moisture, thus helping the soil to rebound against soil compaction. The long-term NT system with continuous living crop cover (cover crops) is a system that closely imitates a natural system. Long-term NT with a continuous living crop cover protects the soil from compaction in various ways: (1) The soil surface with high organic matter acts like a sponge that absorbs the weight of heavy traffic (Håkansson and Reeder 1994); (2) Living plants with active root systems create voids and macropores in the soil so that water and air move into the soil. Oxygen is required for root respiration and supports an aerobic microbial community in the soil; (3) Soil microorganisms (especially fungi) and burrowing soil fauna get their food from plant roots and keep the soil from compaction (Jastrow and Miller 1997); (4) Organic matter added by the decaying plants, animals, and microorganisms is lighter and less dense than soil fractions. The average bulk density (BD) of SOM is 0.3–0.6 Mg m^{-3} compared to soil BD of 1.4–1.6 Mg m^{-3}. So, adding SOM to the soil reduces the average soil BD; and (5) Soil compaction can be reduced by combining microaggregates to form macroaggregates in the soil. Glomalin and polysaccharides weakly combine with microaggregates and form macroaggregates, but this bond is broken down once the soil is tilled or disturbed (Wright and Upadhyaya 1996).

Plant roots and microorganisms combine microaggregates together in the soil to form macroaggregates. Macroaggregates are mainly linked by fungal hyphae, polysaccharides, and root fibers. Macroaggregates with a size of more than 250 μm give soil its structure and improve air and water infiltration (Hoorman et al. 2009). Generally, compacted soils tend to have lesser macroaggregates and more microaggregates. Plant and soil microbes together produce glomalin, which acts like a glue that binds soil particles together and improves soil aggregate and soil structure. Glomalin, a glycoprotein in soil, cements microaggregates together, forms strong macroaggregates, and improves soil structure. Glomalin is in soil created by mycorrhizal fungus with sugars from plant root exudates (Allison 1968; Hoorman et al. 2009). To produce glomalin in soil, plants and mycorrhizal fungus must exist together. Glomalin must be continually produced because it is easily consumed by microorganisms in the soil, especially bacteria. Bacteria survive well under tilled soils because they are hardier and smaller than fungus, so the population of soil bacteria increases in tilled soil (Hoorman et al. 2009; Wright and Upadhyaya 1996). With a constant source of C and continuous living crop cover, fungi grow better under NT soils. Since fungi grow well under NT soils, more glomalin is produced, and higher macroaggregates are formed. On the other hand, under CT soils, fungi do not grow well and produce less glomalin and fewer macroaggregates (Wright and Upadhyaya 1996). Higher macroaggregates are associated with better soil structure, and fewer macroaggregates are associated with poor soil structure and lead to soil compaction. Soil compaction increases due to the lack of the production of polysaccharides, root exudates, and glomalin by active roots and mycorrhizal fungus. Heavy machinery under conventional systems pushes the microaggregates together so they can bind chemically and compact the soil (Hoorman et al. 2009).

The presence of higher organic matter content and enhanced microbial activity in NT soils makes the soil more resilient to compaction. Under the NT system, the presence of a thick layer of plant residues as the protective surface cover can reduce the negative effects of environmental forces such as raindrop impact or irrigation water causing soil crusting. Soil physical properties such as BD, porosity, PR, and soil structure are the most commonly measured properties under tillage conditions (Strudley et al. 2008) (Table 17.2). Soil BD is often used to evaluate the impact of traffic on soil quality. BD is an indicator of soil compaction and soil health (Badalíková 2010). Generally, lower BD values were obtained in CT treatments compared to NT systems (Aikins and Afuakwa 2012; Lampurlanés and Cantero-Martinez 2003; Romaneckas et al. 2009). Soil BD gives an indication of soil's strength and thus resistance to tillage activities. However, Sekwakwa and Dikinya (2012) reported that BD was the lowest under the NT system. Higher BD indicates lower total porosity because total porosity is inversely related to BD. While soil compaction increases BD, it decreases volume and pore size (Logsdon and Karlen 2004). Low porosity increases PR and decreases soil aeration (Kuht et al. 2012; Lampurlanés and Cantero-Martinez 2003). PR changes with soil moisture conditions, and it is one of the common methods used to measure soil strength. Therefore, PR is considered to be a good indicator of soil compaction due to different tillage practices (Celik 2011). Soil tillage and compaction have a close relationship, and generally the highest PRs were determined under NT than CT soils (Aikins and Afuakwa 2012; Lampurlanés and Cantero-Martinez 2003). In contrast, Olaoye (2002) found that NT soils provided the lowest PR. Nkakini and Fubara-Manuel (2012) reported no significant differences in PR and the total porosity under different

Table 17.2 Impact of tillage on soil physical and hydrological properties

Location	Soil type	Parameter	Salient findings	Reference
KwaZulu-Natal Province, South Africa	Haplic Ferralsols (clay loam)	Infiltration	NT soils took 5 min to reach 160 mm and CT soils took more than 50 min to reach a similar depth	Sithole et al. (2019)
South-Central Ohio, USA	Silt loam	Aggregate stability (AS)	AS increased 7% under NT, while it decreased by 2% under CT over time. (NT: 42.6% and CT: 33.8%)	Aziz et al. (2013)
Jokioinen, Finland	Vertic Cambisol	Mean weight diameter (MWD)	0.84 (NT) and 0.55 (CT) mm	Sheehy et al. (2015)
Central semiarid region of Argentina	Entic haplustolls	Bulk density (BD)	Significantly higher BD found at 0.10–0.20 cm under CT than NT (1.26 and 1.21 Mg m^{-3}, respectively)	Quiroga et al. (2009)
Grafton NSW, Australia	Ultisols	Soil strength	1874 kPa under CT and 1236 kPa under NT	So et al. (2009)
		Hydraulic conductivity	The NT surface soil had a greater hydraulic conductivity at field saturation (K_{sat}) and a smaller unsaturated hydraulic conductivity (K_{unsat}) than the CT surface soil	
Southern Queensland, Australia	Alfisol (Typic Natrustalf)	BD	BD under NT (1.44 Mg m^{-3}) was greater than CT (1.38 Mg m^{-3}) at 0–10 cm depth	Thomas et al. (2007)
Pasinler of East Anatolia Agricultural Research Institute, Turkey	Inceptisol	BD	BD under NT (1.38 Mg m^{-3}) was greater than CT (1.17 Mg m^{-3}) at 0–10 cm depth	Gozubuyuk et al. (2014)
		Penetration resistance (PR)	PR under NT (2.60 MPa) was greater than CT (0.51 MPa)	
Kumasi, Ghana	Ferric Acrisol	BD	1.45 Mg m^{-3} under NT and 1.25 Mg m^{-3} under CT	Aikins and Afuakwa (2012)
		PR	Soil PR was significantly higher under NT (661 kPa) as compared	

(continued)

Table 17.2 (continued)

Location	Soil type	Parameter	Salient findings	Reference
			with that in the tilled soil (117 kPa)	
Northeast Ebro Valley, Spain	Fine-loamy, mixed, Mesic Fluventic Xerochrept	BD	BD was greater for NT (1.34 Mg m^{-3}) and lower for CT (1.22 Mg m^{-3})	Lampurlanés and Cantero-Martinez (2003)
		PR	PR in NT was 1 MPa greater than CT in the first 10-cm depth	
Niger State, Nigeria	Ferruginous Ferrisols	PR	PR under NT was 0.18 MPa and 0.76 MPa under CT	Olaoye (2002)

tillage treatments. Lower PR values under the CT system could be associated with the increase in the intensity of soil loosening due to tillage activities. Therefore, following NT and retaining crop residues on the soil surface could improve soil properties and reduce soil compaction and soil erosion.

17.4 Impact of NT on Soil Biological Properties

Tillage systems influence the physical and chemical properties of soil and bring about changes in soil biochemical activities, microbial community structure, and function. CT practices may adversely affect the long-term productivity of soil due to the loss of organic matter and soil erosion. Tillage activities can directly affect microbial communities due to habitat modifications, loss of connectivity between species, disruption of nutrient passage, and increased runoff (Young and Ritz 2000). The frequent soil disturbances under tillage systems may induce changes in soil biodiversity by favoring disturbance tolerating species (Buckling et al. 2000), thus affecting not only the composition of the microbial communities but also their diversity. Human-induced changes in soil microbial community structure, composition, and function are well documented (Andrade et al. 2003; Ceja-Navarro et al. 2010b; Souza et al. 2015). Intensive tillage practices may negatively affect soil biochemical activities and microbial community structure through (1) a reduction of substrate availability (SOM) for the growth of microorganisms, (2) a decline in favorable microhabitat for soil microbes (water-stable macroaggregates), and (3) changes in soil temperature, moisture, and other environmental conditions (Balota et al. 2004; Dilly et al. 2003).

The negative effects of CT on soil erosion, loss of nutrients, SOM, and soil macro- and microorganisms have led to increased usage of the NT system. Currently, NT activities are practiced on nearly 155 M ha worldwide, which comprises 11% of the total arable land in the world (Kassam et al. 2014). South and North America are the largest adopters of the NT system with the adaptation rates of nearly 45% and 32%, respectively (Friedrich et al. 2012). Sustainable conservational practices can be followed through NT, high residue return, and diversified crop rotation (Hobbs et al. 2007). Soil tillage systems, fertilizer management, climatic conditions, and soil types influence the soil microbial and macrofaunal population and diversity (Blankinship et al. 2011; Chan 2001). CT management system and the removal of crop residues have, for many years, resulted in the decline of SOM content, deterioration of soil physical, chemical, and biological properties, and high rates of increase in the risk of soil erosion (Ouédraogo et al. 2006). Conservation tillage practices leave more than 15% of crop residues on the surface as a soil cover, while CT leaves less than 15% residue at the time of planting to the succeeding cash crop. SOM dynamics are highly dependent on the microbial community and diversity (Álvaro-Fuentes et al. 2013). Conservational tillage is comparatively advantageous to CT (moldboard or disk plow) with respect to SOM, microbial activity, enzyme production, soil physical properties, and prevention of wind and water erosion (Bossuyt et al. 2002; Hevia et al. 2007). The response of biochemical activities and soil microbes to tillage activities have been measured by estimating the soil enzymatic activities and the size and activity of the microbial community (Carter et al. 1999).

Mathew et al. (2012) investigated the effects of CT and NT practices on soil microbial communities and enzyme activities in a continuous maize production system. Phospholipid fatty acid (PLFA) analysis revealed that total PLFA increased higher under NT than under a CT system (Table 17.3). Total PLFA is an indicator of viable soil microbial biomass and ranged from 30 nmol g^{-1} of soil under CT at 5–15 cm depth to 104 nmol g^{-1} of soil under the NT system at 0–5 cm depth. They reported that as soil depth increased, total PLFA biomass decreased in both tillage treatments. The results also revealed that soil under the long-term NT system had higher soil microbial community structure and enzyme activities than that under the CT system. These observations are in agreement with previous findings reported by Ceja-Navarro et al. (2010a), Ekenler and Tabatabai (2003), and Helgason et al. (2009). Carpenter-Boggs et al. (2003) evaluated the response of soil microbial activities between CT and NT management in South Dakota. They reported that mineralized C was increased under NT (96 μg C kg^{-1} soil) compared to the CT (62 μg C kg^{-1} soil) system. Collins et al. (2000) also reported that higher soil microbial biomass C accumulated at 0–20 cm under the NT system than CT. The adoption of NT also has a positive impact on soil bacterial assemblages. White and Rice (2009) reported greater microbial abundance under NT compared to CT soils in Kansas, USA. This same study also found that total gram-positive and negative bacterial and fungal PLFA were greater under NT owing to greater crop residue decomposition. Similarly, Mbuthia et al. (2015) observed an increase in the mean abundance of actinomycetes, gram-positive bacteria, and mycorrhizae PLFA biomarkers under the NT system compared to CT in continuous cotton in West Tennessee, USA. Feng et al. (2002) also demonstrated an increase in microbial biomass C under the NT system compared to tilled soils. Mathew et al. (2012) reported a greater total PLFA under the NT system compared to CT soils in Alabama, USA. Dorr de Quadros et al. (2012) found that when NT was implemented, anaerobic communities were dominant in the microbial community

Table 17.3 Impact of tillage on soil biological properties

Duration (years)	Soil type	Depth (cm)	Parameter	NT vs. CT	Location	References
14	Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults)	0–5	Total phospholipid fatty acid (PLFA)	104 and 39 nmol g^{-1}	Alabama, USA	Mathew et al. (2012)
		5–15		38 and 30 nmol g^{-1}		
		0–5	Acid phosphatase	367 and 200 μg of *p*-nitrophenol g^{-1} h^{-1}		
		5–15		307 and 202 μg of *p*-nitrophenol g^{-1} h^{-1}		
6	Highmore silt loam	0–15	Mineralized carbon (C)	96 and 62 μg C kg^{-1} soil	South Dakota	Carpenter-Boggs et al. (2003)
			Alkaline phosphatase	325 and 190 μg NP g^{-1} soil h^{-1}		
12	Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults)	0–3	Microbial biomass C (MBC)	633 and 266 μg g^{-1}	Alabama, USA	Feng et al. (2002)
32	Lexington silt loam (fine-silty, mixed, thermic, Ultic Hapludalf)	0–7.5	Gram-positive bacteria	12.71 and 12.15 nmol g^{-1} soil	West Tennessee, USA	Mbuthia et al. (2015)
			Actinomycetes	5.78 and 5.46 nmol g^{-1} soil		
			Mycorrhiza	3.94 and 3.36 nmol g^{-1} soil		
22	Oxisol (Typic Haplorthox)	0–5	MBC	372 and 145 μg g^{-1}	State of Parana, Brazil	Balota et al. (2003)
			Microbial biomass nitrogen (MBN)	28.3 and 17.2 μg g^{-1}		
			Microbial biomass phosphorus (MBP)	18.3 and 10.7 μg g^{-1}		
20	Muir silt loam	0–5	Total PLFA	NT was 1.5 times higher than the CT	Kansas, USA	White and Rice (2009)

structure. According to Doran (1980), Balota et al. (2004), and DeBruyn et al. (2011), such variation in microbial composition and structure is mainly associated with changes in soil moisture, C, N, and pH.

Soil microbes improve soil health by cycling nutrients and breaking crop residues down into SOM. The reduction in SOM also affects soil macrofauna, which has a key role in soil structural formation, recycling of soil nutrients, and decomposition of SOM. The effect of macrofauna, especially earthworms and termites, on soil structural formation has been well documented and they are considered ecosystem engineers because of their key role in soil structural formation (Blanchart et al. 2004). Earthworms, through their burrowing and casting activities and biological and physicochemical changes, modify soil structure and significantly impact soil physical properties such as water infiltration and aeration (Blanchart et al. 2004). Termites, through their activities of transporting and cementing soil particles, alter the soil structure and its properties (Mando and Miedema 1997). On the other hand, other groups of soil macrofauna such as epigeic earthworms and Mollusca (litter transformers) have little effect on soil structure (Lavelle et al. 1997). These macrofaunae concentrate their activities mostly on surface soil where they physically break crop residues and deposit organic matter. Therefore, maintaining a suitable environment for soil macrofauna and microorganisms in cropland is important to maintain long-term soil health and sustainability of crop production.

17.5 Summary

Conservation tillage systems such as NT have a positive impact on SOC storage, nutrient availability, soil compaction, aggregate stability, soil productivity, and profitability under different climatic and soil conditions. The no-till system is a powerful tool to combat soil degradation because of reduced soil erosion and soil compaction. These systems increase crop residue cover and living roots and create better soil structure. Soils managed with NT systems can be beneficial in increasing SOC content and improving soil aggregation. Living roots and crop residue cover under the NT system increase soil porosity, permeability, infiltration, and water holding capacity. The presence of a thick layer of plant residues as a protective surface cover under the NT system can reduce the negative effects of environmental forces such as raindrops or irrigation water causing soil crusting. These conservation systems protect the soil surface, conserve energy, and improve soil health by enhancing SOM and microbial activity. Practicing NT systems for a longer duration can enhance soil health by improving SOM content, soil structure, infiltration, and microbial diversity.

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18 Impact of Residue Burning on Soil Biological Properties

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Abstract

Crop residue burning is an emerging problem due to shortage of manual labor and mechanization of agricultural practices. It affects not only soil microbial community and nutrient transformation processes in soil but also human and animal health adversely. Soil is a medium for plant growth and a support system of millions of fauna and flora, greatly affected by repeated burning of crop residue in farms. Changes in microbial activity upon crop residue burning depend on soil temperature, length of burning, rain incidence after burning, dominant group of microorganisms, and time of sampling. The adverse effects of residue burning on soil biota and thus on soil health will continue for long term, and that eventually affects sustainable crop production. The increased soil temperature at the time of residue burning not only kills the soil microbes but also depletes soil organic carbon level, which is vital for keeping soil living. In short, adopting suitable location-specific technology is necessary to ensure proper residue management without harming the various life forms on earth. Also, encouraging and incentivizing the farming community for enriching the soil with carbon will help in discouraging the practice of crop residue burning.

Keywords

Crop residue burning · Soil microbes · Soil enzymes

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18.1 Introduction

Soil is a habitat for numerous organisms (flora and fauna) each with specific ecological significance; thus, a handful of it sustains billions of life and represents a medium where thousands of biochemical reactions are on at any given time. Living organisms in soil are the agent who keeps the soil maintained for sustainable crop production provided enough organic resources are added to the soil for maintenance rich biodiversity. In this way, organic matter in soil becomes vital for the survival of soil microbes, and in turn microbes keep soil structured for sustainable production. Immediately after crop residue burning, the surface soil temperature rises to several degrees than normal that can kill the mesophilic organisms actively participating in nutrient transformation at the upper soil layer.

Understanding microbial dynamics is important in the development of new management strategies to reverse declining soil organic matter (SOM) content and improving soil fertility. Management practices such as crop rotation, crop residue management, and N fertilization had a significant effect on soil microbial biomass carbon (SMBC) and nitrogen (SMBN) (Witt et al. 1998, 2000). Collins et al. (1992) measured changes in microbial biomass C and N and populations of several soil microbial groups in long-term plots under different winter wheat (*Triticum aestivum* L.) crop rotations. Wheat-fallow treatments included wheat straw incorporated (5 Mg ha^{-1}), no N fertilization; wheat straw incorporated, 90 kg N ha^{-1}; wheat straw fall burned, no N fertilization; and wheat straw incorporated, 11 Mg barnyard manure ha^{-1}. Annual-crop treatments were continuous wheat, straw incorporated, 90 kg N ha^{-1}; wheat-pea (*Pisum sativum* L.) rotation (25 years), wheat and pea straw incorporated, 90 kg N ha^{-1} applied to wheat; and continuous grass pasture. Total soil and microbial biomass C and N contents were found significantly greater in annual crop than wheat-fallow rotations, except manure-applied treatment. Microbial biomass C in annual-crop and wheat-fallow rotations averaged 50% and 25%, respectively, of that in grass pasture. Burning residues reduced microbial biomass to 57% of that in plots receiving barnyard manure. Microbial C represented 4.3%, 2.8%, and 2.2% and microbial N 5.3%, 4.9%, and 3.3% of total soil C and N under grass pasture, annual cropping, and wheat-fallow, respectively. Both microbial counts and microbial biomass were higher in early spring than in other seasons. According to the Indian Ministry of New and Renewable Energy (MNRE), India generates on an average 500 million tons (Mt hereafter) of crop residues per year with rice (105 Mt), wheat (94 Mt), sugarcane (361 Mt), oilseeds (30 Mt), cotton (35 Mt), jute (11 Mt), and pulses (17 Mt) (Bhuvaneshwari et al. 2019). Biomass burning severely influences the emission of soil and airborne microbes and increases the risk of exposure to their potent pathogenic particles regionally as well as globally (Tyagi et al. 2016).

Burning is an inexpensive, labor-efficient means of removing unwanted crop residues prior to tillage or seedbed preparation. Burning grass pastures results in short-term increases in nitrogen mineralization, which results in a short burst of nutrients available for the plant.

However, frequent burning has detrimental effects such as (1) the removal of the extra vegetative material that would add humus and nitrogen to the soil; (2) destruction of old vegetation in the soil, which functions to increase water-holding capacity; and (3) injury to living vegetation, especially short grasses and shallow-rooted grasses, which may be killed by a single burning. Repeated, long-term burning of crop residue or grass (pastures) can have a more permanent negative effect on soil quality and deteriorates overall soil health (Richard 2001). Repeated burning can cause long-term reduction in yields. These long-term losses in yield cannot be offset by the addition of fertilizer. Additionally, soils that are high in fertility may take several years to show the detrimental effects of burning. However, research has furnished concrete evidence of the slow but sure consequences of repeated burning of crop residue to soil health. Furthermore, what may look like a saving in fertilizer, pesticides for weed control, or insecticides for insect control will eventually turn into increased long-term costs to maintain productivity due to continual loss of organic matter, organic nitrogen, organic carbon, and the size and quantity of microbial pools (Richard 2001).

Soil is the basis for agricultural and rural sustainability and supports the livelihood of almost more than 50% of the Indian population. Approximately 500–550 Mt of crop residues are produced per year in the country from various foods, fiber, millet, pulses, oilseeds, and cash crops (Ramesh et al. 2019). Though a portion of these residues find alternative use in the rural area, viz., cattle feeding, soil mulching, thatching for rural homes, and fuel for domestic use, still, a large portion of the residues are burnt on-farm primarily to clear the field for the sowing of the succeeding crop (Indoria et al. 2018). The rice-wheat cropping system is the dominant cropping system in South Asia. The major constraint in a rice-wheat cropping system is the available short time between rice harvesting (late October and early November) and sowing of wheat (November). Given this short time, farmers find it difficult to utilize the residue, and hence they adopt large-scale residue burning. Burning of crop residue not only leads to pollution but also results in the loss of nutrients present in the residues. The entire amount of C, approximately 80–90% N, 25% of P, 20% of K, and 50% of S present in crop residues are lost in the form of various gaseous and particulate matters, resulting in atmospheric due to sugarcane trash burning followed by rice and wheat straw (Jain et al. 2014). Burning of sugarcane trash led to the loss of 0.84 Mt, rice residues 0.45 Mt, and wheat residue 0.14 Mt nutrient per year out of which 0.39 Mt was nitrogen, 0.014 Mt was potassium, and 0.30 Mt was phosphorus (Jain et al. 2014). Elevated soil temperature due to heat generated from the burning of crop residues causes a temporary decline in the population of active soil flora and fauna including beneficial microbial population; however, repeated burning incidence in fields diminishes the microbial population permanently (Manjunatha et al. 2015). The burning of crop residues immediately increases the exchangeable NH_4^+-N and bicarbonate-extractable P content, but there is no buildup of nutrients in the profile. Long-term burning reduces total N and C, as well as potentially mineralizable N in the upper soil layer. People with respiratory disorders were susceptible to the air pollution caused by burning of agricultural residue. Underlying symptoms either became worse, or additional air pollution-related symptoms were induced. Burning of crop residues emitted 8.57 Mt of CO, 141.15 Mt of CO_2, 0.037 Mt of SOx, 0.23 Mt of NOx, 0.12 Mt of NH_3, 1.46 Mt of NMVOC, 0.65 Mt of NMHC, and 1.21 Mt of particulate matter for the year 2008–2009. The variability of 21.46% in annual emission of air pollutants was observed from 1995 to 2009 (Jain et al. 2014).

Deterioration of soil fertility due to burning and consequent raise in the soil temperature causes depletion of the bacterial and fungal population. The residue burning increases the subsoil temperatures to nearly 33.8–42.2 °C at 10 mm depth, and long-term effect may reach up to 15 cm of the top soil. Frequent burning reduces nitrogen and carbon potential of the soil, kills the micro flora and fauna beneficial to the soil, and further removes the large portion of the organic matter. With crop burning, the carbon nitrogen equilibrium of the soil is completely lost. Burning of 1 t of straw may account for the loss of entire amount of organic carbon, 5.5 kg of nitrogen, 2.3 kg of phosphorous, 25 kg of potassium, and 1.2 kg of sulfur. On an average, crop residues of different crops contain approximately 80% of nitrogen (N), 25% of phosphorus (P), 50% of sulfur (S), and 20% of potassium (K). If the crop residue is retained in the soil itself, it can enrich the soil with C, N, P, and K (Bhuvaneshwari et al. 2019).

18.2 Why Crop Residue Burning Is Practiced by Farmers in India?

Replacement of manual harvesting with mechanical (combined harvester) harvesting practice due to shortage of labor mainly accounts to this problem. Declining population of livestocks, long period required for composting, and unavailability of alternative economically viable solutions compelled farmers to burn the residues (Prasad et al. 1999). Total amount of residue generated in 2008–2009 was 620 Mt out of which ~15.9% residue was burnt on farm. Rice straw contributed 40% of the total residue burnt, followed by wheat straw (22%) and sugarcane trash (20%) (Jain et al. 2014). Farmers opt for burning because it is a quick and easy way to manage the large quantities of crop residues and prepare the field for the next crop well in time.

Burning of field with wheat residue

Burning of field with Paddy residue

Smoke due to burning of sugarcane trash

18.3 Consequences of Crop Residue Burning

The heat from burning cereal straw can penetrate into the soil up to 1 cm, elevating the temperature as high as 33.8–42.2 °C (Gupta et al. 2004). Repeated burning in the field permanently decreased the bacterial population by more than 50%, but fungi appeared to recover and also decreased soil respiration. Long-term burning reduces total N and C and potentially mineralized N in the 0–15 cm soil layer. One of the recognized threats to the RWS sustainability is the loss of SOM as a result of burning. This burning may lead to considerable nutrient loss also. Crop residues are a good source of plant nutrients and are important components for the stability of the agricultural ecosystem. About 25% of N and P, 50% of S, and 75% of K uptake by cereal crops are retained in crop residues, making them viable nutrient sources (Gupta et al. 2004).

18.4 Alternate to Crop Residue Burning Crop: Some Strategies and Solutions

- Educating farmers about ill effects of crop residue burning on soil, plant productivity, and environmental and human health through mass media like radio, television, newspapers, etc.
- Propagation and intensification of composting technology and training farmers for efficiently converting agro-wastes into compost.
- Strengthening basic research for rapid decomposition of agricultural residues and in situ decomposition of residues.
- Conservation agriculture.
- Mechanical intervention like the use of baler to collect and stake the residue after harvesting for off-farm composting.
- Popularization of machines that collects the residue after harvesting the crops, etc.

18.5 Consequences of Crop Residue Burning on Soil Microbial and Biochemical Activities

Soil biological components are the most sensitive indicator of change in response to management practices. The biological component may include but not limited to SMBC, soil enzymes, respiration, soil ATP, soil metagenome, etc. Change in the levels of these components may indicate the effect of imposed management. Very often, the soil microbes have been correlated with the activity of soil enzymes, which determines the soil catabolic ability and nutrient cycling. Thus, soil enzyme assays have been used to monitor the microbial activity related to specific nutrient transformations and effects of the management system on soil quality (Dick 1994). Wheat straw burning reduces the bacterial count in the top 2.5 cm layer by 50% and by 70% compared to treatment where wheat straw was mixed with soil (Hesammi

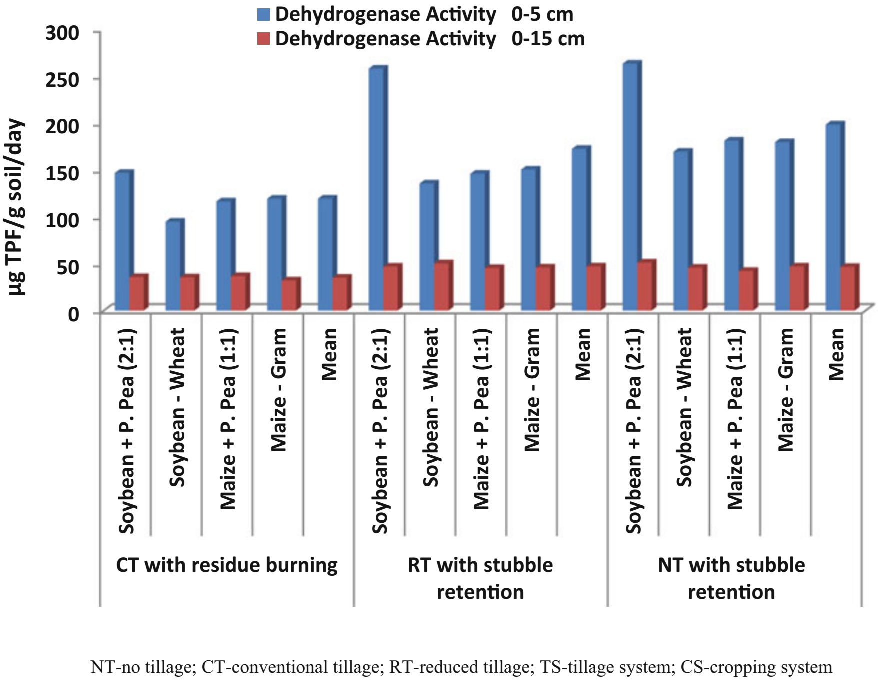

Fig. 18.1 Effect of residue retention and burning under different tillage practices on dehydrogenase activity of soil. *NT* no tillage, *CT* conventional tillage, *RT* reduced tillage, *TS* tillage system, *CS* cropping system

et al. 2014). Long-term annual burning results in lower SOM and net N mineralization rates but higher levels of plant productivity compared with no burning (Ojima 1987). This indicates a change in N cycling and use. Microbial biomass is important to crop, pasture, and grass production in that a constant "pool" of microbes are needed to break down straw, stubble, and duff into nutrients that are useable by plants. When there are very few microbes (a small pool), there is less total activity to break down straw and stubble and, thus, less nutrients available for the plant. This in turn relates to reduced production. Ojima (1987) found that microbial biomass C and N were reduced by long-term annual burning, but were affected very little by short-term burning (1–2 years). They also reported that short-term burning created increased active N and N mineralization rates (increase in available N for the plant). However, long-term burning resulted in a decrease in SOM and N mineralization rates (Fasching 2001). Reduction in level of soil enzyme activity such as dehydrogenase, fluorescein acetate (FDA) hydrolysis, β-Glucosidase, urease, acid, and alkaline phosphatase with sugarcane trash burning in fields (Phalke et al. 2017) suggests the decrease in the microbial activity of the residue burnt soil, which may eventually interfere with nutrient cycling and soil productivity. Soil temperature of 34.8–35.7 °C measured before burning reaches to as high as 51–55 °C during burning (Somasundaram et al. 2018, unpublished data), which can kill mesophilic

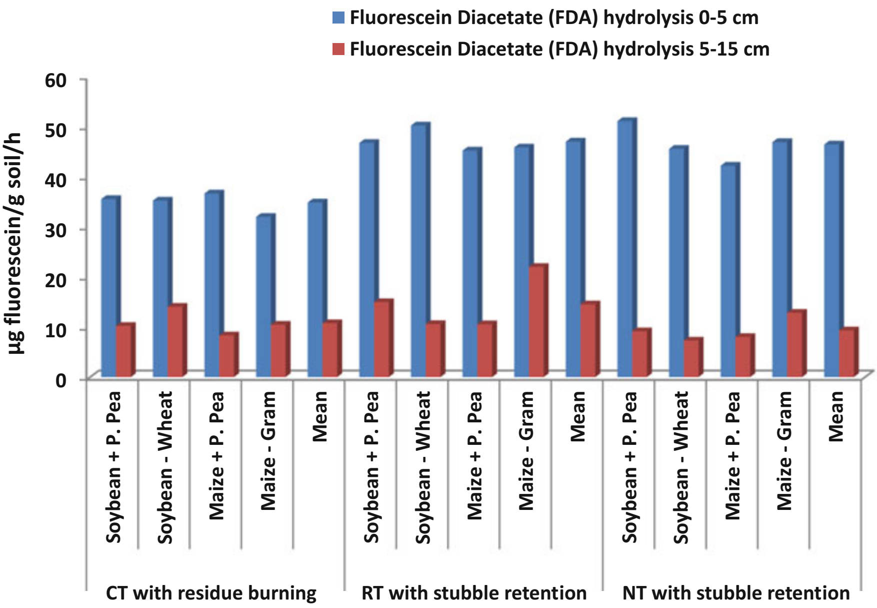

Fig. 18.2 Effect of residue retention and burning under different tillage practices on fluorescein diacetate hydrolysis activity of soil. *NT* no tillage, *CT* conventional tillage, *RT* reduced tillage, *TS* tillage system, *CS* cropping system

populations. Somasundaram et al. (2018, unpublished data) reported that dehydrogenase activity (DHA) in no tillage with stubble retention was 66% higher compared to conventional tillage with residue burning (Fig. 18.1), whereas fluorescein diacetate hydrolysis was higher (47.05 μg fluorescein g^{-1} soil h^{-1}) in reduced tillage with stubble retention compared to conventional tillage with residue burning at surface soil (0–5 cm) (Fig. 18.2). Reduction in measure of total glomalin content and diminished count of Basidiomycete and earthworm populations reported by Wuest et al. (2005) suggests the detrimental effect of residue burning.

18.6 Ex Situ Management Options to Abate Burning

In ex situ management, crop residues can be converted to valuable products like the production of producer gas through the gasification process and biochar through a thermochemical conversion process called pyrolysis in an anoxic environment. Biochar is a carbon-rich porous material and can be used as a soil amendment. Composting through a simple aerobic or anaerobic process can be done to convert agro-residues into a valuable soil amendment. The composting time can be also reduced by manipulating physico-chemical conditions as well as through incorporation of effective microbial inoculums. The agricultural residues can also be utilized as bedding materials for cattle and fuel briquettes and can be used as cattle feed after nutrient enrichment.

18.7 Conservation Agriculture to Avoid Burning and Offshoot Climate Change

Conservation agriculture (CA) involves practices such as minimum or zero mechanical disturbances, crop residue retention, permanent organic soil cover, diversified crop rotations, precise placement of agrochemicals, infield traffic control, and application of animal manure and crop residues. The benefits of CA are lower farm traffic, reduction in the use of mechanical power, labor inputs thus resulting in timely field operations, lower risk of crop failure and ultimately resulting in higher yields, lower costs, and reduction in environmental pollution. The latter relates to reduced use of fossil fuels with associate reduction in CO_2 emissions, improved soil carbon levels, and reduction in the use of fertilizer and chemicals and thus resulting in carbon sequestration. A good number of machines such as no-till drill, strip-till drill, raised bed planter, laser land leveler, straw cutter cum incorporator, straw baler, farm residue collector, and straw combine have been developed and are being propagated. Sowing of wheat with the traditional method requires 7–8 days in field preparation that also delays the sowing of wheat resulting in decrease in yield. Hence, for timely sowing of wheat, a conventional zero-till drill was developed, which consists of a conventional tractor drawn seed cum fertilizer drill with disc coulters attached in front of the fixed-type furrow openers. It can be used for sowing wheat in fields where paddy had been sown earlier (Tandon 2007).

18.8 In Situ Decomposition of Crop Residue

The stubble left after harvesting can be incorporated into the soil along with supplemental doses of nitrogen and water to accelerate decomposition without the immobilization of nitrogen. This practice will not only enrich the soil with organic matter but also foster soil biodiversity, activating the microbes for efficient nutrient cycling. Use of efficient microbial culture can aid in the decomposition process and may cut the time required for composting. The limitation in in situ decomposition process includes no availability of irrigation water, short time gap between harvest of preceding crop and sowing of succeeding crop, and extra labor and cost incurred on the incorporation of residue and application of fertilizers and inoculants.

18.9 Conclusions

Research has shown that occasional burning of straw and stubble may provide the producer with an economical and effective management tool and in some cases increase small grain and grass production in the short term. However, repeated, long-term burning of straw or grass can have a more permanent negative effect on soil quality and overall soil health. Repeated burning can cause long-term reduction in yields. These long-term losses in yield cannot be offset by the addition of fertilizer. Additionally, soils that are high in fertility may take several years to show the detrimental effects of burning. Furthermore, the benefit visualized in terms of saving in fertilizer, pesticides for weed control, or insecticides for insect control will eventually turn into increased long-term costs to sustain productivity lost to the loss of organic matter and shrunken microbial diversity, organic nitrogen, and organic carbon.

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Physical and Hydrological Processes in Soils Under Conservation Tillage in Europe

19

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Abstract

Soil structure is core to many physical soil properties important for sustainable crop production. Aggregate formation and size distribution are related to the pore system, which in turn affects air and water flow. Additionally, soil physical deterioration such as compaction and superficial sealing or crusting derives from poor structural stability, leading to a decrease in infiltration, hydraulic conductivity, and changes in water retention. Consequently, aggregate stability has been used as an indicator of soil structure and soil health. Factors controlling aggregate formation and breakdown are various and operate at different scales. In Europe, it is worthwhile to distinguish among the boreal, temperate, and Mediterranean biogeographic regions as regards as climate concerns. Agricultural practices play an important role at the field scale affecting variables such as the organic matter content, biological activity (roots, earthworms, hyphae, microorganisms, etc.), physical and chemical properties that can induce dispersion or flocculation and of course the mechanical disruption of tillage. However, effects of land use and soil management are soil-specific as the interaction of controlling factors is complex and can lead to site-specific dominant processes.

Keywords

Soil structure · Tillage · Porous system · Aggregates · Organic matter · Soil management

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19.1 Introduction

19.1.1 Soil Structure: Core to Soil Physical Properties

Soils are complex porous media composed of solid, liquid and gaseous constituents. Soil structure is the aggregation of soil particles (sand, silt, clay and organic matter) into granules, crumbs or blocks. Inorganic and organic constituents are bound together forming aggregates and leaving voids in between, which constitute the porous system. Soil structure is the shape that the soil takes based on its physical, chemical and biological properties, regulating the soil-water cycle and sustaining a favourable rooting medium for plants (Kibblewhite et al. 2008). Despite the rigidity of the term, soil structure is dynamic, with cyclical aggregate breakdown and new aggregation, depending on many factors. Aggregate stability is an indicator of soil quality, as in well-structured soils with stable aggregates, water and air have no physical impediment to flow. On the contrary, soils with poor structure have unstable aggregates that break easily into smaller particles, reducing the pore space and its connectivity, inducing numerous problems including waterlogging and oxygen deficits for plant roots and other organisms (Batey 2009; Morris et al. 2010).

There are many factors influencing aggregate dynamics. These factors are from the soil itself (e.g. organic matter, clay, sand and salts content), the environment in which it develops (e.g. climate or topography) and the land use it is subjected to (e.g. forestry, pasture or cereal cropping). Therefore, soil structure and the physical properties which depend on it are soil- and site-specific. Thus, conservation tillage will have different effects on soil physical properties and, in turn, how these influence agricultural production, depending as well on the geographical location.

Conservation tillage (CT) is a term that includes a range of practices that compared to conventional tillage reduce ploughing depth, number of passes or disturbed surface; does not turn over the soil or even drills seeds directly into the undisturbed soil (with the exception of the furrow to place the seed). Farmers around Europe adopt these CT practices in a flexible way, adapting the technology to local conditions and their own personal preferences, resulting in many different farming approaches. Depending on the tillage practice, the environment and the combination of practices of the system in which it is applied, the impacts on the soils' physical and hydrological properties vary.

In Europe, conservation tillage, in any of its forms, is applied in 22.14% of its 102,535,310 ha of arable land, but this percentage varies greatly across regions (EUROSTAT 2010). Another estimate reported that CA is practised on 22.7 Mha, representing 25.8% of arable land in Europe (Kertész and Madarász 2014; Soane et al. 2012). EUROSTAT (2010) data analysis shows that Bulgaria is leading the adoption of conservation tillage, with 55.81% of its arable land. Cyprus, Germany, Czech Republic, the United Kingdom, France, Spain, Austria, Luxemburg, Switzerland and Finland are all above the European average. When focusing on no tillage, the European average that is under this practice is only 3.44% (3,527,214.66 ha). Finland is leading the adoption of no tillage with 7.25% of the arable land, and Romania, Estonia, Spain, Denmark, Italy, Poland and the United

Kingdom are above the European average. In the case of no tillage, Cyprus and Bulgaria have some of the lowest adoption rates. These adoption rates and their variability show that the adoption of conservation agriculture (CA) practices are complex decisions influenced not only by land suitability but also by sociocultural and economic factors.

Any of the conservation tillage (CT) practices reduces the mechanical breakdown of the soil aggregates and the machinery load on the soil. Therefore, aggregates have more time to establish stronger bonds and become more resistant to other disturbances. By reducing the number of field operations, CT also decreases the number of passes of heavy machinery through the field and therefore decreases the risk of soil compaction, whereas in conventionally ploughed fields, below the plough layer, compaction can lead to the formation of a plough pan, which constitutes a physical barrier for root development and water flow. Furthermore, the benefits of CT on soil structure stability increase with the adoption of CA systems, including surface protection and crop rotation. This is because these practices add organic matter and increase soil biological activity, which are aggregation agents that contribute to a more stable soil structure.

19.1.2 Soil Structure and Aggregate Dynamics

Research advances have developed our understanding of soil structure and aggregate dynamics and how they are affected by numerous factors that vary geographically, including tillage practices.

Tisdall and Oades (1982) introduced the importance of soil organic matter (SOM) in the aggregation process. They proposed a hierarchical model in which larger aggregates are formed by smaller aggregates. Moreover, they stated that each aggregate size had its own major binding agent. Indeed, the effectiveness of binding agents depends on their own dimensions in relation to the voids and particles they have to bridge (Kay 1990 cited in Jastrow and Miller 1997). The nature of the aggregation agents leads to differences in aggregate stability. Thus, roots and fungal hyphae are the major binding agents for macroaggregates (>250μm diameter), whose labile characteristics explain why macroaggregates break down into smaller particles easier than microaggregates (<250μm diameter), which are bound together by more recalcitrant organic matter or more stable aggregation agents.

Further development of the hierarchical model helped to relate soil structure to the carbon cycle, in a process that follows organic residue decay, successive integration in soil, occlusion in soil aggregates and sorption to clay minerals (Golchin et al. 1994), which represent consecutively increasing carbon sequestration potential. Afterwards, it was shown that microaggregates form inside macroaggregates (Angers et al. 1997). Since the latter provides physical protection from microbial attack of fresh organic matter, giving it time to establish chemical or physico-chemical bonds with clay particles or more stable organic compounds (Balabane and Plante 2004).

Time is precisely what conservation tillage provides, by avoiding mechanical disturbance, therefore allowing the development of more stable aggregates. On the contrary, macroaggregate turnover rates in cultivated land are only between 5 and 33 days (Plante and McGill 2002a, b). Even the hierarchical model highlighted the vulnerability of macroaggregates to tillage, since their binding agents are labile. More recently, the disruptive effects of tillage have been ratified by other researchers, proving that tillage disturbance increases macroaggregate turnover and carbon mineralisation (Six et al. 1998). Notwithstanding the generally accepted slower turnover rates in microaggregates, Virto et al. (2010) found similar ages of organic matter from within silt-size microaggregates and from outside those silt-size microaggregates, therefore questioning the understanding of turnover rates of this aggregate fraction, which would be much quicker than previously thought.

Besides, the major influence of organic matter in aggregate dynamics, aggregate formation and breakdown is a complex process influenced by many other factors. Even the authors of the hierarchical model highlighted that organic matter becomes the major bonding agent only in soils where other binding agents are absent. Amézketa (1999) showed there are many intrinsic or extrinsic factors affecting soil aggregate stability in different soils, making it a site- and soil-specific property. Among the binding agents are calcium carbonate, calcium sulfate (gypsum), silica, iron or aluminium oxides, clays and organic matter. In turn, their effects can be influenced by the soil solution electrolyte concentration, clay mineralogy, the nature of the organic compounds, climate, time (or ageing), roots, soil microbes, edaphofauna and agricultural management (i.e. tillage, irrigation, organic matter amendments, crop type and crop rotation, chemical amendments, etc.). Additionally, aggregate stabilization factors have interactions. For example, in an experiment in Argentina investigating the interaction between water regimes and vegetation, the results showed that aggregate stability was higher under wet and dry cycles with vegetation compared to the same moisture conditions in sterile soil (Taboada et al. 2004). Therefore, the importance of the synergies among CA practices, including soil surface protection with crop residues or cover crops, and crop rotation and diversification becomes apparent.

Across Europe, different soils and locations have distinct combinations of aggregation agents, which might be dominated by one particular agent. Cementing compounds are major aggregation agents in different soils; for example, Regelink et al. (2015) described the importance of Fe-(hydr)oxides in Austria, Czech Republic and Greece, and Boix-Fayos et al. (2001) stressed the importance of calcium carbonate in Spain. Furthermore, clay mineralogy has been studied by Norton et al. (2006), through soils of a range of clay types and under a range of land uses. They discovered that under cultivation, kaolinitic (1:1 clays, less reactive) soils had greater aggregate stability than in illitic or smectitic soils (2:1 clays, more reactive) but that kaolinitic clays associated with iron oxides, provided the stability that might be resistant even to land use change. However, the importance of studying the aggregation of distinct clay types stemming from the same soil has been emphasised, to avoid interferences of other aggregation agents; thus, Virto et al. (2008) and Fernández-Ugalde et al. (2013) showed that microaggregates tend to form in the more reactive 2:1 clays than kaolinite-type clays (1:1 type) or quartz. In the same soil, the latter were more abundant in non-aggregated particles.

Aggregate dynamics depend also on aggregate breakdown, which is not exclusively linked to organic matter decay. The disruptive processes that lead to aggregate breakdown also include physico-chemical dispersion, slaking, differential swelling and the impact of mechanical forces (Le Bissonnais 1996). Physico-chemical dispersion occurs in soils containing high concentrations of monovalent cations such as sodium from sodium chloride salt deposits. They act as dispersants between clay particles, whereas polyvalent cations, such as calcium, act as flocculants. Physico-chemical dispersion leads to aggregates breaking down into elemental particles. Several researchers observed that soil management history influenced clay dispersibility (Kay and Dexter 1990; Curtin et al. 1994, and Watts 1996, cited in Amézketa 1999). Furthermore, slaking disrupts aggregates during wetting due to forces generated by trapped air; it occurs at the same time as differential swelling, whose origin is influenced by the diverse expanding behaviours among soil compounds when moist. As a result of slaking and differential swelling, aggregates break into smaller aggregates. Finally, mechanical disruption occurs when external forces impact on soil aggregates, such as the "splash effect" from raindrops or the impact from tillage. According to soil composition, some soils, for example, saline soils rich in sodium, are naturally more vulnerable to any of these aggregate disruptive processes, and therefore they have to be treated with special care "during" agricultural land use (Rengasamy and Olsson 1991).

19.1.3 The Porous System

In parallel to aggregates, the soil structure is characterised by its voids or porous system. The pore system defines air and water flows through the soil and organisms' habitat. The formation of pore networks operates across many spatial scales. Earlier porous system models were based on textural properties, but these simplistic models have developed to include more realistic concepts such as pore connectivity and pore tortuosity. Logically, the pore system is linked with soil aggregate size distribution and vice versa (Lipiec et al. 2007).

Therefore, as a consequence of soil aggregation following a hierarchical model, a hierarchy in the pore system also exists. Accordingly, Elliott and Coleman (1988) described four pore sizes linked to the aggregate hierarchy which was further developed through hydraulic modelling, leading to the distinction of three categories with several subcategories as presented in Kutílek (2004):

- Macropores can either be formed by roots and earthworms resulting in stable pores; by cracking of swelling clays that shrink when the soil dries out; or by tillage, with their location limited by depth and their dynamics evolving throughout the growing season. In general, macropore size or diameter (typically $>250\mu m$) enables water to drain quickly at field capacity and to provide a path for macroarthropods.

- Micropores, also known as capillary pores, have a size or diameter (typically <250 μm) small enough to retain water at field capacity. In this category, there are inter-aggregate pores, big enough to be inhabited by nematodes, and a matrix of intra-aggregate pores. The pores within macroaggregates may be inhabited by small nematodes, protozoa and fungi, whereas the micropores within microaggregates may be around 1μm and inhabited mostly by bacteria.
- Submicroscopic pores (typically <30 μm) are so small that they restrict continuous water flow and cannot be inhabited by microorganisms.

19.1.4 Methods to Study Soil Structure

Traditionally soil structure has been defined through aggregate size distribution and aggregate stability tests. Tests include sieving through a series of decreasing mesh sizes. Dry or wet soil samples can be used. According to the purpose of the research, the chosen method will vary: dry sieving is used mainly in relation to wind erosion, whereas wet sieving is related to rain and runoff erosion, infiltration and formation of surface seals. It is important to note that the method highly influences the results, making it impossible to separate one from another (Nimmo 2005). Additionally, if the method requires wetting, the manner in which it is performed (quick wetting, slow wetting, in vacuum or through vapour) also produces slaking and differential swelling, which disrupts the soil aggregates and influences the results (Nimmo 2005). In any case, indexes have been developed to compare soils, the most widely used is the mean weight diameter (MWD), defined as the sum of the weighted mean diameters of all aggregate classes. The idea behind it is that the bigger the stable aggregate size, the more stable the soil itself (Nimmo 2005).

Another commonly used index is the water-stable aggregates (WSA), which is the proportion of dry sieved aggregates that resist water disruption. Barut and Celik (2017) found that on a clay soil in Turkey, under all tillage strategies, WSA increased in depth and that no tillage had greater WSA than conventional tillage (38.52% and 28.09%, respectively), whereas Sheehy et al. (2015) found the greatest difference in MWD between no tillage and conventional tillage on a silt clay soil (0.28 and 0.58 mm, respectively), whilst on clay soil the differences were not always statistically significant.

Nonetheless, Young et al. (2001) attributed the lack of a mathematical link between soil structure and soil functions to research being too focussed on aggregate stability. Furthermore, he questioned the use of aggregate stability as an indicator, stressing the absence of information about spatial and temporal heterogeneity. Instead, he proposed a focus on topology, which is the three-dimensional soil structure, or where the aggregates and pores locate themselves in the soil continuum. Some of the available technologies to study soil structure and its related properties include in situ methods such as environmental scanning electron microscopy (ESEM), nuclear magnetic resonance (NMR), ground-penetrating radar (GPR), electromagnetic induction (EMI) and proximal or remote sensing and ex situ methods such as sequenced thin sections, X-ray or gamma-ray computed tomography and electrical resistivity tomography (ERT). Developments of these new technologies make it possible to look at the topology (e.g. connectivity of pore space) in undisturbed soils. However, these technologies are still constricted in terms of detectable soil features, required sample size, penetrating depth, spatial resolution, temporal frequency, cost (Lin 2012) and sample preparation time requirements, when required.

An additional barrier that has to be overcome is the diverse focus of different sub-disciplines when studying soil structure. Traditionally, the focus was either on the solid matrix (pedology), the pore system (soil hydrology) or the habitats and interfaces (soil biology and biogeochemistry) (Lin 2012). Nowadays, the concept of soil architecture relates the solids with the pores and the interfaces within and between them (Lin 2012). Whether the concept of soil architecture is different from the soil structure or not, the integration of the three components (solid, pores and interfaces) is necessary for a better understanding of the link between these physical properties and physical, chemical and biological soil functions.

19.2 Conservation Tillage Effects in European Biogeographic Regions

19.2.1 Mediterranean Region

The Mediterranean climate is characterised by hot summers, mild winters and specifically irregular rainfalls and drought risk. Moreover, rainfall during the warmer season occurs in intense events (cold front), which, combined with the land topography and soil properties, leads to high risk of erosion for the whole region. Nonetheless, the rainfall irregularity and the uncertainty of water availability during the growing season are the main risks farmers confront in rainfed crop production.

Due to its climatic characteristics, the soils in the Mediterranean region have lower soil organic carbon (SOC) and higher content of soluble components. As the rainfall is lower than in other European regions, biomass production also decreases, which leads to a reduction in organic inputs. Additionally, higher temperatures enhance microorganism activity, producing greater organic matter mineralisation, which contributes to lower soil organic matter contents in soils. This affects soil physical and hydrological properties, as organic matter enhances soil aggregation and water holding capacity. Furthermore, a less percolating climate means that more soluble components remain in the soil. Depending on the parent material, soils contain calcium carbonate and salts. In this case, aggregate stability and breakdown depend on the particular chemical compound, and as mentioned earlier, calcium carbonate is a cementing agent, whereas salts, such as sodium chloride, are dispersants. Additionally, low rainfall and high evapotranspiration values can result in the formation of calcium carbonate crusts, which are physical barriers that influence water flows, root growth and the overall land suitability for agricultural practices.

Conservation tillage (CT) has been introduced mainly in the rainfed systems because of its potential to reduce fuel consumption and labour. It is generally viewed by farmers and promoted by agricultural extension institutes as a way to reduce the investment in a system in which yield, and therefore investment return, is not always assured. Thus, CT is used among other measures of cost reduction such as lower fertilization rates, lower seeding densities and in general less field operations. Furthermore, predominantly it is used in a flexible manner, alternating no tillage with minimum tillage and even conventional tillage, according to farmers' assessment of tillage needs to manage soil compaction or weed infestation. However, farmers who have adopted no tillage for economic reasons have seen some benefits in terms of soil physical and hydrological properties.

One of the main soil health benefits of CT is that it increases soil structural stability because of the reduction of mechanical disruption and the increase in soil organic matter (SOM). Evidence for this under Mediterranean conditions has been found in Greece (Sidiras et al. 2001) and in Spain for different soil types, with loam and clay textures and with calcium carbonates (Hernanz et al. 2002; Álvaro-Fuentes et al. 2008; Apesteguía et al. 2017). Also in Spain, Plaza-Bonilla et al. (2013) studied the effects of no-tillage adoption on soil aggregation on a chrono-sequence in a loam Typic Xerofluvent (Soil Taxonomy, 1994). Starting from conventional tillage, they compared soil properties after 1, 4, 11 and 20 years of conservation agriculture (CA) practice. The results showed a high correlation between water-stable aggregates and SOC. They also found that after 11 and 20 years of no tillage, the proportion of large water-stable aggregates was greater than those found in conventional tillage plots and even those from plots after only 1 or 4 years of no-tillage adoption. However, these differences were restricted to the surface soil layer (0–5 cm). Deeper (5–10 cm) layers only showed differences after 20 years of no-tillage adoption, and at increased depths, no statistically significant differences were found. Thus, no-tillage benefits on soil aggregation are a function of time and soil depth.

Soil compaction is one of the major barriers that prevent farmers from no-tillage adoption. Field operations with heavy machinery, animal grazing and the lack of reiterated soil loosening by tillage can lead to compaction. However, better soil aggregate stability permits higher load strength providing the soil with higher resistance to compaction. When comparing no-tillage systems with conventional tillage systems, soil compaction is a function of soil moisture and time since the ploughing event. Results of bulk density analysis in a variety of soil textures are shown in Table 19.1. Penetration resistance values in these studies, when performed, correlate with bulk density values. Karamanos et al. (2004) report bulk densities dynamics for the growing season, concluding that after 5-month no-tillage duration, bulk density became the lowest but similar to conventional tillage values. Nonetheless, the overall results show that, although in some cases bulk density decreases under no tillage, in general, bulk density is greater in no-tillage fields.

Bescansa et al. (2006) attributed the higher bulk density values to a reorganisation of the soil structure and pore system. They studied soil porosity, and results showed an increase of pores below 9μm, resulting in greater soil water content in no-tillage

Table 19.1 Topsoil bulk density values for different soil textures and tillage systems in the European Mediterranean region

Country	Soil texture	Sample depth (cm)	Bulk density ($kg\ m^{-3}$)		Reference
			No tillage	Conventional tillage	
Spain	Clay	0–5	1.69–1.78	1.50–1.55	Apesteguía et al. (2017)
Spain	Clay	0–3	1.05–1.20	1.04–1.13	Ordóñez Fernández et al. (2007)
Greece	Silty clay	0.5–3	1.31–1.48	1.09–1.16	Cavalaris and Gemtos (2002)
Greece	Clay loam	0–30	1.27	1.37	Karamanos et al. (2004)
Spain	Clay loam	0–15	1.62	1.52	Bescansa et al. (2006)
Italy	Sandy clay	0–45	1.42	1.16	De Vita et al. (2007)
Spain	Sandy clay loam	0–20	1.51–1.64	1.25–1.33	Pelegrin et al. (1990)
Spain	Sandy loam	0–5	0.91–0.95	1.04–1.05	Gómez-Paccard et al. (2015)

fields, compared to conventional tillage, which had bigger pores with lower water holding capacity. These results are consistent with higher porosity under conventional tillage but greater water content in no-tillage soils as presented in Cavalaris and Gemtos (2002), De Vita et al. (2007) and Pelegrin et al. (1990). When soil water content is linked to wheat yield, De Vita et al. (2007) found that it depends on rainfall during the growing season (from November to May); if it is below 300 mm, no tillage, due to its increased soil water holding capacity, presents higher yields, whereas in wetter years, conventional tillage performed better.

A particular case is presented by Gómez-Paccard et al. (2013) for a sandy loam Paleoxerult during the water excess period. In this case, no tillage had greater porosity and exhibited higher water content at saturation, saturated hydraulic conductivity and water infiltration rates, compared to conventional tillaged plots that even presented waterlogging problems.

Greater cumulative infiltration rates have also been reported in Greece (Papayiannopoulou et al. 2008). Generally, this phenomenon is attributed to greater pore connectivity and vertical macroporosity generated by roots and earthworms. Studies have also shown greater earthworm populations in conservation tillage fields, but the correlation between earthworms population and increased macroporosity is difficult to establish and has only been done qualitatively. Tarolli et al. (2019) presented an interesting microtopography soil study where no tillage presented greater surface roughness, including more concavities and tortuous surface water flows, potentially enhancing water infiltration and reducing runoff, which is especially desirable in intense but scarce rainfall events in Mediterranean rainfed fields.

19.2.2 Atlantic and West Continental Regions

The climate in the Atlantic region is influenced by the ocean, resulting in mild winters, relatively fresh summers and rainfall distributed throughout the year, whereas the continental region has contrasting temperatures and rainfall values between the summer and the winter months. These contrasting effects are stronger the further away from the coastline, whilst the western part is still influenced by the Atlantic Ocean. Topographically, the European Plain covers Belgium, the Netherlands, Germany, Denmark, Poland and Russia and is intensively farmed by commercial agriculture.

In this region, farmers' concerns about compaction and weed management increase, as the climate becomes more humid and soil workability is compromised. Additionally, farmers include potatoes and sugar beet in their crop rotations along with cereals and leguminous plants. Harvest of those tube crops involves higher soil disturbance; additionally, crop establishment seems to fail under no-tillage conditions. These concerns are depicted in a preference for minimum tillage, also known as reduced tillage or mulch tillage, rather than no tillage, which has low adoption rates.

Accordingly, to intensive land use and agricultural practices, research interest has focused on structural stability, the formation of plough pans and soil strength against heavy machinery load. In general, the same trends as those in the Mediterranean region are seen in terms of bulk density increase under CA practices compared to conventional tillage (Tebrügge and Düring 1999; Dexter et al. 2008; Czyz and Dexter 2009; Vogeler et al. 2009; Rücknagel et al. 2017; Schlüter et al. 2017). These studies were performed mainly on silt loam or loam sand soils developed from loess in Germany and Poland, after reduced tillage was performed up to 25 years. Nonetheless, Vogeler et al. (2009) saw a change in the increased bulk density values in the surface layers after a period of 5 years, presenting similar values to conventional tillage, and at the end of the experiment even reversing the situation, although the subsuperficial layers, at 20 cm depth, were still presenting higher compaction in the reduced tillage plots.

Equally, the structural changes of soils due to the adoption of conservation tillage, which are shown as higher bulk densities, lead to lower total porosity (Schlüter et al. 2017) or macroporosity (Tebrügge and Düring 1999) but higher soil water content in the surface layers (Czyz and Dexter 2008, 2009). Gruber et al. (2011) found higher water content in no-tillage fields during the spring but slightly lower water content during the autumn when compared to conventional tillage. These conditions during spring can imply cooler soils, which are detrimental to crop development, whereas slightly drier soils in autumn would reduce optimal conditions for seed germination. Therefore, the authors conclude that conventional tillage present slightly better conditions in the given location and climatic conditions.

Saturated hydraulic conductivity presented inconsistent results among studies, having better (Vogeler et al. 2009), worse (Tebrügge and Düring 1999) or inconsistent but generally better (Rücknagel et al. 2017) performance in reduced tillage. Pöhlitz et al. (2018) compared strip tillage, no tillage and reduced tillage and found that strip tillage combined benefits from no tillage and reduced tillage, presenting greater soil moisture in the rows between seeding as no tillage does, and lower bulk density in the rows within seeding where minimum tillage is performed.

Wiermann et al. (2000) concluded that conventional tillage, compared to reduced tillage, leads to permanent destruction of the aggregates resulting in a weak structure against dynamic pressure, showing impacts after a single compression by a 2.5 Mg load, whereas the reduced tillage system developed a structure that resisted this load. Similarly, also in Germany, Tebrügge and Düring (1999) and Rücknagel et al. (2017) found conventional tillage plots were more vulnerable to structural settlement after compression; however, the resulting bulk densities between treatments were similar. Further studies on structural stability in Poland show greater amounts of readily dispersible clay in conventionally tillaged fields, which represents weaker soil structures (Czyz and Dexter 2008, 2009). Moreover, in Germany, reduced tillage had higher yields of macroaggregate water-stable aggregates than conventional tillage, although the dynamics of the macroaggregates in tilled land was unclear, as there were no differences in results from before and after a single ploughing event (Andruschkewitsch et al. 2014).

19.2.3 Boreal Region

In the boreal biogeographical region, agriculture is concentrated in the southern part where soils are more suitable and the growing season is longer, although the short window for biomass production is still the main limitation for agriculture in the region, varying from 100 to 200 days. Acidic soils and peat soils are common in the area, although agriculture usually is established on nutrient-rich mineral soils.

In several studies on different soil types around the boreal region, no and minimum tillage increased bulk density (Comia et al. 1994; Rasmussen 1999; Tamm et al. 2016) compared to conventional tillage, despite increasing aggregate stability at surface layers (Rasmussen 1999; Sheehy et al. 2015). Similarly, as in the other biogeographical regions, studies show that by increasing bulk density, conservation tillage practices generally decrease macroporosity, although it increases mesopore abundance and has no effect on microporosity. When looking at the origin of the pores, conservation tillage practices increased biopores on a clay Vertic Cambisol in Finland (Aura 1999). Equally, as in the previously presented cases in other regions, these increases in mesopores translate into a higher soil moisture content (Aura 1999; Rasmussen 1999; Kankanen et al. 2001). However, moister soils during spring are a limitation for crop growth as it reduces soil temperature, delaying crop development in a region that already has constrained growing seasons.

When it comes to water and airflow, pore connectivity is especially important. Rasmussen (1999) found a higher hydraulic conductivity and air diffusivity in conventionally ploughed fields, compared to no-tillage fields. Conversely, Comia et al. (1994) found better pore connectivity, and therefore greater hydraulic conductivity and air diffusivity in minimum-tillage fields of clay and clay loam soils in Sweden. Indeed, more recent studies in Lithuania showed that the effects of conservation tillage on soil physical properties are soil-specific (Feiza et al. 2015; Feiziene et al. 2018). Feiziene et al. (2018) found that crop residues behaved as aggregation agents on fine-textured soils, whereas on coarse-textured soils, residues obstructed the pore system increasing waterlogging. Additionally, Feiza et al. (2015) found overall porosity was higher on a silt loam Planosol but pore obstruction by crop residues occurred, whereas the sandy loam Cambisol was more suitable due to greater macroporosity. Therefore, as Rasmussen (1999) stated in his review, suitability of conservation tillage is climate-, soil- and crop-specific.

19.3 Conclusions

Healthy soils are well structured, with high aggregate stability and continuous porous systems, enabling air and water flows and benefiting crop growth. Therefore, maintaining these soil properties has to be considered an aim for any farming practice.

Conservation tillage effects on soils' physical and hydrological properties vary geographically because the intrinsic and environmental factors that influence aggregate stability, soil structure and consequently the porous system vary geographically.

Organic matter plays an important role as an aggregation agent and in stabilising soil structure, but in some locations, other agents have this major role. Conservation tillage practices have shown to increase aggregate stability in the Mediterranean, Atlantic and West Continental and Boreal regions, increasing soil structural stability and soils' bearing capacity for heavy machinery.

Overall, conservation tillage increases bulk density; however, it rarely has a limited effect on root growth. The increase in bulk density is linked to a reorganisation process of soils' structure, resulting in a decrease of macropores and an increase of meso- and micropores, increasing soils' water holding capacity, which can be considered a benefit depending on the geographical region and crops' needs during their growing cycle.

Better surface structural stability under conservation tillage might increase infiltration rates, and maintenance of vertical biopores might improve drainage. However, the evidence is inconsistent with other cases under different conditions reporting pore clogging due to crop residues.

The complexity of the interactions among all the factors influencing soil physical and hydrological processes highlights that site-/farm-specific variations in climate, soil and cropping system, and overall land suitability should be carefully considered by farmers before using conservation practices. Flexibility within the choice of tillage is also important for successful adoption of conservation tillage.

Further research with new technologies focusing on soil topology and involving farming communities, who are leading the spread of conservation agriculture, will increase and improve our current knowledge about conservation tillage effects on soils' physical and hydrological processes.

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Nutrient Management Strategies in the Climate Change Scenario

20

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Abstract

The climate change, as evidenced by changes in temperature rise and increased CO_2 concentration, is a major concern. According to the Intergovernmental Panel on Climate Change (IPCC), global temperature is anticipated to upsurge between 1.1 and 6.4 °C during the twenty-first century followed by alteration in precipitation patterns. Soils are directly linked to the climate system through the carbon, nitrogen, and hydrologic cycles. Because of this, the altered climate will have an effect on soil processes and properties. In the recent past, there are numerous studies conducted to study the impact of climate change on crop performance and soil properties. These studies indicated that climate change has a negative impact on soil health by increasing soil degradation through the loss of soil organic carbon, soil erosion, salinization, sodification, acidification, etc. Reversing these downward spirals implies the implementation of best-proven technologies, such as conservation agriculture, integrated nutrient management, precision agriculture, and use of biochar. Bringing back degraded soils under cultivation and sustaining soil health by the adoption of climate-smart agricultural practices is the only way to combat the negative imprints of climate change on soil health and fulfilling the food demands of the ever-growing population.

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Keywords

Climate chage · Consrvation agriculture · Soil health · Nutrient use efficiency · Soil degradation

20.1 Introduction

India is basically dependent on agriculture as it contributes about 35% of the gross national product (GDP) and as such plays a crucial role in the country's development. India is having a total geographical area of 328 M ha, out of which agriculture occupies about 141 ± 1 M ha. And almost 60% of the country's net cultivated area is rainfed and exposed to abiotic and biotic stresses (Pathak 2015). Hence, meeting the demand for the increasing population is a major challenge for Indian agriculture. A profound change in the global food and agriculture system will have to be incorporated if we are to feed today's 925 million hungry people, of which 230 million live in India and about 2 billion people are expected to be added to this category by 2050, mostly in developing countries (ICAR 2015), and this demand has to be met from the net sown area in the country, which will not be going to increase in future. In the global context, India with 2.4% of the world's total land area and only 4.0% of the total replenishable freshwater has to cater to 17% of the world's population (Pathak 2015). Therefore, the sustainable management of land and water is crucial for the food and nutritional security of the country, particularly with the global climate change scenario.

Food grain production quadrupled during the postindependence era; this growth is projected to continue. The rise in global food prices (Koning et al. 2008; Swinnen and Squicciarini 2012) has raised concerns about food security (Godfray et al. 2010). Global food production now faces greater challenges than ever before due to changing climate, increasing land degradation, and decreasing nutrient use efficiency. Nutrient mining is a major cause of low crop yields in parts of the developing world. Especially nitrogen and phosphorus move beyond the bounds of the agricultural field due to inappropriate management practices as well as failure to achieve good congruence between nutrient supply and crop nutrient demand (Pandian et al. 2014). If it is unchecked, it severely affects food production. Hence, increasing nutrient use efficiency continues to be a major challenge for agriculture. Changing climate highly influences plant growth, and nutrients must be available in sufficient and balanced quantities. Soils contain natural reserves of plant nutrients, but these reserves are largely in unavailable forms to plants, and only a small portion is released each year through biological activity or chemical processes. This release is too slow to compensate for the removal of nutrients by agricultural production and to meet crop requirements. Therefore, fertilizers are designed to supplement the nutrients already present in the soil. The use of chemical fertilizer and organic fertilizer judiciously has its own advantages under changing climate and its advantages are to be integrated in order to make optimum use of each type of fertilizer and achieve balanced nutrient management for different crops under this starving situation. Considering this in view, an attempt was made in this article to summarize the nutrient management practices that can enhance nutrient use efficiency and sustain agricultural crop production under changing climatic scenarios.

20.2 Contribution of Agriculture in Climate Change

Agriculture releases to the atmosphere significant amounts of CO_2, CH_4, and N_2O (Paustian et al. 2004). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter (Janzen 2004). CH_4 is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (Mosier et al. 1998). N_2O is generated by the microbial transformation of nitrogen in soils and manures and is often enhanced where available nitrogen exceeds plant requirements, especially under wet conditions (Oenema et al. 2005). Agricultural N_2O emissions are projected to increase by 35–60% up to 2030 due to increased use of nitrogen fertilizer and increased animal manure production (FAO 2003). Similarly, the area of rice grown globally is forecast to increase by 4.5% by 2030 (FAO 2003), so methane emissions from rice production would not be expected to increase substantially. According to USEPA (2006), aggregate emissions are projected to increase by ~13% during the decades 2000–2010 and 2010–2020. Assuming similar rates of increase (10–15%) for 2020–2030, agricultural emissions might be expected to rise to 8000–8400, with a mean of 8300 Mt CO_2 by 2030. Agricultural greenhouse gas (GHG) fluxes are complex and heterogeneous, but the active management of agricultural systems offers greater possibilities for mitigation. Many of these mitigation opportunities use current technologies and can be implemented immediately.

20.3 Effect of Climate Change on Soil Properties

Low soil fertility is currently a food security problem in many developing countries, particularly in Africa and South Asia (St Clair and Lynch 2010; Sanchez and Swaminathan 2005; Lal 2004a, b). Africa and South Asia are also among the regions most at risk of food insecurity (Lele 2010; Sanchez and Swaminathan 2005; Huntingford et al. 2005) and deteriorating soil health due to climate change (Tan et al. 2010). Proper soil management has the potential to drastically reduce food security issues in these regions. Recent study in Birbhum district of West Bengal, India, indicated that about 97.4% area is affected by the deficiency of either single or multiple nutrients (NBSS & LUP 2010), of which deficiency of phosphorus, potassium, and zinc together was mapped on 47% area of the district. Interpretation of data on a smaller scale revealed that potassium mining was extensive in prevailing rice-rice or rice-vegetable or rice-potato cropping sequence (NBSS & LUP 2010). The changes in climate will be expected to increase temperature, precipitation, and evaporation with concomitant increase in organic matter turnover, which leads to higher losses of CO_2 in mineral and organic soils (Karmakar et al. 2016). These losses in carbon will also affect other soil functions such as poor soil structure, loss of topsoil, loss of water holding capacity, less nutrient availability, and ultimately crop productivity. The most rapid processes of chemical and mineralogical change under external conditions would be loss of salts and nutrient cations where leaching increases and salinization where net upward water movement occurs because of the increased evapotranspiration or decreased evapotranspiration or irrigation water supply (Brickman and Sombroek 1996). The problem of salinity and sodicity is associated with many ways of cultivating the marginal land with inadequate management and techniques. For example, an increase of soil pH was reported by 0.2 units in a span of 27 years in an arid region of India without appreciable increase in salt content (Singh et al. 2009).

20.4 Soil Health a Way Towards New Revolution

India and China, the most densely populated countries of the world, to keep pace with the growing population and to sustain world food security, will require maintaining at least a 4–5% annual growth rate in agriculture. India supports about 17% of the human population and 11% of the livestock population of the world just on 4.2% of water resources and 2.8% land (Singh 2015). As per recent estimates, India will need to produce about 281 million tonnes (mt) food grains, 53.7 mt oilseeds, 22 mt pulses, 127 mt vegetables, and 86 mt fruits by 2020–2021 (Singh 2015). In India, the average food consumption at present is 550 g per capita per day, whereas in China and the USA, it is 980 and 2850 g, respectively (Mall et al. 2005, 2006). To meet the demand for food from this increased population, the country's farmers need to produce 50% more food grain by 2020 (Kumar and Gautam 2014). In order to enhance crop production in the future, soil health has got paramount importance. At present, land degradation due to salinization, sodification, loss of top fertile soil due to erosion, loss of organic matter, decreasing nutrient use efficiencies, etc. are adversely affecting agricultural crop production. The extent of land degradation in India is presented in Table 20.1. To enhance food production under changing climatic conditions such as aberrant weather, rising CO_2 concentration, and rising temperature and sea level, we require the reorientation of agriculture from current practices to more sustainable and eco-friendly practices. In this context, scientists are more focused on climate-smart or climate-resilient agriculture. Moreover, climate-resilient agriculture helps to improve food security under changing climatic situations while also reducing food waste globally (CCAFS 2013) and minimizing the risk and degradation of natural resources.

Table 20.1 Extent of degraded lands in India

S. No.	Type of degradation	Area (M ha)
1	Gullied lands	1.90
2	Land with or without scrub	18.80
3	Waterlogged	0.97
4	Saline/alkali	1.20
5	Shifting cultivation	1.88
6	Degraded forest and agricultural land under forest	12.66
7	Degraded pastures/plantation	2.15
8	Sands	3.40
9	Mining and industrial wastelands	0.20
10	Barren/stony/snow covered	12.11
	Total	55.27

Adapted from Sharda (2011)

20.5 Climate-Smart Nutrient Management Strategies

20.5.1 Conservation Agriculture

Conservation agriculture (CA) is defined as resource-saving agriculture crop production that strives to achieve acceptable profit together with high and sustained production levels while concurrently conserving the environment. It also enhances natural biological processes above and below the ground. CA is characterized by three linked principles:

- Developing and promoting a system of raising crops with minimum soil disturbance through operations involving direct seeding of crops in untilled soils.
- Keeping the soil surface covered by practices such as leaving and maintaining crop residues cover on the soil and/or growing cover crops.
- Adopting diversified crop rotation, spatially and temporally.

The CA is globally promulgated to enhance crop yield, conservation of the soil, and development of resilient systems to stresses which are induced by weather including those created due to irregularity and change in climate (Choudhary et al. 2016). The approach enables addressing the immediate concerns of enhancing productivity, long-term sustainability, and food security concerns. Worldwide CA covered about 11% of the arable land (Kassam et al. 2015), although in India it has spread only to 5 M ha due to the lack of adoption by farmers' perception/mindset, nonavailability of suitable machinery, and CA strategies that are different from those we have adopted for many decades (Choudhary et al. 2016). Since soil is the fundamental material for sustainable agriculture, agricultural production cannot be sustained to meet ever-growing food demand without good fertile soil as well as best management practices. Conversion from conventional cultivation practices to CA can be the better option for improving nutrient status, enhancing soil health and crop productivity (Leys et al. 2007; Meena et al. 2016). The CA practices are capable of promoting soil health by increasing organic C and soil aggregation (Somasundaram et al. 2017), thus improving infiltration and minimizing erosion losses (Govaerts et al. 2009). The CA-based cropping systems improved soil properties and availability of nutrients (N, P, K, Zn, Fe, and Mn) in the surface soil layer compared to conventional farmer's practice. Jat et al. (2018) concluded that an appreciable amount of N and K fertilizer nutrients can be saved to the tune of 30% and 50%, respectively, under the CA-based management system.

20.5.2 Nutrient Management Strategies in Conservation Agriculture

Nutrient management is an important aspect of CA for crop productivity and for the adoption of CA by farmers (Vanlauwe et al. 2014). The practice of modified tillage, residue management, and crop rotation had a significant impact on nutrient distribution and transformation in soils (Somasundaram et al. 2017). The CA improves nutrient use efficiency (NUE) as it reduces soil erosion and prevents nutrient loss from the field (Dordas 2015) due to reduced runoff and the appropriate use of deep-rooting cover crops that recycle nutrients leached from the topsoil (FAO 2001). This leads to the greater availability of both native and applied nutrients to crop plants which can have a significant effect on fertilizer efficiency. NUE is an important index that can be used in CA in order to quantify the different nutrient management practices and to determine which is better for increasing the NUE. The presence of mineral soil N available for plant uptake is dependent on the rate of C mineralization. The higher loss of nitrate nitrogen under conventional tillage system over no tillage has been reported by Randall and Iragavarapu (1995). Similarly, Wienhold and Halvorson (1999) reported an increase in N mineralization rate with the decreasing intensity of tillage in the upper soil layer. The tillage system determines the placement of residues. In a conventional tillage system, crop residues are incorporated, while in the case of zero tillage, residues are left on the soil surface. These placement differences contribute to the effect of tillage on N dynamics. Incorporated crop residues decomposed 1.5 times faster than surface-placed residues (Kushwaha et al. 2000; Balota et al. 2004). However, the type of residues and the interactions with N management practices may also affect C and N mineralization (Verachtert et al. 2009).

The accumulation of soil P in the upper soil layer under no tillage (Matowo et al. 1999) is a common phenomenon due to the limited mixing of fertilizer P with soil. One of the long-term studies conducted by Ismail et al. (1994) revealed that after 20 years of NT, extractable P was 42% greater at 0–5 cm but 8–18% lower at 5–30 cm depth compared with conventional tillage in a silty loamy soil. Deeper placement of P in NT may be profitable if the surface soil dries out frequently during the growing season as suggested by Mackay et al. (1987). According to Govaerts et al. (2007), permanent raised beds had a concentration of K 1.65 times and 1.43 times higher in the 0–5 cm and 5–20 cm layer, respectively, than conventionally tilled raised beds, both with crop residue retention. In both tillage systems, K accumulated in the 0–5 cm layer, but this was more accentuated in permanent than in conventionally tilled raised beds. Other studies have found higher extractable K levels at the soil surface as tillage intensity decreases (Lal et al. 1990). Du Preez et al. (2001) observed increased levels of K in NT as compared to conventional tillage, but this effect declined with depth.

20.5.3 Adoption of Stewardship 4R Principle

The 4R nutrient stewardship provides a framework to achieve cropping system goals, such as increased production, increased farmer profitability, enhanced environmental protection, and improved sustainability. To achieve those goals, the 4R concept (Fig. 20.1) incorporates the:

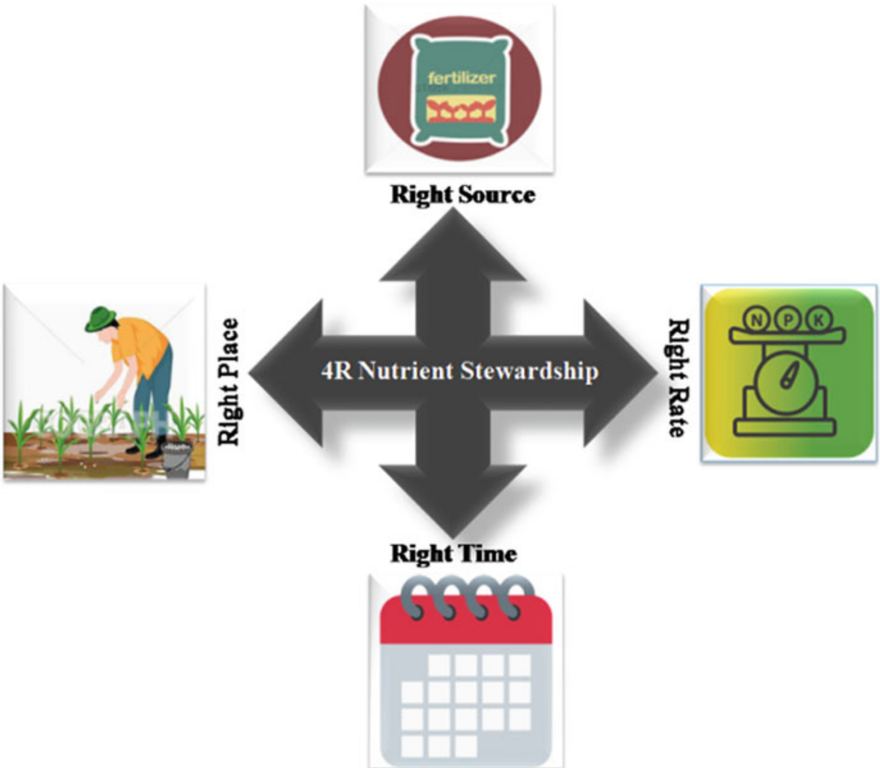

Fig. 20.1 4R Nutrient stewardship for fertilizer management. (Modified from Roberts 2010 http://www.ipni.net/ipniweb/portal/4r.nsf/article/communicationsguide)

- Right source: The type of fertilizer applied can impact the amount of nitrogen that leaves the field. For example, ammonium (NH_4^+) fertilizers are more stable than some other forms and can minimize leaching.
- Right rate: Using field measurements of nitrogen in soils and knowledge of the crop's needs, farmers can better estimate the amount of fertilizer to apply.
- Right time: Timing the application to coincide with when the crop needs the nutrient most can help reduce losses.
- Right place: Applying nutrients closer to crop's root zone where it will be able to make the best use of them can also help to reduce nutrient loss.

The simple agronomic practice of split-applying nutrients does not increase production cost by much, but it significantly improves NUE. It is now well established that for most crops, N must be applied in 2–3 or more spilt, thus coinciding with the crop growth stages when N requirement is high. An appropriate rate, source, and application method increase nutrient utilization by crop plants.

20.5.4 Precision Agriculture

Precision agriculture or soil-/site-specific technology includes a set of practices that are based on an appropriate combination of sensors, information technology, appropriate machinery, and other research management practices designed to optimize the use of inputs on the basis of variability in soil properties and other attributes of the landscape that affect crop growth and agronomic production (Gebbers and Adamchuk 2010). These technologies based on specific soil/animal/tree units optimize resource use, minimize the environmental footprint, and improve production. The strategy is to monitor the lifecycle and optimize resource use at every step of the production chain. However, the low adoption rate of precision agriculture technology is attributed to a range of factors (Tey and Brindal 2012): (1) socioeconomic factors, such as operators' age, years of formal education, years of farming experience, farmers' perception/mindset, land tenure, farm size, and financial status; (2) agroecological factors composed of climate, biome, soil quality and its assessment, nutrient reserves and availability, soil moisture content and its spatial variability, soil erodibility, and the topsoil depth; (3) institutional factors, including infrastructure, access to the market, extension services and information availability, farm location, and proximity to a road or railway line; and (Alauddin and Quiggin 2008) technological factors, such as irrigation and computers. In developing countries like India, where landholding is small, the adoption of precision farming is again constrained. Under these circumstances, the adoption of precision agriculture will only possible under cooperative mode.

20.5.5 Balance Fertilizer Management

Increasing NUE is an offspring of balanced fertilization and sound management practices and decisions. Balanced fertilizer use is not only the first requirement but also a prerequisite for enhancing NUE (Pandian et al. 2014). When balanced fertilization is practiced, one nutrient increases the efficiency of others through a synergistic effect. Traditionally, in India, balanced fertilization indicates the use of N, P, and K in a certain ratio (ideally 4:2:1) on a gross basis both in respect of areas and crops. Singh et al. (2019) studied the long-term fertilizer experiments at fixed sites in different agroecological zones in India covering major soil types and predominant cropping systems during the early 1970s to monitor the changes in soil quality/health, crop productivity, and sustainability under continuous application of plant nutrient inputs through fertilizers and organic sources. Results revealed that the balanced application of nutrients and also their conjoint application in an integrated manner through inorganic and organic sources sustained higher stable yields and improved the NUE over the years (Table 20.2). Finally, they concluded that the balanced and integrated application of nutrients sustains crop productivity, improves soil quality/health (Meena et al. 2019), and helps in mitigating climate change.

Table 20.2 N, P, and K use efficiency at different locations under long-term fertilizer experiments in India

	Ludhiana		Udaipur		Raipur	Pattambi
Treatment	Maize	Wheat	Maize	Wheat	Rice	*Rabi* rice
Nitrogen						
100% N	12	26	11	23	20	10
100% NP	19	41	18	34	39	13
100% NPK	24	48	23	39	40	16
100% NPK + FYM	37	54	31	50	46	27
Phosphorus						
100% N	7	15	6	8	11	6
100% NP	12	24	10	12	21	8
100% NPK	14	27	12	15	22	11
100% NPK + FYM	22	31	16	18	25	17
Potassium						
100% N	62	124	69	137	66	25
100% NP	96	198	116	202	126	33
100% NPK	119	230	146	126	129	42
100% NPK + FYM	186	257	194	297	148	69

Adapted from Singh et al. (2019)

20.5.6 Modified Fertilizer Materials to Enhance Nutrient Use Efficiency

Controlled release or enhanced efficiency of fertilizers generally work by controlling the speed at which fertilizer or a coating applied to it dissolves in soil water. By affecting the timing of nitrogen release from fertilizer, these compounds have the potential to reduce the loss of nitrogen and therefore improve nitrogen use efficiency. Similarly, soluble fertilizers formulated with inhibitors reduce or block the conversion of nitrogen species by affecting specific types of microbes involved. This helps to keep nitrogen in the form of ammonium for a longer period, encouraging uptake by crops and helping to prevent N_2O emissions from either nitrification or denitrification (Ruser and Schulz 2015). Exploitation of specially designed mineral fertilizers such as nitrification inhibitors, coated fertilizers, and urease inhibitors certainly curtails the global GHG emissions under a variable climate.

20.5.7 Integrated Nutrient Management

Integrated nutrient management (INM) may be defined as the maintenance or adjustment of soil fertility and of plant nutrient supply to an optimum level for sustaining the desired crop productivity through the optimization of benefit from all possible resources of plant nutrient in an integrated manner. There are three main principles that govern INM: (1) use all possible sources of nutrients to optimize their input, (2) match soil nutrient supply with crop demand spatially and temporally, and (3) reduce N losses while improving crop yield (Wu and Ma 2015). In the current situation of reducing nutrient use efficiency and fertilizer application response under changing climatic scenarios, the integrated use of organic and inorganic fertilizers is the most logical concept for managing and sustaining long-term soil health and crop productivity. In the long-term INM experiment in central India, Meena et al. (2019) reported that the application of higher doses of FYM at 20 Mg ha^{-1} and STCR based 75% NPK + FYM at 5 Mg ha^{-1} recorded higher crop yield, nutrient use efficiency, and residual soil fertility (NPK). The $KMnO_4$–N, Olsen-P, and NH_4OAc–K declined in unfertilized plots by −9.32, −1.95, and −7.42 mg kg^{-1}, respectively, over the initial values. These results highlight the importance of the inclusion of organics along with chemical fertilizers for maintaining soil health over a longer period of time. Similar kinds of results were also observed at different locations by Acharya (2002), Antil and Singh (2007), Bhattacharyya et al. (2016), Meena et al. (2013), and Meena et al. (2015).

20.5.8 Use of Biochar

Biochar is a stable, carbon-rich form of charcoal that can be applied to agricultural land as part of agronomic or environmental management. It can be produced by pyrolysis of lignocellulosic materials, where biomass such as crop stubble, wood chips, manure, and municipal waste is burnt with little or no oxygen condition (Sparkes and Stoutjesdijk 2011). Biochar itself can be used for direct absorption of nutrients from crops; however, under some interactions in the soil, it will slowly release some nutrients into the soil, supplementing the source of soil nutrients for plant absorption and uses. A study has shown that the porous structure, large specific surface area, and charge density of biochar increase the ability to hold soil moisture and nutrients, delay the release of fertilizer nutrients, and reduce the loss of fertilizer and soil nutrients, which indirectly influences soil fertility (Yu et al. 2013; Farrell et al. 2014). Gao et al. (2018) reported that the application of biochar significantly improved soil organic matter content, available N, available P, and available K in the soil. However, there was no significant improvement in soil total nitrogen, total phosphorus, and total potassium. The other experiments with biochar revealed that biochar can effectively reduce the ammonia volatilization in field soil and reduce ammonia volatilization, thereby improving the utilization of nitrogen in soil, and it can also effectively reduce the loss of soil farmland N, P, and other nutrients, except for adsorption by keeping N element. Biochar can also regulate nitrification and denitrification processes to reduce the loss of N, thereby reducing the amount of fertilizer applied (Wu et al. 2014). Glaser et al. (2002) and Jha et al. (2016) found that using biochar could reduce the content of active Al and increase the content of available N, P, K, Ca, and Mg.

20.6 Restoration of Degraded Lands

A large proportion of agricultural lands have been degraded by excessive disturbance, erosion, organic matter loss, salinization, acidification, or other processes that curtail productivity (Lal 2004a, b). Often, carbon storage in these soils can be partly restored by practices that reclaim productivity including revegetation (e.g., planting grasses); improving fertility by nutrient amendments; applying organic substrates such as manures, biosolids, and composts; reducing tillage and retaining crop residues; and conserving water (Paustian et al. 2004). In India, about 6.73 M ha of land is affected by salinity and sodicity problems, and the forecasts indicate that the country will have 11.7 M ha affected by salinity and sodicity by 2025 (Chaudhari et al. 2013). Gypsum is the most common amendment used for the reclamation of these soils. However, nowadays, the gypsum availability is problematic, and also considering its huge cost for purchase and transportation, farmers are unable to ameliorate sodic soils. An ideal amendment for the reclamation of sodic soils should not only reduce sodicity but also improve soil health in terms of nutrient availability. Shirale et al. (2018) studied the effects of crop residues and green manuring effects on nutrient availability in sodic soils and reported that organic amendments performed in improving major and micronutrient status compared to gypsum, which leads to higher yield performance by crops. The practice of green manuring in degraded soils will not only ameliorate sodicity but also improve soil health, carbon sequestration, and biological properties in these soils (Shirale et al. 2017).

Where these practices involve higher nitrogen amendments, the benefits of carbon sequestration may be partly offset by higher N_2O emissions.

20.7 Conclusions

Climate changes raised a serious issue of soil health maintenance for future generations. Rise in temperature and unprecedented changes in precipitation pattern lead to soil degradation by the erosion of top fertile soil, loss of carbon and nitrogen, and increasing area under saline soils, sodic soils, and acid soils. In order to meet the food demand of the growing population, global food production must be increased substantially over the next several decades. Sustainable intensification of agriculture, based on proven technologies, can increase food production on existing land resources. Therefore, conservation agriculture, precision agriculture, recycling of crop residues, carbon sequestration in soils and ecosystems, integrated nutrient management, and balanced use of agricultural inputs are the proven technologies of sustainable intensification in agriculture. More importantly, among the climate-smart agricultural practices, the selection of appropriate measures must be soil-/site-specific for sustaining resource base for future generations. Further, research must be initiated to fine-tune the existing climate-smart agricultural practices to suit different climatic situations, and these practices must be in accordance with the further changes in climatic situations.

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21 Use of Herbicide and Its Implications Under No-Till Farming: An Overview

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Abstract

No-till farming is an age-old practice followed thousands of years ago, with the primitive farmers who used to make a hole in the soil and put seeds into it and then cover the seeds. During the year 1999, no-till farming was adopted on 45 million ha worldwide, which extended to 72 million ha in 2003 and to 157 million ha in 2013–2014. No-till farming paves the way for optimizing productivity and ecosystem services. It also has economic, environmental, and social benefits to the producer as well as to the society. Adoption of no-till farming also enables agriculture to respond to some of the global challenges that are associated with climate change and land and environment degradation, thereby increasing the cost of food, energy, and production inputs. In order to recognize no-till farming as a truly sustainable system, we have to ensure that it is being adopted in areas where it is currently low in practice. No-till or zero-tillage technology may be the possible substitute as this method reduces weed density and depress weeds growth. Also, there is reduction in production costs by saving water, energy, labor, and farm machinery and improving production while conserving natural resources and ensuring environmental safety. The global scenario also shows that no-till farming cannot be any more thought as a craze and non-sustainable but the system has established itself as a farming practice. Currently, sustainable agroecosystem management is gaining importance, and it can no more be neglected or ignored by scientists, extension workers, farmers, etc. While practicing no-till farming, it is inevitable that we need to apply herbicide rationally to control weeds. In India being an agrarian country, more than 50% of people are dependent on agriculture for their livelihood. Estimations clearly indicate that the annual crop losses could double without the use of crop

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production products. So we need to rely on agrochemicals, and they are the key inputs in agriculture for crop protection and better yield. The latest annual report (2017–2018) released by the Department of Chemicals and Petrochemicals has declared that the production capacity of agrochemical players in India is around 292 (000′ MT). In the current financial year, the production has risen by 2.9%. India's agrochemical consumption is one of the lowest in the world with per-hectare consumption being just 0.6 kg. However, the use of herbicides has been increasing due to shortages of farm labor and concerns about the affordability of labor costs. The aforementioned reasons have been the primary drivers for the growing popularity of agrochemicals and herbicides, which is expected to emerge as a key growth segment. However, continuous use of herbicides for a prolonged period creates herbicide resistance and dominance of particular weed species or changes in weed flora to a greater extent. In this chapter, an attempt has been made to crystallize the information on the use of herbicides and its implications under no-till farming.

Keywords

No-till farming · Conservation agriculture · Herbicides in no-till farming

21.1 Introduction

No-till farming is a profitable resource-saving technology in the Indian and global context. We are in need of such a system which involves the successful management of resources to fulfill changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources. In the last few decades, several cultivation methods were followed to improve the yield of different crops (Swanton and Weise 1991) and also to enhance the ecosystem services such as increase in soil organic matter (SOM), water retention capacity, and soil biodiversity (Lal 2013). Soil tillage has been practiced many years ago as it reduces weed density by positively affecting water and nutrient availability (Lal 2009). Also, short exposure to sunlight after tillage can speed up the germination of deeply buried weed seeds (Scopel et al. 1991).

Increasing the scope of area under no tillage from 45 million ha in 1999 to 157 million ha in 2013–14 shows acceptance of this technology among the farmers (Derpsch and Friedrich 2009; Kassam et al. 2009; FAO 2010). The reason behind the advantages of following no-till farming is that it can be adopted in all soils and climatic conditions which were earlier thought impossible. Around the world, in almost every country, there are some activities on no tillage, be it research sector or farmer adoption (FAO 2008; Friedrich et al. 2009a). The main success of no-till farming around the world is because it is economic and social and has many environmental advantages, and it is also recognized as truly sustainable farming. No-till farming increases the amount of water in the soil, decreases erosion, increases the amount and variety of life in and on the soil, and increases herbicide usage. In practice, the farmers spread the manure from cattle and swine onto their fields. This manure is rich in nitrogen, which is needed for plant growth.

No-till farming is in accordance with the concept of conservation agriculture (CA), which is based upon three principles that are applied simultaneously in practice (Kassam et al. 2009; FAO 2010; Friedrich et al. 2009a). They are (i) continuous minimum mechanical soil disturbances, (ii) permanent soil organic cover, and (iii) diversification of crop species grown in sequence and rotation. Conservation agriculture is an alternative to conventional tillage, and this practice alters the soil as little as possible. It is recognized as an activity that improves soil and water quality, reduces erosion, and also reduces the impact of the agricultural sector on greenhouse gas pollution (Gupta et al. 2002; Hobbs 2007). In addition, it is time-saving and direct cost-saving for machinery and fuels, making it a more economically profitable alternative (Kassam et al. 2012).

21.2 Advantages of No-Till Farming

Because of many advantages, no-till farming methods and no-till cultivation have been increasing nowadays. No-till farming helps in improved aggregation and a high proportion of water-stable aggregates. It increases the SOM content and high biotic activity of soil fauna. Soil detachability is also reduced by a high proportion of roots concentrated in the topsoil horizons. It also helps in reduced rill erosion due to decreased runoff rate, amount, and velocity. No-till farming helps to maintain the long-term productivity of soil. The herbicide runoff and other chemical runoff are reduced under no-till farming when compared to conventional tillage farming. As the fertility of the topsoil is maintained/improved, the farmers need not apply fertilizers as they do in conventional tillage farming. Erosion assessment technology on corn (*Zea mays*) revealed that over 20 years, sediment loss can be reduced by 99% and over 100 years by 90%, with no-till practices (Vogel et al. 2016). No-till farming is widely recommended to protect soil against erosion and degradation of structure (Petersen et al. 2011), creates greater aggregate stability (Fernández et al. 2010 and Zotarelli et al. 2007), increases SOM content, and enhances sequestration of carbon (West and Post 2002; Six et al. 2000). Retention of crop residues provides a food source to beneficial insects, earthworms, and predators. No-till farming provides the widest way to tackle pest problems. In no-till farming, the straws/stubbles are not burnt, as a result of which there is reduction in carbon dioxide emission. Also, there is reduced consumption of diesel by tractors during field preparation, and less carbon dioxide is produced. No-till farming mitigates greenhouse gas (GHG) emissions (Kong et al. 2009). Efficient use of inputs needs improvement in soil properties, better rate and extent of germination, and better growth from seedling to maturity stage.

The infiltration rate is increased due to improved soil aggregate stability. Porosity is also increased as there is increase in the number of worm channels and their continuity and stability. There is less traffic on the soil surface, more organic matter, and good soil structure. Formation of plow pan does not occur. Crop residue lowers the maximum soil temperature and improves germination, seedling establishment, and crop growth and yields. It also increases the soil organic matter, soil water retention capacity, and soil biodiversity (Lal 2013).

Regarding the soil pH, increased acidification is found due to the nitrification of ammonia from acid-forming N fertilizer applied to the soil surface. The acidification problem occurs in a thin layer at the soil surface, so neutralization is easier. Crop residues influence nutrient availability by altering temperature and moisture regimes. Soil organic carbon (SOC) and nitrogen levels tend to be higher in no-till systems near the soil surface, which is where the majority of crop roots are located (Arshad et al. 1990; Fan et al. 2016; Thomas et al. 2007). Fertilizers are more responsive to crop under no tillage. The lower quantity of nitrate in the upper soil layer is due to more leaching of nitrates. No-till soils had significantly higher levels of cation exchange capacity (CEC) (26%) than conventional tillage. Farmers save money as they no longer have to pay for the labor and fuel, as a result of which they get profit.

In tillage farming, as the equipment usage is less, they reduce dust in the atmosphere, and less carbon from soil is released to the atmosphere when compared to tillage farming. As no-till farming leaves crop residues on soil, it helps in reducing the loss of water from soil and also reduces runoff, which in turn increases the amount of infiltration of water into the soil thereby beneficial for the growth of crop plants. As the soil fertility increases, the overall soil ecology gets healthier and healthier, as a result of which there is increase in the microbial population. No-till farming improves biological activity (Helgason et al. 2010). Since the soil fertility is maintained along with water in the soil, this leads to increase in crop yield. However, it may take decades for the result to be realized when we transit from farming to no-till farming.

21.3 Disadvantages of No-Till Farming

No-till farming requires special machinery to drill through the crop residue. Moreover, no-till farming may not be successful in certain types of soil. This type of farming requires high usage of herbicides. As the soil moisture is maintained, this leads to an increased risk of fungal crop diseases. As the usage of herbicide is more in no-till farming, it leads to increased use of herbicide-resistant genetically modified organism (GMO) crops.

21.4 Fundamental Change in Agricultural Production System

No-till farming also depends on the plant nutrients that are liberated as a result of biotransformation of organic matter and that can be supplemented by adding artificial fertilizers in case if there is going to be any nutrient deficiency. Organic matter also provides the macronutrients but may not be available "from the bag." Adoption of no-till farming retains the soil original characteristics, helps to sustain the soil health, and is also capable to regenerate in poor conditions (Doran and Zeiss 2000). Hence, it is a powerful tool to promote soil and thus agricultural stability.

Agriculture accounts for 10–12% of total anthropogenic emissions of greenhouse gases (GHGs) globally and is raising year by year (Smith et al. 2007). No-tillage farming is one of the mitigation measures that are suggested to reduce the GHG emissions from agriculture.

21.4.1 Use of Herbicides and Its Impact in No-Till Farming

The only way to control the weeds in no-till farming is by using herbicides. The most commonly used herbicides are as follows:

1. 2,4D, which belongs to the phenoxy group and is used in turf and no-tillage farming. It is the most widely used herbicide in the world.
2. Atrazine, a triazine herbicide which is still used to control broadleaf weeds and grasses as its cost is low.
3. Clopyralid, which belongs to a pyridine group and is used mainly in turf and to control noxious thistles. It is notorious for its ability to persist in compost.
4. Dicamba, which is a persistent broad-leaf herbicide active in the soil.
5. Glyphosate, a systemic nonselective herbicide highly used in no-till farming. Imazapyr is again another nonselective herbicide used to control the broad range of weeds.
6. Metalachlor, which has highly replaced atrazine in controlling weeds.
7. Paraquat, which is a broad spectrum nonselective herbicide that removes almost all weed growth. It is fast and more reliable in action at all conditions of weather, even when there is only a short interval to spray between the showers.

There is no doubt farmers have to apply the herbicides if no tillage is practiced. In such a situation, the farmers have to apply the herbicide at the recommended dose that is specified on the label. When farmers apply the herbicides above the recommended dose, then it remains in soil, which will damage the emerging of seedling in the next cropping season. When animals feed on the trash and stubbles that contain herbicide residues, it naturally enters into the animal, and there is no doubt their manure also contains these residues. Moreover, each and every herbicide has to be applied in the correct stage of crop growth, failing on which will cause crop damage.

There are many other environmental problems with the overusage/overapplication of herbicides. When a herbicide is sprayed in a site, there are all means that it gets drifted to the nontarget site too, which may cause damage to the crops in that site or contamination of soil or water body depending on the site nearby the target site. Not only the crops in the nontarget site are affected, but also the person who is spraying the herbicide is exposed directly and indirectly through drift or residues in food. Most of the herbicides are plant poisons and do not affect other crops or organisms. However, by making vast vegetation changes, they can indirectly affect the birds and animals.

Glyphosate is the world's most widely used herbicide. In fact, glyphosate plays a vital role in the adoption of no-till farming. It is a powerful tool in modern agriculture as it is very effective in killing weeds, thus saving farmers a lot of time. Glyphosate is applied to soil before sowing. Plants absorb it through stems and leaves and die. It is also applied before harvest so that weeds die and the harvesting becomes easier.

The biggest obstacle for extending the no-till practice and weed control required appropriate technical solutions (Mann et al. 2004; Junior et al. 2012). Adoption of no-till farming was feasible with the marketing of paraquat and glyphosate for total weed control (Wall and Causarano 1993). Further availability of many other effective herbicides and the more efficient no-tillage seeding equipment had led to unprecedented growth of no-tillage in South America (Derpsch 2001 and Bernoux et al. 2006). Brazilian companies started glyphosate production in the 1980s that led to reduced prices and facilitated the adoption of no-till farming (Ribeiro et al. 2007).

Repeated application of herbicide continuously over a time period results in the weeds that are resistant to herbicides. The resistant ones survive and produce seeds; they will continue to increase till such a situation when they are dominated by weed in the field. The factors that influence the development of herbicide-resistant weeds is due to the following factors: (i) the high number of seeds produced per plant, (ii) the high level of seed germination, (iii) several seed flushes per season, and (iv) high frequency of resistant given. Apart from this, there are other factors that lead to the development of herbicide resistance like (i) no crop rotation, (ii) limited or no-tillage practices, (iii) high dependency on herbicide, and (iv) limited herbicide with the desired model.

Weed control in no-till farming varies with weed species and the herbicides used. Herbicide-tolerant crops (HTCs) are a tool used by farmers against weeds and are compatible with no-till methods and help to preserve topsoil. This gives farmers the flexibility to apply the herbicides only when needed and to use herbicides with preferred environmental characteristics. Herbicide-resistant crops also facilitate low or no-tillage cultural practices, which are considered to be more sustainable.

In no-till farming, a shift in weed populations from annuals to perennials is observed. Perennial weeds thrive in reduced or no-tillage systems as they have the ability to reproduce from several structural organs other than seeds (e.g., Bermuda grass (*Cynodon dactylon*), nutsedge (*Cyperus rotundus*), and Johnson grass (*Sorghum halepense*). They reproduce from underground plant storage structures: stolons, tubers or nuts, and rhizomes, respectively. As there is no tillage, the perennial reproductive structures are neither buried deep so that conditions are not favorable for emergence nor failing to uproot and kill them. However, the recent development of postemergence broad-spectrum herbicides provides an opportunity to control weeds in no-till farming.

21.5 Conclusions

It is not that easy to switch over from conventional-tillage based farming to no-till farming. Farmers very well realize that agriculture is not a fail-safe profession, but still they hesitate to adopt a new farming technique. When we switch over, there is change in weed and pests. The absence of tillage makes the farmers depend heavily on herbicides and other weed management options. Advantages of no-till farming make it desirable for practice to face the increasing population growth in the world, environmental degradation, rising energy costs, and climate change.

No-till farming practice is in fact needed in order to preserve agricultural productivity, thereby meeting the future global food needs. In order to follow this practice, conservation agriculture (CA) systems are necessary to preserve agricultural productivity and meet future global food demands. To implement these systems, adequate weed control is crucial in their success. Herbicide use has been a valuable asset when adopting no-till farming/CA practices; however, prudent use of chemical weed control is essential to fulfilling the goals of CA, reducing detrimental environmental impact, and reducing herbicide resistance development. Further development and testing of alternative weed management practices that can be utilized along with herbicide applications must be pursued in order for CA practices to remain successful. A farmer has to have good knowledge of herbicides, weeds, and application technology (Derpsch 2001). The key skills required are the following: selecting the type and quantity of herbicide used, regulation of sprayer pressure, output, speed and timing of herbicide application, and using spot spraying with weed-specific herbicides (Sorrenson 1997). The main barriers to its adoption are the human mindset, know-how, availability of adequate machines, and availability of suitable herbicides for weed management (Friedrich and Kassam 2009). These barriers must be overcome by not only farmers but also scientists, research workers, extension workers, etc., if we aim at achieving greater adoption (Friedrich et al. 2009b). The quicker we adopt no-till farming, the sooner we reverse the process of soil degradation, thereby maintaining the soil health and fertility for "**SOIL** is the **SOUL OF INFINITE LIFE**."

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Conservation Agriculture for Carbon Sequestration and Mitigation of Climate Change

22

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Abstract

Climate change is expected to intensify existing problems and create new combinations of risks, particularly in India. The situation is made worst due to factors such as widespread poverty, malnutrition, overdependence on rainfed agriculture, inequitable land distribution, limited access to capital and technology, and long-term change in weather. By lessening the severity of key damages to the agricultural sector, the adoption of conservation agriculture (CA) is the key sustainable measure. CA is an approach to farming that seeks to increase food security, alleviate poverty, conserve biodiversity, and safeguard ecosystem services. CA practices can also contribute to making agricultural systems more resilient to climate change. In many cases, CA has been proven to reduce farming systems' greenhouse gas (GHG) emissions and enhance their role as carbon (C) sinks. CA systems influence several ecosystem services in various types of environments while improving agricultural sustainability and soil health through climate change mitigation and biodiversity conservation. The increasing temperature and climate change have warned agriculture production and threatened the food security with variable rainfall and other abnormal climatic conditions. Extreme weather conditions such as irregular rainfall amount and distribution, droughts, floods, etc. are likely to continue to increase with serious impacts on agricultural productivity in the future. At the same time, CA could be an effective

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adaptation option under these situations as it protects natural biodiversity, strengthening the ability of the agroecosystem to respond to these stresses, minimizing environmental pollution, reducing the incidence of insect pests, diseases, and weed problems, securing food supply opportunities, and also providing producers with alternative means of generating income.

Keywords

Carbon sequestration · Climate change · Conservation agriculture

22.1 Introduction

Conservation agriculture (CA) is a resource-saving farming production system to increase crop production and attain high productivity while sustaining the natural resources with the incorporation of three related principles, besides other good crop production principles and practices of pest management and plant nutrition. It is a process of environment protection, mitigating and adapting climate change, and sustainable land and agriculture management (Kassam 2019; FAO 2020). FAO describes conservation agriculture (CA) as a resource-saving agricultural production concept based on enhancing the above and below the ground biological and natural and processes. Minimum tillage and soil disturbance, permanent soil cover with crop residues and live mulches, and crop rotation and intercropping are the three key principles of the CA system (FAO 2020). In recent times, CA is becoming increasingly popular due to the compound benefits it delivers like enhanced production efficiency, crop and soil productivity, protection of soil from erosion, and climate change mitigation (Busari et al. 2015; Ngoc et al. 2018); enhances infiltration and increases soil water content (Kassam et al. 2009; Blanco-Canqui and Ruis 2018; Zhang and Han 2019); and prevents the growth and infestation of predaceous nematodes while increasing and fastening the multiplication of all soil micro- and macroorganisms (Henneron et al. 2015).

CA systems influence several ecosystem services in various types of environments while improving agricultural sustainability and soil health through climate change mitigation and biodiversity conservation (Ghosh et al. 2019). CA system is also reported to reduce blast disease in rice (Lakhran et al. 2017). Ella et al. (2016) reported that besides increasing soil organic carbon (SOC), CA systems also increased residual water content in upland crop production systems in the Philippines. CA can act as a strategy to reduce GHG emissions and to mitigate climate change. The different CA practices introduce the changes in C dynamics of soils and lead to increase in soil carbon status. In CA practice, the tillage operations are reduced extremely or completely abandoned, which slows the process of organic matter mineralization in soil (Sommer et al. 2011; Alvaro-Fuentes et al. 2012; Almagro and Martinez-Mena 2014). Also reduced or no-tillage operations are energy-saving; hence, they save energy, fuel, and time and reduce GHG emission (West and Marland 2002; Ogle et al. 2019).

22.2 Climate Change, Agriculture, and Conservation Agriculture

According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is the occurrences of several alterations or changes in the present climate witnessed over comparable periods attributed to direct or indirect human activities leading to the altered composition of the earth atmosphere and can be connected to the natural discrepancy of the climatic parameters (González-Sánchez et al. 2017). The earth's average temperature has been witnessed an increase of 1.3 °C in the last 57 years, while the average earth's surface temperature in Southern Asia and India has marked an increase of 1.2 and 1.1 °C, respectively (FAOSTAT 2020, Fig. 22.1a). By the end of the twenty-first century, the temperature in India is likely to increase by 1–5 °C (IPCC 2007; Intergovernmental Panel on Climate Change 2014; Basha et al. 2017; Joshi et al. 2018). The increasing temperature and climate change have warned agriculture production and threatened food security with variable rainfall and other abnormal climatic conditions. Extreme weather conditions such as irregular rainfall, droughts, floods, sharp changes in maximum and minimum temperatures, etc. are likely to continue to increase with serious impacts on agricultural productivity. Countries like India are more vulnerable to the effects of climate change. Climate change may affect the distribution of plant species (Sharma et al. 2010) and may also increase the incidence of pests and diseases (Harrington et al. 2001; Samways 2005; Diffenbaugh et al. 2008; Bale and Hayward 2010; Danielle 2018). The changing climate scenarios may have some

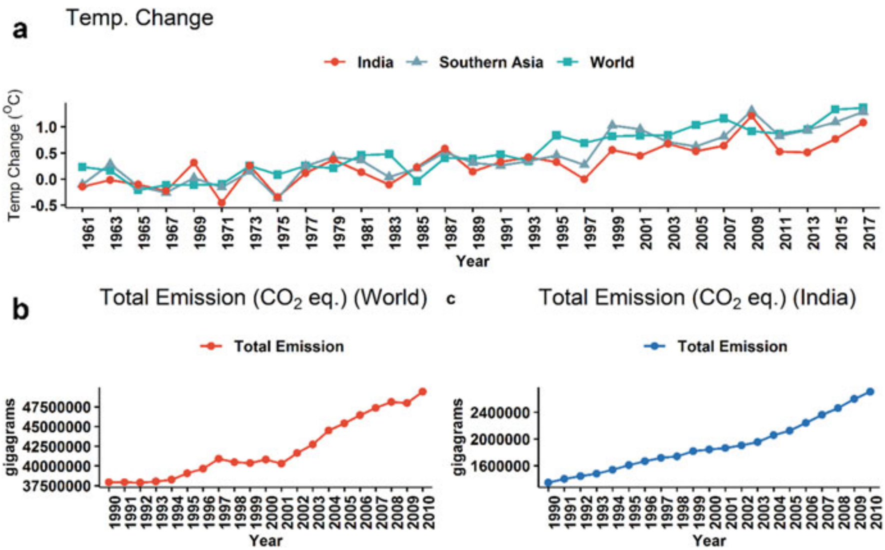

Fig. 22.1 Change in the average temperature of the world, Southern Asia, and India (**a**); trend in total emission (CO_2 eq.) of greenhouse gases (GHGs) by all sectors in the world (**b**); and India (**c**). (Source: FAOSTAT 2020)

positive effects on crops; for example, increase in CO_2 concentration may increase the photosynthetic activity in plants as a result of CO_2 fertilization effect and leads to higher productivity in some crops (Allen Jr et al. 1995; Singh 2007; Degener 2015; Lone et al. 2017). Temperature rise may result in the introduction of new crops in cold areas. However, the negative impacts of changing climatic scenarios are more serious and threatening. These negative impacts may further increase the incidence of weeds, pests, and diseases, thermal stress in plants due to ambient temperature, damage in vernalization, frequencies of droughts and floods, salinity and erosion problems, etc. These negative impacts of climate change may pose a serious problem in the agriculture production system with a decline in productivity under the arena of the ever-increasing population (Mall et al. 2006; Gornall et al. 2010).

Lead by the several anthropogenic activities, a notable gain in the atmospheric concentration of greenhouse gases (GHGs), *viz*., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), has been witnessed during the last couple of centuries. Carbon (C) is the source of origin of GHG emission, and these GHGs are responsible for global warming (Ritchie and Roser 2020). In the last several years (1990–2010), the total GHG emission (CO_2 eq. of CO_2, CH_4, and N_2O) has noticed a worldwide increase from 38 million gigagrams to 49 million gigagrams (Fig. 22.1b); as far as the total GHG emission (CO_2 eq.) from India is concerned, it was 1.35 million gigagrams in 1990 and increased to 2.70 million gigagrams in 2010 (Fig. 22.1c), indicating a twofold increase within a period of 20 years (FAOSTAT 2020).

Among all the sectors responsible for GHG emission, the contribution of agriculture is about 10% of total GHG emission (CO_2 eq.) worldwide, whereas it is 23% of total GHG emission in India. The share of different sectors in total greenhouse gas emission (CO_2 eq.) in the world (left) and India is depicted in Fig. 22.2. The energy sector contributes nearly half of the total GHG emission. The global GHG emission from the agriculture sector has increased from 2.75 million gigagrams in 1961 to 5.41 million gigagrams in 2017. In India, the GHG emission from the agriculture sector was 0.34 million gigagrams in 1961, which has turned up to 0.63 million gigagrams in 2017 (Fig. 22.3). In 1750, the concentration of CO_2, CH_4, and N_2O in the atmosphere was 280 ppm, 715 ppb, and 270 ppb, respectively, which increased to 405 ppm, 1850 ppb, and 330 ppb, respectively, in 2017 (EEA 2019).

The two GHGs produced by the agriculture sector are CH_4 and N_2O contributing 55% and 45% of emissions, respectively. With respect to global warming potential, CO_2 and CH_4 are having a global warming potential (GWP) of 25 and 298 times that of CO_2 (IPCC 2007). GWP is a measure of how much heat the emission of 1ton greenhouse gas traps in the atmosphere over a given period of time (usually 100 years' time slice), relative to the emissions of 1 ton CO_2. Since agricultural activities contribute 45% of N_2O emission of total GHG emission and the GWP of this gas is 298 times greater than CO_2, a very small emission of this gas may have a huge effect on climate change. Soil microbial processes like nitrification and denitrification are responsible for the transformation of elemental soil N to N_2O and large-scale emission of this GHG emission. Rice cultivation, due to its significant contribution to methane (CH_4) and N_2O emission and global warming, appealed a

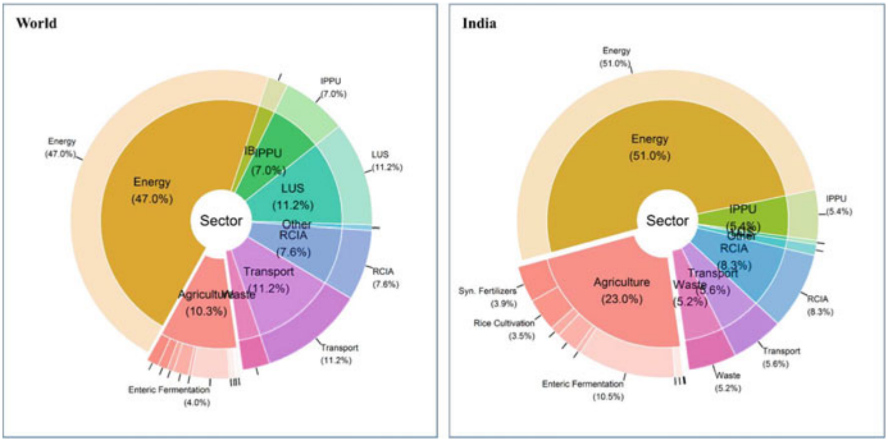

Fig. 22.2 Share of different sectors in total greenhouse gas emission (CO_2 eq.) in the world (left) and India (right). Energy includes energy, manufacturing and construction industries, and fugitive emissions. *RCIA* residential, commercial, institutional, and AFF, *IPPU* industrial processes and product use, *LUS* land use sources, *IB* international bunkers. Data is based on the year 2010. (Source*:* FAOSTAT 2020)

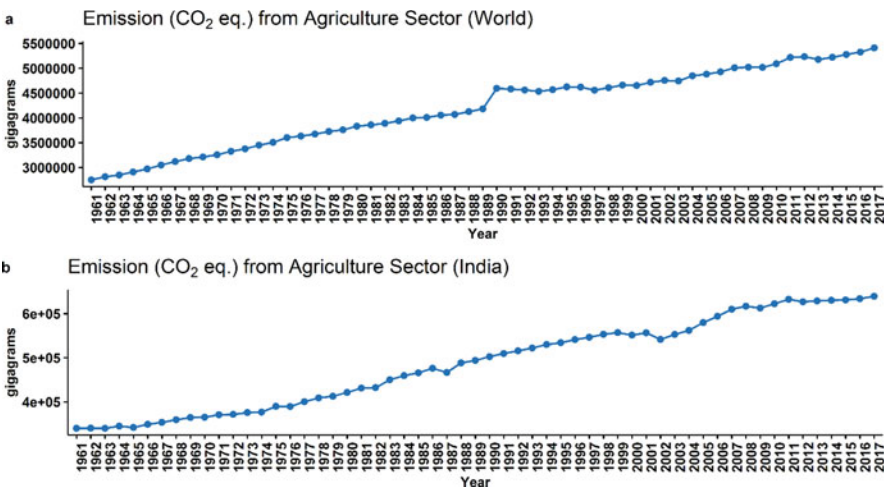

Fig. 22.3 Trends in total emission (CO_2 eq.) of GHGs from the agriculture sector in (**a**) the world and (**b**) India. (Source: FAOSTAT 2020)

large interest (Jat et al. 2016). The methane emission from rice cultivation is due to the presence of methanogenic bacteria in the methane anaerobic soils of flooded paddy fields and the enteric fermentation [digestive systems of ruminant livestock (e.g., cattle, sheep, goats, horses)] being two important sources of methane emission; the other sources like manure decomposition and crop residue decomposition under wet conditions also contribute in methane emission from the agriculture sector.

Other sources of CH_4 from agriculture are from the decomposition of animal manure, especially when stored in lagoons, and from crop residues when decomposing under very wet conditions. In contrast, in the well-aerated soils with high organic matter content, crop residues on the surface may absorb methane from the atmosphere.

On one hand, agricultural activities are considered to be the cause of climate change; on the other hand, they are also affected by it. However, if well managed, the use of less productive factors in agriculture can reduce CO_2 emissions, and this can mitigate the effects of climate change caused by agriculture (Gornall et al. 2010; Liu et al. 2016). If we include the total anthropogenic emission from the agriculture sector with the emission from deforestation due to agriculture area expansion, the share of agriculture in global GHG emission may reach 30% (IPCC 2007). However, agriculture can mitigate about 5.5–6 Gt of CO_2 eq. per year, and a large portion of this potential can be covered through carbon sequestration. Conservation agriculture (CA) can act as a strategy to reduce GHG emissions and to mitigate climate change. The different CA practices introduce the changes in C dynamics of soils and lead to increase in SOC status. In CA practice, the tillage operations are reduced extremely or completely abandoned, which slows the process of mineralization of organic matter in soil. Also, reduced or no-tillage operations are energy-saving; hence, they save energy, fuel, and time and reduce GHG emission (Kassam et al. 2012; Carbonell-Bojollo et al. 2019).

22.3 Conservation Agriculture and C Sequestration

Several CA practices comprising zero tillage has been reported to increase the soil organic carbon (SOC) concentration in the upper soil layers; however, it is not always true in all cases, but increase in SOC content is important for climate change (Shi et al. 2012; Powlson et al. 2014; Williams et al. 2018). However, it is also not true that management practices resulting in increased CO_2 concentration always lead to climate change mitigation (Powlson et al. 2016). As GHG emission from agricultural activities adds a large contribution to global emission, currently, carbon (C) sequestration is considered as the most practical option with respect to reduction in GHG emission and mitigation of climate change (Kimble et al. 2002).

The process of transfer of CO_2 from the atmosphere to the soil system in the form of long-lasting pools of C is defined as carbon sequestration (Yu et al. 2015). Organic and inorganic forms of C pools in soil are the most long-standing global C sequestration forms. Soil organic C sequestration in the form of plant biomass offers a counterbalanced approach for climate change mitigation and also important for improving the physical, chemical, and biological soil conditions, enhancing soil fertility, and cherishing soil biodiversity while checking soil erosion (Ngoc et al. 2018). Increased SOC levels improve and maintain the productivity and sustainability of agricultural production systems, prevent surface runoff and check soil erosion, and improve the overall soil quality as a result of increased microbial activity (Lal 2015). Besides these benefits, it provides a number of significant off-farm paybacks to the public. These off-farm advantages may include enhanced wildlife habitat and protection of water bodies from sediment runoff from cultivated fields.

The amount of SOC added in the soil profile, enumerated as a function of C input from crop residue addition, bulk density, and protection by aggregates relative to soil particles fraction, SOC concentration, and depth, is considered as SOC accumulation. Encouragement of C sequestration in soil is greatly considered as a potent approach of the reduction of GHG emission and climate change mitigation (González-Sánchez et al. 2017). Several factors, viz., C input, tillage, crop rotation, climate, and fertilization, greatly affect the rate of SOC sequestration. Han et al. (2016) stated that increased C inputs are the most efficient way to uplift SOC sequestration. In the coarse soil textures or soils with rapid decomposition rates of OM with low inherent soil organic matter, the addition of C in soil surface is a typical key of CA practices—even though it is sometimes likely to attain momentous SOC sequestration with increased deepness in some soils (Fisher et al. 1994). As SOC symbolizes the key C sink in terrestrial environments, C sequestration in soil by increasing SOC is considered a unique approach for climate change mitigation (Wang et al. 2015).

22.3.1 Zero Tillage for C Sequestration

Tillage systems which exclude regular soil disturbances and physical manipulation of soil, maintain a permanent surface cover with crop residues, and adopt crop rotations have been found to increase SOM level and carbon sequestration in various types of soils under different climate regimes (Kassam et al. 2012). The systems of conservation tillage are often claimed to improve SOC stocks, increase soil C sequestration, and mitigate the GHG emission related to agricultural operations. Scientific evidences suggested that zero-tillage practices may lead to increased C sequestration and climate change mitigation as it slows down the decomposition rate of organic C present in soil and helps in stabilizing in added organic C, but frequently, the impact of SOC is considered as a matter of depth reallocation instead of the net accumulation (Powlson et al. 2016).

In the Indo-Gangetic Plains (IGP), the rate of SOC increase under zero or reduced tillage (0.3 Mg C ha^{-1} $year^{-1}$) is consistent, while in Sub-Saharan Africa (SSA), the rate of increase of SOC stock has a great variability between 0 and 1 Mg C ha^{-1} $year^{-1}$ (Mangalassery et al. 2015). This suggested that the adoption of zero or reduced tillage may have some potential value as a strategy of climate change mitigation approach; however, the impact may differ greatly within regions. Powlson et al. (2014) opined that the extent of impact is less than as often claimed. In Central Morocco, the no tillage (NT) was introduced in wheat-based systems for two different soils (cambisols and vertisols), and after the 5 years' study, the system of NT was recorded to have 2% and 10% increase in SOC content, respectively, in both soils, when compared to the conventional tillage (CT) (Moussadek et al. 2014). In the rainfed lands of China, the transformation of conventional tillage into conservation tillage improved the carbon sink from 0.84 Mg C ha^{-1} $year^{-1}$ to 2.69 Mg C ha^{-1} $year^{-1}$ (Lu et al. 2018). From all the examples given above, it is clearly indicated that CA practices like zero tillage have in themselves some potential of climate change mitigation by increasing the SOC stocks on a long-term basis.

22.3.2 Cover Management for C Sequestration

Leaving crop residues on the soil surface to maintain a permanent soil cover is another important principle of CA. However, in developing countries, crop residues are used for livestock feed and for fuel purposes, so using the crop residues on surface soil as a cover has the cost of fuel and livestock feed. Plants absorb CO_2 from the atmosphere, and through the photosynthesis process, it is stored in plant tissues biomass, and on the decomposition, the stored C is returned to the soil as soil C pool. This is the principle process of transferring C from the atmosphere to the soil by photosynthesis (Kell 2011).

In general agreement, cover crops have the potential to sequester C, but the magnitude is still debated. The magnitude of C sequestration potential of cover crops may differ with plant species, climate, soil type, and management practices. It is estimated that cover crops can sequester 0.22 t $acre^{-1}$ $year^{-1}$ of C in cultivated soils (Ruis and Blanco-Canqui 2017). Besides having several benefits such as the ability to reduce erosion, capacity to fix atmospheric nitrogen, and improving soil health, in recent time, cover crops are gaining importance with increase in adoption coordinated benefits with the alertness of climate change as the adaption and mitigation strategy, which is an additional yet important advantage of cover crops but not listed under traditional benefits from cover crops (Kaye and Quemada 2017). Several models and meta-analysis studies established the fact that while acting as a cover to the soil surface, cover crops enhance C sequestration with significant variability across sites; beneficial impacts of cover crops increase with crop rotation, zero tillage, and optimum use of N inputs (McDaniel et al. 2014). Carbon sequestration by cover crops gets influenced by reduced rates of soil erosion with dependency on decomposition balance.

Another way to maintain permanent soil cover under the CA system is the retention of crop residues on the surface soil. When these residues were applied alone, the increase in SOC was very small (0.2 Mg C ha^{-1} $year^{-1}$), but when residue retention was combined with zero tillage, the increase in SOC was to 0.45 Mg C ha^{-1} $year^{-1}$. Similarly, in temperate regions, the effect of cereal straw incorporation for 25 years continuously was found nonsignificant indicating the importance of climatic features for residue decomposition and SOC accumulation for surface application of residues than for incorporated (Powlson et al. 2016). It is expected that in tropical regions, the rates of SOC accumulation are lower due to the faster decomposition of organic matter under high temperatures (Krishna and Mohan 2017). Even if the SOC buildup under residue retention or incorporation is smaller, constituting a very limited climate mitigation potential, it provides a genuine climate change mitigation over the practice of residues burning after the harvest of rice and wheat in many parts of India, where the carbon present in residues emitted back into the atmosphere during the burning (Singh and Sidhu 2014; Bhuvaneshwari et al. 2019).

22.3.3 Crop Diversification and Carbon Sequestration

One aspect of CA which has genuine potential for climate change mitigation and C sequestration but often overlooked is crop diversification. Besides increasing soil organic C pools, crop diversification can benefit farmers with the monetary value of additional crops (Powlson et al. 2016). Crops which profuse growth to cover the soil surface mimic the natural vegetative conditions and produce the comparable SOC pools (Sa and Lal 2009). The continuous mass and energy flow provided by the crops in a diversified crop system stimulates the soil biodiversity and changes in SOC pools.

In CA systems, certain crop diversification strategies lead to increased C sequestration through the higher rates of photosynthesis. Increased rates of C sequestration were reported when legumes were intercropped between the rows of cereals (Thierfelder et al. 2013) or when an extra crop was incorporated between the period of two crops where the field otherwise would be fallow (Ghosh et al. 2012). Replacement of one of the crops in crop systems with others may also increase C inputs in soil. The amount of increased C inputs may depend on total biomass, the proportion of above- and belowground biomass produced by the replacement crop, and the rate of decomposition of the replacement crop as it is affected by the composition of the replacement crop. Powlson et al. (2016) reviewed that the SOC accumulation rates under CA-based crop diversification were to the tune of 0.5 Mg C ha^{-1} year^{-1} in IGPs.

22.4 Conservation Agriculture for Climate Change Mitigation

CA is an approach to farming that seeks to increase food security, alleviate poverty, conserve biodiversity, and safeguard ecosystem services. CA practices can also contribute to making agricultural systems more resilient to climate change and weather aberration. In many cases, CA has been proven to reduce farming systems' greenhouse gas (GHG) emissions and enhance their role as C sinks.

22.4.1 Zero Tillage

Tillage practices contribute to mitigation and adaptation strategies to climate change in different ways. Conventional tillage (CT) is known for stimulating the mineralization process of SOC, using energy for operations, and creating soil erosion problems and hardpans (Rusu 2014). CT practices that consist of reduced and zero or no tillage have the potential to reverse these negative effects, but sometimes these practices may also be associated with reduced yields. Different agriculture practices contribute to GHG emission through the alteration of the soil microenvironment. For instance, tillage operations break down the soil aggregates, which leads to a rapid SOM decomposition and limits C and N concentration (Alvaro-Fuentes et al. 2008). In contrast, no tillage enhances the soil macroaggregate stability leading to reduced heterotrophic respiration and depresses CO_2 emission. In maize monoculture, the reduced soil disturbance added with residue retention was associated with the increased C pools in macroaggregates in a surface soil layer and declined CO_2 emission compared over CT with no surface residue retention (Fuentes et al. 2012).

Shallower depth tillage with lower intensity compared to the conventional plowing in combination with crop rotation, weeding, and green manuring in an organic farming system is referred to as organic reduced tillage systems. In a study on organic reduced tillage system following 13 years, effects of system were of minor importance in relation to N_2O and CH_4 emissions when compared to plowing in slurry fertilized plots, and after single tillage, the N_2O fluxes in the reduced system were higher. Further, with slight effects on CH_4 uptake, fertilization with manure compost increased N_2O emission compared to fertilization with slurry indicating the importance of the combination of reduced tillage (RT) and manure application in climate change mitigation compared to the traditional plowing system (Krauss et al. 2017).

Reduction in CH_4 oxidation with tillage was assumed due to the disturbances in the methanotrophic microbes, alteration in gas diffusion, or damage to methane forming microbes due to soil structure disruption as a result of tillage. In conflict, some studies found that CH_4 uptake may increase under no-tillage (NT) treatment as NT improves soil structure, which may be a cause to improve oxygen and CH_4 flow between atmosphere and soil (Ussiri et al. 2009). Compared to the normal tillage system, some studies reported comparable or even reduced CH_4 changes under RT or NT systems (Omonode et al. 2007). Different tillage systems and their effect on CH_4 uptake may have not been thoroughly assessed; however, several reports advocated higher uptake with RT/NT management.

After the transfiguration from conventional tillage to reduced/no tillage, N_2O emission increased in the first 10 years and then decreased or may not vary generally (van Kessel et al. 2013). Identifying the soil aeration as a factor, Rochette (2008) claimed higher N_2O emission in poorly aerated soils under NT compared to CT, but the reverse was found in soils with good aeration. In some situations, NT may result in increased N_2O emission, but this case is not very common. In this regard, evidences are lacking to draw strong conclusions. However, this is a vital issue as a very small rise in N_2O emission will counterbalance a considerable gain in SOC; every one kg extra emitted N_2O ha^{-1} is responsible to counterbalance 0.13 Mg C ha^{-1} sequestered (Grandy et al. 2006).

Under the rice-wheat crop system, two studies in almost similar conditions showed contradictory results. Bhatia et al. (2010) reported a marginal increase in N_2O emission with zero tillage (ZT), while Pandey et al. (2012) reported decreased N_2O emission in ZT. In a study in China with the wheat-maize crop system under high rates of N fertilizer application, NT combined with straw retention resulted in decreased N_2O emission, but the yield was equal or increased with CT with no straw retention (Huang et al. 2015). In a study in China with a wheat-maize system in an environment similar to the IGP, there was a degree of helpful synergy between CA practices and N_2O emissions. In a situation with high rates of N fertilizer, a combination of no-till and straw retention led to a decreased N_2O emission but equal or increased crop yields compared to CT with straw removed (Huang et al. 2015). By contrast, no N_2O emission differences were detected between traditional hand plowing and direct-seeded mulch-based system under an intercropped maize soybean system in Madagascar (Chapuis-Lardy et al. 2009).

22.4.2 Permanent Soil Cover and GHG Emission

Besides tillage, crop residue retention on the soil surface can greatly influence the CH_4 and N_2O emission by altering surface soil properties such as moisture, porosity, and temperature (Yao et al. 2009). Global annual production of crop residues has extended around 4 billion metric tons. These residues can play a beneficial role in C sequestration if retained on the soil surface. However, it is also possible that beneficial effects of residue retention may be offset by increased emission of N_2O. A meta-analysis by Chen et al. (2013) suggested that residue retention did not help in the reduction of N_2O emission. However, the residue impacts on N_2O emission were subjected to soil properties, especially soil moisture content and soil texture.

In another study, Sapkota et al. (2015) could not trace detectable level of CH_4 emission under zero-tillage rice crop both with and without residue retention due to the arrested methanogenesis process under higher redox potential of soil. Wang et al. (2016) found that the practice of removing cane debris from the soil surface reduced N_2O releases by 24–30%, representative of the promoting effects of trash removal on N_2O emissions. Due to the lack of synchronization between demand and supply, more than 60% of applied nitrogen is lost, which in turn may lead to increased cultivation cost, natural contamination, and reduced N use efficiency (Kumar et al. 2019). Nitrogen fertilization is considered responsible for 60% of nitrous oxide (N_2O) anthropogenic emissions.

Cover crops are a good option for both soil and water nitrate concentrate reduction, and in turn they are expected to reduce the mobility of N_2O between soil and the environment. The application of N inputs immediately after harvesting of legume crop leads to high nitrification and denitrification rates, which raises N_2O losses; however, the magnitude of losses is depended on the crop type (Sainju 2017). Kaye and Quemada (2017) assumed that cover crops do not have any effect on CH_4 flux from soil. According to them, cover crops were not good enough for the mitigation of GHG emission as the global widespread adoption of cover cropping system is estimated to mitigate only 10% of GHG emissions from agriculture. However, the mitigation potential of maintaining a cover by growing cover crops is comparable to other practices such as zero tillage; it can be a beneficial management practice to stable the yield levels and minimize N losses under climate change situations.

22.4.3 Crop Diversification

Introduction of new crops or cropping systems on a farm refers to crop diversification. It is the practice of changing the existing cropping pattern with the addition of a new crop. Crop diversification helps farmers to increase the income sources and the variety of potential foods. Crop diversification also plays an important role in climate risk management under resource-limited areas. Crop diversification is becoming increasingly popular around the world because of the advantages it provides like gain in production stability (Mhango et al. 2013), suppression of weeds and plant diseases (Kutcher et al. 2013), increased monetary returns, enhanced ecosystem productivity (Gan et al. 2015), and reduced C footprint (Yang et al. 2014). Due to the possible impacts of climate change on agriculture production, consideration of diversified cropping is more insistent.

A more viable tactics in crop diversification is the addition of grain legumes as these crops have the ability to fix atmospheric nitrogen and reduce dependence on synthetic N fertilizers and the higher rate of residue decomposition due to the narrow C:N ratio. Besides increasing the soil N availability, the legume residues also increase the pace of SOM decomposition known as the "priming effect" (Kuzyakov 2010). However, this priming effect may influence the N_2O flux between soil and atmosphere; hence, good synchrony between soil available N and applied N is suggested to prevent N losses via leaching and denitrification process. Management practices such as crop rotation with legumes and CA can alter the GHG emission (Guardia et al. 2016). Many studies have reported legumes as an N_2O mitigation approach as legumes reduced the quantity of fertilizer N added. However, legumes are also reported to produce N_2O via N release from root exudates and crop residue decomposition after crop harvest (Tellez-Rio et al. 2015).

Residue management practices and the soil and environmental condition influence the N_2O flux resulting from legume crops in crop diversification. A high variability of N_2O fluxes (0.03–7.09 kg N_2O–N ha^{-1} year^{-1}) has been reported by previous studies (Jensen et al. 2012). A study in China showed that the rice-rice-potato system with straw mulching produced the highest CH_4 emission during both early and late seasons of rice growing. When compared to the rice-rice system with winter fallow, the total N_2O emission was increased by 0.013 g m^{-2} in the rice-rice-rapeseed system and 0.045 g m^{-2} in the rice-rice-potato system with straw mulching indicating that crop diversification had no beneficial effect on reducing N_2O emission when introduced with straw mulching (Tang et al. 2015). Weller et al. (2015) reported that diversification from flooded crop systems to non-flooded crop systems leads to changes in the pattern of N_2O and CH_4 emissions. Flooded crop systems had high CH_4 emissions, while upland crop systems had high N_2O emissions; however, the GWP of non-flooded crops was lower compared to flooded rice. Weller et al. (2016) conveyed that N_2O emission was increased by two- to threefold in diversified crop systems but the large reduction in CH_4 emission resulted in a significant reduction in annual GWP compared to the traditional double-rice cropping system.

22.5 Conclusions

Conservation agriculture involves minimum soil disturbance, continuous ground cover, and diversified crop rotations or mixtures. CA production systems have the potential to improve soil quality if appropriate cropping systems are developed. Sequestering organic C in soil, creating a nutrient-rich environment for the proliferation of plants, and allowing water to pass through and conserved are some critical soil functions that can be enhanced with CA systems. Conservation tillage, increased cropping system complexity, cover cropping, animal manure application, optimum fertilization, and rotation of crops with pastures are effective strategies to enhance SOC sequestration. CA has the potential to contribute to soil C sequestration and reduced greenhouse gas emission. However, all circumstances are not perfect always. CA practices can reasonably be regarded as contributing to climate change adaptation and to sustainable intensification, whether or not they consistently deliver increased crop yields in every season.

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Implication of Different Tillage System on Root System Architecture and Their Environment

23

Nishant K. Sinha, M. Mohanty, Somasundaram Jayaraman, Jitendra Kumar, Dhiraj Kumar, and Alka Rani

Abstract

Root architecture serves as a promising target for efficient resource capture below the soil. Understanding its dynamics and performance under varying management practices is quite pivotal for the development of efficient cultivars in the era of resource crunch and vagaries of climatic scenarios. Because of the tedious methodology and time involvement, there is a limited study of root system architecture (RSA) performance under management practices; thus, in the present chapter, we reviewed the effect of varying tillage on root proliferation, resource capture, and its uptake. There is a presence of nutrient-specific transduction systems in roots for selectively absorb nutrients from the soil, and they modify as per the level of stress in the soil. This chapter also highlights how tillage alters both biotic and abiotic factors that, in turn, affect the root growth significantly. In addition, studies on the long-term effect of management practices on root dynamics/RSA are quite necessary for a complete understanding of resource capture and the pattern of its distribution in soil.

Keywords

Root system architecture · Tillage · Conservation agriculture · Carbon storage

23.1 Introduction

World agriculture is facing a greater challenge to produce more food and feed on diminishing natural resources, especially arable land, which is under an increasingly erratic environment. While arable land and water resources are dwindling by

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industrialization and urbanization, global capacities for food and feed production will increasingly have to compete with a growing need for energy and chemicals and the production of plants for purposes other than nutrition (e.g., clothing, housing, and biofuel). The only option left with us is to increase the crop productivity under the reduced nutrient and water inputs. Thus, it's inevitable to have a well-developed and efficient root system that can be brought through improved crop management and plant breeding. However, the study of plant roots is one of the most promising but least explored areas of research related to plant growth. The study of the root system is not new, with research papers going back in the literature over 100 years (Hanstein 1870; Janczewski 1874; Vines 1888; Pfeffer 1894; Nemec 1900).

Nevertheless, the aerial portions of plant species have received greater attention, probably because of their conspicuousness and easy access, while the underground portions have been neglected because of the difficulty of observing and sampling them and the disruption of root systems when they are removed from the soil. Roots play a vital role in connecting the plant to its environment and perform an essential function such as water and nutrient acquisition, plant anchorage, resource storage, and support of soil microbial communities (Bardgett et al. 2014). Root growth and development are highly plastic in response to the environmental condition and strongly determine plant performance and crop yield (Palta and Yand 2014).

Roots play a significant role in connecting the plant to the soil and thereby the soil to the atmosphere. The growth and development of aboveground plants depend on the acquisition of soil nutrients and water and so are closely associated with root morphology and physiology (Ju et al. 2015). Root interaction with the soil, the rhizosphere, symbiotic interactions with bacteria and fungi, exploitation of soil and increased surface by root hairs, and even more specific root characteristics such as Casparian bands in the endodermis, cellular characteristics of the root apex and the root cap all represent the basic knowledge of root biology (Ju et al. 2015). Regardless of long-standing observations and intensive research over generations, the root system architecture has mostly been ignored by mainline plant scientists and has remained "the hidden half" of the plant body (Waisel et al. 2002).

23.2 Root System Architecture

Soil is a heterogeneous medium with high spatial and temporal environmental variability at a wide range of scales, including those relevant to plant roots. The root system can be considered as an evolutionary response to such spatiotemporal variability in resource supply and associated constraints upon growth (Harper et al. 1991). Therefore, the extension of the root system in space and time is greatly governed by environmental conditions. The spatial configuration of the root system (number and length of lateral organs), so-called root architecture, vary greatly depending on the plant species, soil composition, and particularly water and mineral nutrient availability (Malamy 2005). Plants can optimize their root architecture by initiating lateral root primordia and influencing the growth of primary or lateral roots. The root system results from the coordinated control of both genetic endogenous programs by regulating growth and organogenesis and also the action of abiotic and biotic environmental stimuli (Malamy 2005; Hodge et al. 2009).

Root architecture addresses two important concepts: (a) the shape of the root system and (b) its structure. The shape defines the location of roots in space and the way the root system occupies the soil. Its quantification is generally achieved by measuring variables such as root depth, lateral root expansion, and root length densities. In contrast, root structure describes the variety of the components constituting the root system (roots and root segments) and their relationship (e.g., topology—the connection between roots; root gradients). However, root differentiation has important impacts upon structure–function relations (Clarkson 1996). The rhizosphere (i.e., the volume of soil around living plant roots that are influenced by root activity) (Hinsinger et al. 2005) is often simply thought of as a cylindrical shape around the root. However, this oversimplification does not account for integration at the root system level or for the inherent complexity of root systems that arise from the geometry, temporal dynamics, and heterogeneous aspects of roots. These complexities are incorporated into the concept of root architecture (Lynch and Brown 2001). Root geometry is complex because of the specific motion in space of each root, the relative locations between roots, and the possible overlapping of their zones of influence. The temporal dynamic comes both from the growth of the different root axes and from physiological processes associated with root segments (i.e., tissue differentiation), resulting in the temporal and spatial variability of function along the root axes. The diversity among roots within the root system and soil heterogeneity further increase this variability (Hodge et al. 2009). The spatial configuration of the root system i.e., root architecture, vary greatly depending on the plant species, soil composition, and particularly water and mineral nutrient availability (Malamy 2005). Plants can optimize their root architecture by initiating lateral root primordia and influencing the growth of primary or lateral roots.

Coupland and Johnson (1965) classified root systems architecture into (a) herringbone, comprising of the main axis and laterals only, or (b) dichotomous, where each lateral bifurcates. Much of the literature today uses Fitter's expansion of topological definition as an architectural trait (Fitter 1987, 1991). Taxonomically, most monocots have herringbone architecture, while most dicots have dichotomous architecture. More complex definitions of root architecture have also been proposed in which angiosperms are considered to have five distinct root types: tap, lateral, adventitious, basal, and collateral (Zobel 1986). While not commonly used in the studies of root architecture, this sort of classification can serve as a reminder that any changes in orientation, branching, elongation, and the relative distribution through the soil depth can give rise to a remarkable diversity of architecture (Bassirirad 2015).

Lynch (1995) quoted that the term "root architecture" may be used in various contexts to refer to distinct aspects of the shape of root systems. He further defined several terms related to the root system that delineates architecture from other terms (Table 23.1).

Roots can be defined as a continuum of root segments that vary in anatomy, morphology, and physiology, both spatially (different parts of the same root system)

Table 23.1 Important terminology in root system study

S. No.	Root-related terminology	Description
1.	Root morphology	It refers to the surface features of a single root axis as an organ, including characteristics of the epidermis such as root hairs, root diameter, the root cap, the pattern of appearance of daughter roots, undulations of the root axis, and cortical senescence. Anatomical features of a root related to cell and tissue organization are not usually part of architectural considerations
2.	Root topology	It refers to how individual root axes are connected to each other through branching. As in mathematical usage, root topology is stable to the deformation or rotation of the axes themselves and therefore is possible to measure on excavated root systems
3.	Root distribution	It refers to the presence (rather than the orientation) of roots in a positional gradient or grid. Typically, studies of root distribution are concerned with root biomass or root length as a function of factors such as depth in the soil, distance from the stem, and position between neighboring plants. Measurement of root distribution in agricultural and natural plant communities often includes roots of more than one plant or more than one species
4.	Root architecture	It refers to the spatial configuration of the root system, i.e., the explicit geometric deployment of root axes. Usually, studies of root architecture do not include fine structural details, such as root hairs, but are concerned with an entire root system or a large subset of the root system of an individual plant

Source: Lynch (1995)

and temporally (plastic changes, root aging), and perform multiple functions (Pregitzer et al. 2002; Wells and Eissenstat 2002). A schematic view of the typical root system is illustrated in Fig. 23.1. Among various root components, fine roots have been the focus of most research as it has been considered as critical for most root functions, including root elongation, nutrient and water acquisition, association with symbionts, and carbon exudation (Freschet and Roumet 2017). Detail of root traits contributing to plant functioning is described in Table 23.2. The root orders such as first, second, and third, generally, display thin, N-rich tissues that support mycorrhizal colonization and perform uptake of soil resource (Guo et al. 2008; Jia et al. 2013). In contrast, higher-order roots are thicker and longer-lived and generally perform transport and storage functions (Rewald et al. 2011). The first three order of the root is collectively known as absorptive roots, whereas higher-order roots (>3 order) may also be called as transport roots (Freschet and Roumet 2017).

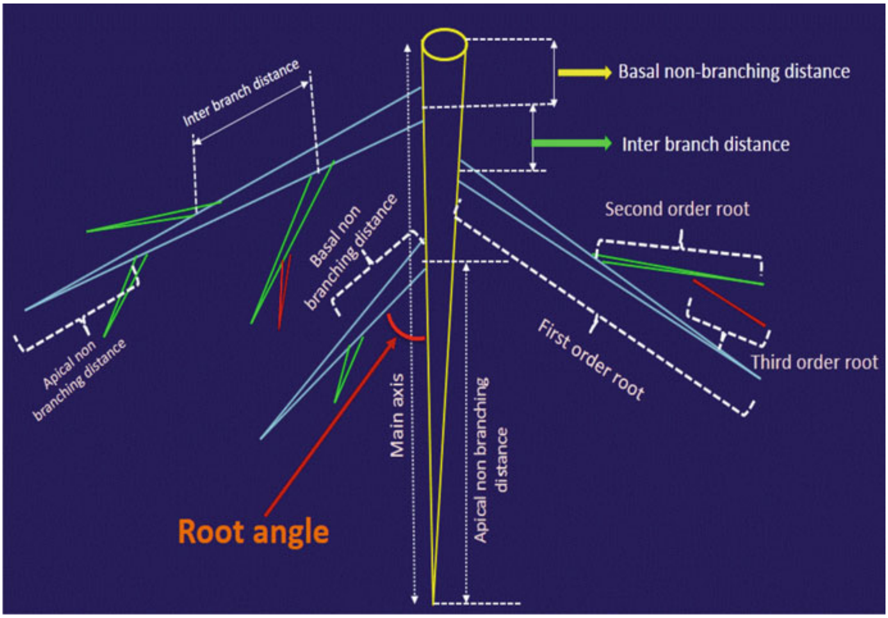

Fig. 23.1 A schematic view of the root system and its components

23.3 Methodology to Study of the Root System and Characterization

Agricultural crops usually need a well-developed root system in order to exploit deeper soil layers. They are then more resistant to periods of stress that often occur during growth and are more likely to yield well. Farmers should know what factors promote and impede root growth. With this knowledge, they can purposefully encourage root growth. Such help to the farmer is the ultimate aim of ecological research on roots (Schuurman and Goedewaagen 1965). Many techniques have been used to increase the accessibility of plant roots. Kolesnikov (1971) and Böhm (2012) summarize several methods of root studies. Some of them are (a) excavation methods, (b) monolith methods, (c) Auger methods, (d) profile wall methods, (e) glass wall methods, and (f) container methods. These methods are classical and still in use for root system characterization. However, with advancements in computing technology, a lot of innovative methods have been evolved with time. Recently, Paez-Garcia et al. (2015) reviewed strategies and approaches for root study in the field as well as in the laboratory. Those methods are presented in Table 23.3. Every method has its own advantages and disadvantages, which is well explained by Wasaya et al. (2018) and presented in Table 23.4.

Although phenotyping the field crop is becoming a focus of crop research, field-based phenotyping is largely subjected to a dispute (Chen et al. 2018). Not only the

Table 23.2 Plant function and associated root components

S. No.	Plant function	Root category	Root traits
1.	Soil exploration/ exploitation	Entire root	Specific root length, root vertical distribution, maximum rooting depth, root growth angle, branching intensity
		First three order of roots	Root mycorrhizal colonization, fine root mass fraction, branching intensity, root diameter
2.	Plant nutrient acquisition	Entire root	Nutrient uptake rate, N_2 fixation, mycorrhizal type
		First three order of roots	Nutrient uptake rate, specific root length, root mycorrhizal colonization, root hair length and density, root diameter, respiration rate
3.	Plant water acquisition	Entire root	Maximum rooting depth, root vertical distribution, root length density
		First three order of roots	Fine-root mass fraction, root cortex thickness, Specific root length, root diameter, root mycorrhizal colonization
4.	Carbon and nutrient conservation	Entire root/first three order of roots	Life span, root tissue density, root resorption
5.	Storage	Tap root/ rhizome/entire roots	Root diameter, element concentration.
6.	Anchorage, resistance to uprooting	Entire root	Root length density, maximum rooting depth, root tensile strength
7.	Penetration force in soil	First order of roots	Root diameter
8.	Penetration against herbivores	First three order of roots	Root mycorrhizal colonization, root phenolic concentration
9.	Penetration against pathogen	First three order of roots	Root mycorrhizal colonization

Adapted from Freschet and Roumet (2017)

interactions among plant genomics, field environment, soil, and crop management complicated the experimental design in the field, but also, in general, the objective of a field-based phenotyping task could be inconspicuous, due mainly to a poor definition of target traits. Some researchers even stated that phenotyping for field crops could never be possibly made because the plant phenotypes are infinite; they vary morphologically and molecularly over developmental time and in response to the environment (Chitwood and Topp 2015). The more we examine the root system, the more complicated their responses and interactions prove to be (Hodge et al. 2009).

Recent advancement of RSA-related phenome research has promoted the provision of a number of modern tools, many of which were resorted to computer science or image processing, e.g., DART (Le Bot et al. 2010), SmartRoot (Lobet et al. 2011),

Table 23.3 Strategies and approaches for root system architectural studies

S. No.	Plant cultivation system	Growth media	Descriptions
1.	Growth and luminescence observatory for roots	Soil (lab)	This method combines custom-made growth vessels and new image analysis algorithms to nondestructively monitor RSA development over space (2D) and time. The technique allows information on soil properties (e.g., moisture) to be integrated with root growth data. The system makes use of luminescence imaging of roots expressing plant codon-optimized luciferase
2.	X-ray computed tomography	Soil (lab and greenhouse)	Nondestructively visualizes opaque root structures by measuring the attenuation of ionizing radiation as it passes through the root. A series of projections are acquired and combined to reconstruct a 3D image of the root system
3.	Rhizophonics	Liquid media (lab)	Combines hydroponics and rhizotrons. System is made of a nylon fabric supported by an aluminum frame. The setup is immersed in a tank filled with liquid media. Allows nondestructive, 2D imaging of root architecture while simultaneously sampling shoots
4.	Clear pot method	Soil (greenhouse)	Uses transparent pots filled with soil or other potting media. Seeds are planted close to the pot wall to enable high- throughput imaging of roots along the clear pot wall. To prevent light exposure, the clear pot is placed in black pots while roots are developing
5.	Rhizoslides	Paper-based (lab, greenhouse)	The setup consists of a plexiglass sheet covered with moistened germination paper. Seeds are planted on the slit of the plexiglass. The system allows the separation of crown roots from embryonic roots
6.	Shovelomics	Soil (field-based)	Involves manual excavation of plants and separating roots from the shoots. Washed roots are then placed on a phenotyping board for root trait quantification. New algorithms allow the extraction of several root traits in a high-throughput manner
7.	Soil coring	Soil (field-based)	Uses a tractor-mounted, hydraulic soil corer to drive steel alloy sampling tubes into the soil. When combined with novel planting configurations (e.g., hill plots), this method allows for phenotyping deep-rooted crop varieties

(continued)

Table 23.3 (continued)

S. No.	Plant cultivation system	Growth media	Descriptions
8.	Rhizolysimeters	Soil (field-based)	Elaborate facility consisting of an underground corridor and concrete silos and pipes to house soil-containing soil cores for direct root observation
9.	Minirhizotrons	Soil (field-based)	A transparent observation tube permanently inserted in the soil. Images of roots growing along the minirhizotron wall at particular locations in the soil profile can be captured over time.

Source: Adapted from Paez-Garcia et al. (2015)

RootNav (Pound et al. 2013), RootTrace (French et al. 2009), RhizoScan (Diener et al. 2013), and Root System Analyser (Leitner et al. 2014). As these platforms are largely varied from one to another, cross-platform protocols are needed, paving the way for inter-platform exchanges of information, e.g., archiDART package (Delory et al. 2016) and RSML package. However, most of these RSA trait-analyzing platforms were still used for sub-root system-level parameters, i.e., geometrical or segmental level indices (Chen et al. 2018).

23.4 Root System Architecture and Water Uptake

Plant root systems perform many essential adaptive functions, including water and nutrient uptake, anchorage to the soil, and the establishment of biotic interactions at the rhizosphere. Changes in the architecture of the root system, therefore, can profoundly affect the capacity of plants to take up water and nutrients (López-Bucio et al. 2003). Three major processes affect the overall architecture of the root system. First, cell division at the primary root meristem (i.e., of initial cells) enables indeterminate growth by adding new cells to the root. Second, the formation of the lateral root increases the exploratory capacity of the root system, and third, the formation of root hair increases the total surface of primary and lateral roots. Alterations to any of these three processes can have profound effects on root-system architecture (RSA) and on the capacity of plants to grow in soils in which nutrient resources are limiting (López-Bucio et al. 2003).

There is much evidence that water availability can regulate root architecture. Del Bianco and Kepinski (2018) reviewed various studies on the root system and reported that water deficiency in the upper soil layer suppresses lateral root growth and root growth angle in *Arabidopsis* (Rellán-Álvarez et al. 2015) and crown root growth in *Setaria viridis* (Sebastian et al. 2016). Flooding, on the other hand, promotes adventitious root formation in rice and elongation in *Arabidopsis* (Lin and Sauter 2018). The genetic responses to drought and flooding are also very complex and involve variations in both the transcriptome (Janiak et al. 2016;

Table 23.4 Advantages/disadvantages of methods used for growing plants for root phenotyping

Growth environment	Advantages	Disadvantages	Examples
Laboratory	• It allows for easy and nondestructive visualization of RSA • It is easy to assess root growth • It does not require any washing of roots • It is time-saving as it does not require soil excavation as in the field • It is easily repeated under controlled conditions • It requires less resources • It gives a clear picture of all root types and RSA	• The root system architecture in laboratory-grown plants does not accurately reflect real-time field conditions • Controlled conditions also eliminate possible interaction with beneficial microbes due to the use of growth media other than soil as in field conditions • As plants are grown in controlled conditions, which prevents their exposure to environmental conditions, therefore, the physiological relevance of roots need further evaluation	EZ-Rhizo RootNav Root Reader 3D X-ray computed tomography SmartRoot
Greenhouse/ glasshouse	• Close to the field conditions as the medium used may be soil- or sand-filled pots • A large number of varieties can be evaluated in a shorter period of time • Easy to handle the experiments compared with the field • Less time is required for root washing as compared to the field	• Some roots may be destroyed during washing • RSA may be affected by the growth container • As plants are grown in controlled conditions, which prevents their exposure to environmental conditions, therefore, the physiological relevance of roots need further evaluation	Root Reader 2D WinRhizo
Field	• It gives a true picture or presentation of the root structure • It gives a clear physiological and practical picture as plants grow by facing all the environmental factors	• Roots form an extensive network which is difficult to excavate all the roots • Labor-intensive and time-consuming • Root excavation is very tedious and energy-intensive work • Washing of roots is also time-consuming • Destructive method as roots may be destroyed during excavation and washing • Problems may occur due to variability in the field or soil conditions	Shovelomics, DIRT WinRhizo X-ray computed tomography

Adapted from Wasaya et al. (2018)

Kwasniewski et al. 2016; Opitz et al. 2016) and the methylome (Chwialkowska et al. 2016), representing changes in gene expression over both short and longer timescales. Different cell types respond differently to water status (Opitz et al. 2016), although root hairs seem to be the prime site of water availability perception (Kwasniewski et al. 2016). Responses to variations in water availability involve auxin (Ma et al. 2017; Nakajima et al. 2017), cytokinin (Xu et al. 2016), H_2O_2 (Giuliani et al. 2005; Ma et al. 2017), ABA (Kong et al. 2016), and ethylene (Ali and Kim 2018). Flooding and drought can affect different crop species in distinct ways (Striker and Colmer 2017; Pavlović et al. 2018). In particular, structural differences, such as the number of xylem bundles (Prince et al. 2017; Considine et al. 2017) or crown roots (Gao and Lynch 2016) for drought and root porosity for flooding (Striker and Colmer 2017), are major components of such variation. From a molecular point of view, auxin has been revealed to be required for hydrotropism in pea and rice, but not in *Lotus japonica* (Nakajima et al. 2017).

Classical measures to characterize RSA include total root length, root surface area, and root volume. While total root length is related to the soil volume explored by the root system, root surface area is important for uptake and exudation mechanisms that occur across the root–soil interface, and root volume can be seen as a measure of carbon investment into a specific root structure. The number of branches (or the number of root tips) gives information about the degree of branching within a root system. Maximum rooting depth and maximum horizontal spread of the root system are negatively correlated and determine whether the root system is of steep and deep (Lynch 2013) or of shallow appearance, which has direct implications on root foraging, while deep-rooting plants can take up water from deeper soil layers and are thus advantageous in dry climates and during drought periods (Schnepf et al. 2018). The benefit of deep root systems in drought-prone environments has been demonstrated experimentally in rice (Steele et al. 2013), wheat (*Triticum aestivum*; Manschadi et al. 2010), maize (Hammer et al. 2009, 2010), legumes (Vadez et al. 2013), grapes (*Vitis vinifera*; Alsina et al. 2011), or trees (Pinheiro et al. 2005). However, other results seem to indicate that deep root systems are not always linked to an increase in yield. Experiments with chickpea (*Cicer arietinum*; Zaman-Allah et al. 2011a, b) and wheat (Schoppach et al. 2013) indicate that drought tolerance, especially in terminal drought conditions, can be linked to a conservative use of water throughout the season rather than deep rooting. In such cases, plants tailored for improved root length density at depth are likely to use too much water early in the season and reduce the reserve of water in the profile during the grain filling stage (Lobet et al. 2014).

Substantial variation in root architecture has been reported both among plant species (Kutschera 1960; Fitter and Stickland 1992; Bouma et al. 2001) and within genotypes of crop species (Liao et al. 2001; Sinha et al. 2017) in terms of traits such as depth of rooting, root elongation rate, root distribution at depth, xylem vessel diameter, root growth angle, and root-to-shoot dry matter ratio (Manschadi et al. 2010). The growth angle of root axes or root gravitropic response is a principal component of RSA, which has been strongly associated with temporal and spatial acquisition efficiency of soil resources. In common bean (*Phaseolus vulgaris* L.), for instance, the angle of basal roots is the major determinant of root architecture, while genotypes exhibiting a wider basal root angle appear to develop a shallower root system, which enhances topsoil foraging and thus phosphorous acquisition (Lynch and van Beem 1993; Nielsen et al. 1999; Liao et al. 2001; Lynch and Brown 2001). Likewise, Kato et al. (2006) demonstrated that the growth angle of nodal roots in rice (*Oryza sativa* L.) affects vertical root distribution and rooting depth, which are considered important traits for drought adaptation in upland rice. In wheat, Nakamoto and Oyanagi (1994) demonstrated significant genotypic variation in the angular spread of seminal roots in the Japanese germplasm and argued that deep-rooted wheat genotypes exhibit a narrower angle of seminal roots, while genotypes with a shallower root system tend to grow their seminal roots more horizontally.

Wasson et al. (2012) discussed the important strategies in the selection of RSA traits to increase uptake of stored soil moisture. These traits are (a) deeper root systems, (b) increased root length density in medium and deep soil layers, (c) reduced root length density in the topsoil, and (d) decreased resistance to water movement from soil to root by increasing root hair growth and xylem diameters (Fig. 23.2). However, Wasson et al. (2012) suggested these traits for the wheat crop, but these are applicable for most of the cereal crops for efficient uptake of soil water in rainfed conditions.

23.5 Root System Architecture Versus Nutrient Uptake

Worldwide, 60% of arable soils suffer from growth-limiting problems, with both deficiencies and toxicities of mineral nutrients (Cakmak 2002). Also, nutrient supply to the plants is frequently suffered from adverse soil conditions such as soil pH and redox state, which impact the phyto-availability of mineral nutrients and the concentrations of toxic elements in the soil solution (White and Greenwood 2013). Sparks and Benfey (2017) also stated that the amount of a nutrient that a plant will acquire depends on several factors, including the soil availability, the root system structural features, the plant stores of the nutrient, and the efficiency of nutrient uptake and utilization. However, it is not only the soil properties that affect the capability of soils to deliver nutrients. Soils also need to sustain root growth so that the growing plants can capture a sufficient proportion of the available nutrients and water (White et al. 2013; Schjoerring et al. 2019). Root size and architecture play a major factor in the nutrient uptake efficiency of plants (Fitter 1991; Bar-Tal et al. 1997). A plant's ability to explore the soil and to compete for soil resources is mainly dependent on the architecture of its root system (Lynch 1995). There is scientific consensus that root branching is subject to genetic control and influenced by biotic and abiotic factors. Therefore, manipulating RSA has emerged as a fundamental strategy to enhance nutrient and water acquisition, especially in low-input agricultural systems (Duque and Villordon 2019).

The contrasting availability of nutrients in time and space and their dependence on soil chemistry and microbiology entail trade-offs for root foraging strategies. For example, strategies to improve the capture of nitrate, which is highly mobile, often

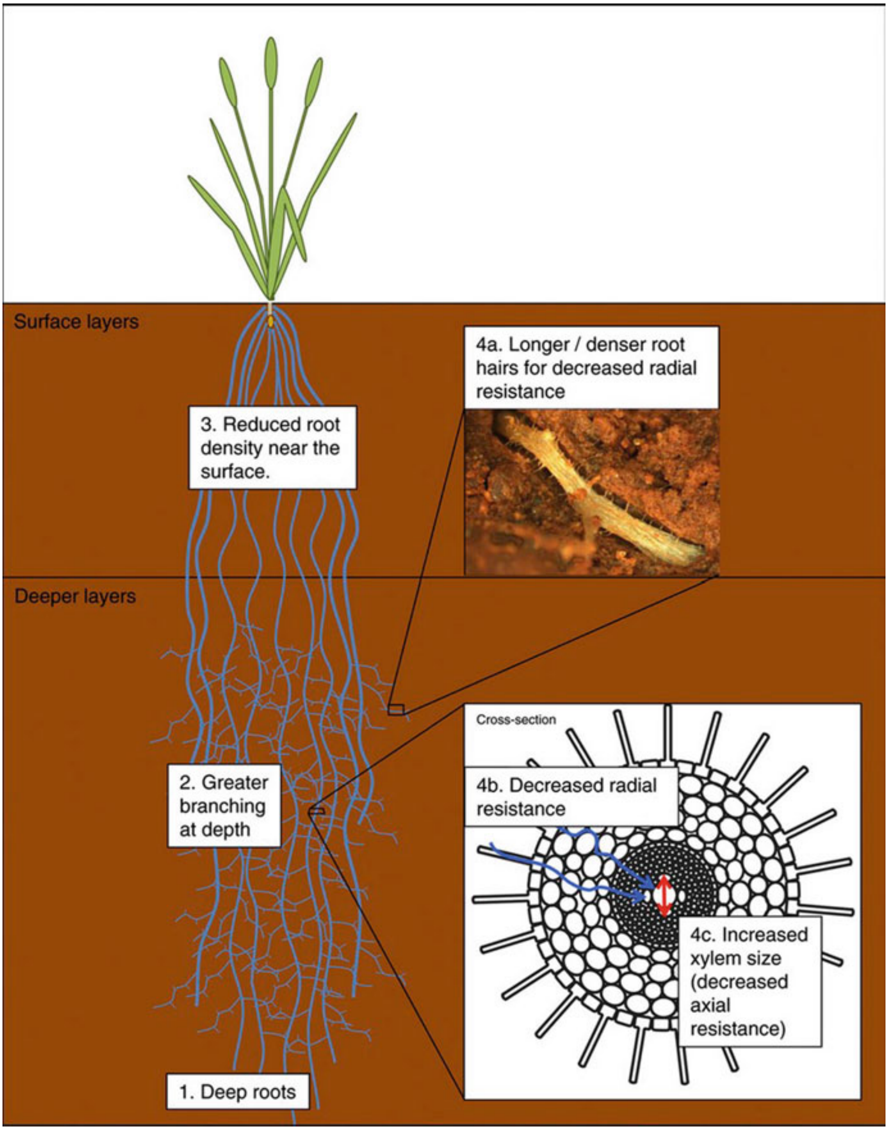

Fig. 23.2 Illustrating four desirable traits to increase deeper water uptake. (Adapted from Wasson et al. 2012)

incur trade-offs for the capture of phosphorous, which is relatively immobile. Further, the utility of strategies to improve nutrient availability via rhizosphere modification depends on whether the bulk soil is acid or alkaline (Hinsinger 2001). In soil, localized depletion of mineral nutrients by root limits continued resource capture (Barber 1984), necessitating continued exploration of new soil domains and intensifying interplant competition. Root phenotypes are the result of long and intensive selection for efficient and effective capture of soil resources, and efficient utilization of acquired nutrients has been subject to natural selection since the origin of life (Lynch 2019).

Nitrogen and phosphorus are among the elements considered most limiting to plant growth and productivity because they are often present in small quantities locally or are present in a form that cannot be used by the plant (Morgan and Connolly 2013). Plants are able to directly acquire nitrate and ammonium from the soil. However, when these nitrogen sources are not available, certain species of plants from the family Fabaceae (legumes) initiate symbiotic relationships with a group of nitrogen-fixing bacteria called rhizobia. These interactions are relatively specific and require that the host plant and the microbe recognize each other using chemical signals. The interaction begins when the plant releases compounds called flavonoids into the soil that attract the bacteria to the root. This form the bacteroids, which allow bacteria to enter the cytoplasm of cortical cells where they convert atmospheric nitrogen to ammonia, a form that can be used by the plants. (Limpens and Bisseling 2003; Ferguson et al. 2010; Morgan and Connolly 2013). Recently, Lynch (2019) presented the ideotype in terms of root system architectural parameters for efficient uptake of different nutrients. For example, the steep and deep root ideotype for improved N acquisition in maize consists of architectural, anatomical, and physiological traits. Architectural traits include steep root growth angles, few nodal roots, sparse lateral branching, and low architectural plasticity in response to environmental cues. Reduced root production is beneficial for N capture by reducing competition among root axes for internal (e.g., carbohydrate) and external (i.e., nitrate) resources (Postma et al. 2014). Guo et al. (2008) suggested an idiotypic root architecture for efficient N acquisition in maize that includes (a) deeper roots with high activity that are able to uptake nitrate before it moves downward into deep soil, (b) vigorous lateral root growth under high N input conditions so as to increase spatial N availability in the soil, and (c) strong response of lateral root growth to localized nitrogen supply so as to utilize unevenly distributed nitrate, especially under limited N conditions.

Unlike nitrate, which readily moves in soil toward the roots via both mass flow and diffusion, phosphate (Pi) is highly immobile. Mass flow typically delivers as little as 1–5% of a plant's P demand, and the amount intercepted by growing roots is only half of that (Lambers et al. 1998). The rest of all required Pi must reach the root surface via diffusion. Increasing Pi delivery to roots via mass flow can be achieved by enhanced transpiration rates, but this cannot have a major effect and would be at the expense of a plant's water use efficiency. Root interception of Pi can be increased by root proliferation, increased frequency and length of root hairs, a modified root architecture that enhances allocation to shallow soil horizons, and mycorrhizal symbioses. The diffusion of Pi toward the root can be increased by increasing the moisture content of dry soil or by increasing the Pi concentrations in the soil solution through the release of Pi from complexed, sorbed, or organic form of P Lambers et al. 2006). For efficient phosphorous acquisition, Lynch (2019) suggested two options to focus on (1) improving foraging in P-rich soil domains (i.e., the topsoil in

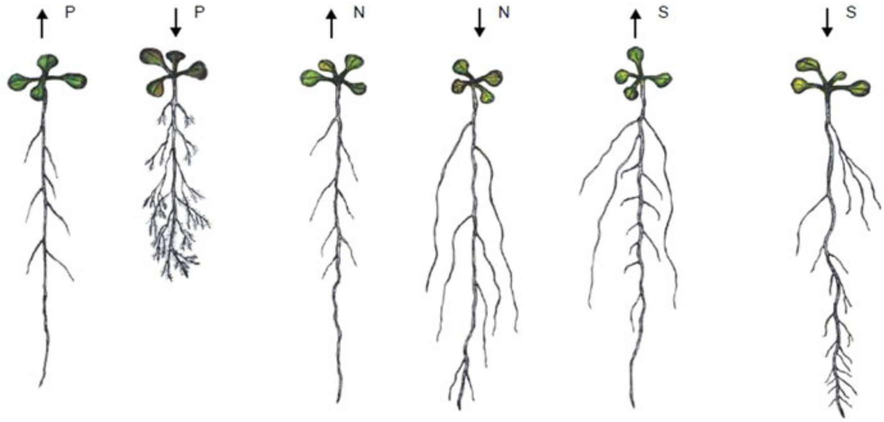

Fig. 23.3 Root system under the different nutrient concentrations. (Adapted from López-Bucio et al. 2003)

most agricultural soils) and (2) improving the exploitation of those domains through increased P solubilization. Topsoil foraging can be enhanced through greater production of axial roots, shallower axial root growth, angles, greater lateral root density, reduced root metabolic cost, and greater root hair length and density. Regarding the phosphorous solubilization in the rhizosphere, worldwide researchers showed the possibility of harnessing genetic variation in P-solubilizing exudates to develop P-efficient crop lines (Richardson et al. 2009). Natural and induced genetic variation for the production of these compounds is associated with P mobilization in vitro, but rigorous analyses have failed to show a benefit of such variation for P acquisition in a range of soils in the field, whether it be due to carboxylates (Pearse et al. 2007; Ryan et al. 2014) or phosphatases (George et al. 2008). This lack of response may be due to various factors, including limited spatiotemporal distribution of exudate production in root systems and their limited lifespan and mobility in the rhizosphere due to microbial metabolism and chemical fixation (Lynch 2019).

The ability of plants to respond appropriately to nutrient availability is of fundamental importance for their adaptation to the environment. Nutrients such as nitrate, phosphate, sulfate, and iron act as signals that can be perceived. The responses of root architecture to nutrients can be modified by plant growth regulators, such as auxins, cytokinins, and ethylene, suggesting that the nutritional control of root development may be mediated by changes in hormone synthesis, transport, or sensitivity. Recent information points to the existence of nutrient-specific signal transduction pathways that interpret the external and internal concentrations of nutrients to modify root development (López-Bucio et al. 2003). A study on the effect of various nutrient concentrations on the root system was published in "Current Opinion in Plant Biology" (López-Bucio et al. 2003). The following Fig. 23.3 is adapted from this study to understand the dynamics of the root system under the different nutrient concentrations.

23.6 Root System Architecture and Tillage System

Soil tillage has been a major farm operation of crop production for centuries. Tillage has been used to optimize edaphological conditions, such as soil water and soil temperature regimes (Somasundaram et al. 2018a), soil aeration, seed-soil contact, nutrient availability (Hati et al. 2015), bulk density, porosity, pore size distribution (Somasundaram et al. 2018b, 2019), and pest activity. Tillage aims to support seed germination, seedling establishment, plant, and root growth (Lal and Shukla 2004; Mehra et al. 2018). However, tillage operations are primarily aimed at loosening the soil (i.e., increasing porosity and reducing soil bulk density). The consequences of the soil interacting with equipment used for tillage and the timing of operations may result in soil compaction (Batey 2009; Reicosky 2003). Particle-to-particle or aggregate-to-aggregate contact affects the physical status of the soil matrix and its associated water, air, and temperature properties (Six et al. 2002). Furthermore, soil hardens upon drying act as a physical barrier to root development (Iqbal et al. 1998; Choudhary et al. 2015). The potential of plants to obtain water and mineral nutrients from the soil is primarily attributed to their capacity to develop extensive root systems (Guan et al. 2015). Huwe and Titi (2003) reports that tillage influences both biotic and abiotic processes, modifying structural properties such as cracks, aggregates, and pore continuity, as well as affecting soil aeration, temperature, and moisture levels. By greatly changing soil properties, tillage also greatly influences root growth. Mosaddeghi et al. (2009) conclude that the most important impact of tillage on crop development is achieved by affecting root development and function. Therefore, the root system serves as a bridge between the impacts of agricultural practices on soil and changes in shoot function and harvested yield.

Yeboah et al. (2017) found that no tillage with straw retention significantly decreased soil bulk density and boosted soil moisture content compared to conventional tillage with straw removed and no tillage with straw removed at the topsoil depth (0–30 cm), therefore, significantly affects the root length, root surface area, root diameter, and root volume through the 0–50 cm soil profile. The increased root morphological characteristics (root length, root surface area, root diameter, and root volume) under straw-amended soils, particularly in no-tillage (NT) system up to 50 cm soil depth, could largely be attributed to the decreased soil bulk density and the enhanced soil moisture, which promotes root proliferation during the growing season of wheat. At almost every growth stage, the root morphological characteristics in the top 50 cm soil depth under NT with straw retention were significantly greater than that under the NT and conventional tillage (CT) with straw removed treatment. In contrast, Guan et al. (2014) studied root development under three tillage systems, viz., no tillage (NT), plow tillage (PT), and rotary tillage (RT) in maize crop. The study showed that root biomass under PT and RT was significantly higher than under NT across 0–40 cm soil profile. Some other researchers also showed that maize roots are generally greater under PT than NT at all depths (Karunatilake et al. 2000; Sheng et al. 2012). Root length density (RLD) and root surface area density (RSD) are pertinent parameters for characterizing root systems (Amato and Ritchie 2002; Doussan et al. 2006). Guan et al. (2014) found that RLD in the uppermost soil profile (0–10 cm) showed no evident differences among tillage practices at the silking stage, but RLD under PT and RT was significantly greater than under NT at maturity. Similar findings were reported for tillage systems on chickpea by Muñoz-Romero et al. (2012), on maize by Karunatilake et al. (2000) and Mosaddeghi et al. (2009), and on spring wheat by Munoz-Romero et al. (2010). Qin et al. (2006) reported that RLD is significantly higher under NT than under CT (plow tillage) at a depth of 5 cm, whereas it is higher under CT than under NT in 10–50 cm soil profile.

Moreover, there is no difference in RLD between the tillage practices below 50 cm. Guan et al. (2014) found the RLD under PT was markedly higher than under NT in the 10–50 cm soil profile at silking and maturity stages, and there was no significant difference in LSD of 60–100 cm soil profile among tillage practices at maturity. RLD and RSD under PT and RT in the upper soil profile were high compared to under NT, which could be due to the existence of high soil compaction under NT. Mehra et al. (2018) used micro X-ray tomography (μXCT) to study the root phenotypes under the different tillage systems. Quantified root phenotypes over the plant growth stages show that the mean root volume was 9.6% higher in the top 20 cm of the soil in NT than CT practice. The vertical distribution of roots and root architectural measurements evaluated through μXCT indicated increased root length (8.7%) and root surface area (2.6%) under the CT system compared to NT. The higher root volume under the NT system could be related to the presence of higher mesopores in the top 20 cm soil, which have the ability to store more water and nutrients (Murphy 2014) than macrospores, thereby resulting in higher root volume in the NT system compared to CT.

It is universally accepted that soil bulk density is the highly dynamic soil attribute, affected prominently by the different management practices, including cropping systems and tillage management practices (Kushwa et al. 2016; Sinha et al. 2014a, b). A common response of the root system to increase in bulk density (BD) is a decrease in root length, concentrating roots in the upper layer, and decreasing rooting depth (Lipiec and Hatano 2003). The root elongation rate is decreased with the response to higher BD in cotton (*Gossypium hirsutum*) and peanut (*Arachis hypogaea* L.) (Taylor and Ratliff 1969), in pea (*Pisum sativum L.*) (Vocanson et al. 2006), in maize (*Zea mays* L) (Bengough et al. 2006), and in tomato (*Solanum lycopersicum*) (Tracy et al. 2012). Konopka et al. (2009) found that maize roots were more tortuous in compacted soil, with a greater branching density and shorter lateral roots. It has also been observed that moderate compaction of the seedbed may be beneficial for root growth and resource capture (Atkinson et al. 2009) and reduces the risk of lodging in cereals in light textural soils (Scott et al. 2005). Choudhary et al. (2015) determine the effect of soil compaction levels by varying the soil bulk density (BD) on rooting parameters of two contrasting chickpea cultivars in central India. The BD considered were (a) 1.2, (b) 1.4, (c) 1.5, and (d) 1.6 Mg/m^3 and rooting parameters studied were main axis length, number of nodes, number of primary roots, sum of the length of primary roots, root diameters, and root insertion angle. Results indicated that when BD was increased from 1.2 Mg/m^3 to 1.6 Mg/m^3, there was 59% and 45% reduction in root length of JG 11 and JG

130, respectively. On average, an increase in BD by 0.1 unit resulted in 19.34% and 19.11% decrease in the root main axis length of JG 11 and JG 130, respectively. The total number and length of primary roots were also significantly ($P < 0.05$) decreased by compaction levels. On average, the total primary root length decreased by about 66% in both the cultivars by increasing BD from 1.2 to 1.6 Mg/m^3. The same level of increase of BD resulted in 65% and 47% decrease in the number of nodal roots in JG 11 and JG 130, respectively.

Furthermore, it has also been observed that toward higher compaction levels, a small increase in BD resulted in a greater reduction in root architectural parameters. For example, an increase in BD from 1.2 Mg/m^3 to 1.4 Mg/m^3 resulted in 23% reduction in main axis length in JG 130, whereas further increase in BD from 1.4 Mg/m^3 to 1.6 Mg/m^3 resulted in 33% reduction in the main axis. Similarly, for JG 11, the same increase in BD resulted in 32% and 45% reduction in main axis length. At a higher compaction level, both the cultivars tend to increase its root diameter. An increase of 33% and 21% in root diameter was observed for JG 11 and JG 130 in response to an increase in BD from 1.2 to 1.6 Mg/m^3 (Table 23.5). It was observed that the angle became wider as the compaction levels increased. At higher compaction level, i.e., at BD 1.6 Mg/m^3, an angle of 60° was dominant in both cultivars, while a smaller angle of 40° was observed at lower compaction levels. As the BD levels increased from 1.2 to 1.6 Mg/m^3, the root angles also increased from 40° to 60°. Under the stressed condition, roots may have an optimum root angle to achieve the most efficient distribution and maximize the volume of soil explored for water and/or nutrient uptake (Lynch and Brown 2001; Tracy et al. 2012).

23.7 Impact of Root System Architecture/Pattern on Carbon Storage

Roots play a major role in carbon (C) storage in soil. Due to their rapid decomposition and turnover rate of fine roots, they provide primary input of organic C into the soil to the tune of 30–80% of the total (Steele et al. 1997; Brown 2002; Ruess et al. 2003; Howard et al. 2004). However, due to root biomass dynamics, production rate, monthly succession, seasonal rate of growth, architecture, and their pattern of proliferation, the rate of C storage mostly by fine roots varies greatly among different species. One of the most important factors dictating the decomposition of the fine roots is the C:N ratio, where evidence suggests that a low C:N ratio results in more decomposition of roots. Both abiotic and biotic factors affect the roots' decomposition and their transformation into the C stock of the soil. Moreover, the fine dynamics studies under different cropping systems and ecologies are very limited due to their tiresome methodology and the involvement of time. There is an urgent need to understand the root dynamics and production under a fluctuating environment for a better understanding of their contribution toward carbon storage in soil.

Table 23.5 Root architectural parameters of chickpea as affected by different levels of bulk density

	Main axis length (cm)		Number of nodes		Number of primary roots		Sum of length of primary root (cm)		Root diameter (mm)		Insertion angle[a] (degree)	
	JG-11	JG-130	JG-11	JG-130	JG-11	JG-130	JG-11	JG-130	JG-11	JG-130	JG-11	JG-130
BD-1	16.67a	17.00a	15a	16a	20a	23a	54a	57a	0.12b	0.19a	40 (30–65)	40 (30–65)
BD-2	11.33b	13.00b	12a	15a	15b	19ab	37b	36b	0.13ab	0.20a	40 (40–60)	40 (20–45)
BD-3	8.83b	9.17c	8b	14a	10c	17b	24c	25c	0.15a	0.20a	40 (40–70)	40 (30–80)
BD-4	3.77c	4.00d	7b	10b	7d	12c	18c	19c	0.16a	0.22a	60 (40–70)	60 (30–70)

[a]Angle presented as "mode." [*]Value in parenthesis indicates range. BD1 = 1.2 Mg/m^3, BD2 = 1.4 g/m^3, BD3 = 1.5 Mg/m^3, BD4 = 1.6 Mg/m^3. Same letters (a, b, c, . . .) in a column indicate a nonsignificant difference between the treatments Choudhary et al. (2015)

23.8 Conclusions

In this chapter, we summarized behaviors of root system architecture proliferation under varying management conditions. Root system parameters found to be very sensitive to small changes in both biotic and abiotic factors that get changed due to the adoption of varying tillage options. Study of root system architecture on a long-term basis is quite necessary along with the aboveground plant component for better understanding of resource acquisition, nutrient cycling, carbon dynamics, and storage in soil.

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Conserving Soil and Reverting Land Degradation Through Conservation Practices with Special Emphasis on Natural Resource Conservation

24

Shakir Ali and Somasundaram Jayaraman

Abstract

Degradation of the land ecosystem is a major problem in India due to biotic and abiotic interferences. About 121 M ha land has been degraded and largely falls under rainfed regions. It has negative impacts on agricultural production and economy and the natural environment. In India, the per capita availability of both land and water is declining exponentially due to increasing population pressures. The arable land has dwindled from 0.48 ha in 1950 to 0.15 ha in 2000 and is likely to further reduce to 0.08 ha by 2020. The water availability declined from 1816 m^3 in 2001 to 1511 m^3 in 2011 against the world's average of 7400 m^3 and Asian countries' average of 3240 m^3. These issues and challenges need to be addressed by the adoption of smart, site-specific soil and water conservation practices. The field studies conducted in the semiarid agroecological region showed that the implementation of various conservation practices increased crop yield and biomass production, reduced runoff and soil loss, increased groundwater recharge, and improved socioeconomic conditions of the farmers. Therefore, the conservation practices tested in the semiarid region of India can be extended to other agroecological regions of the world for better management of degraded lands for reducing runoff and soil erosion for sustaining and stabilizing productivity of the food, fodder, and fuel.

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Keywords

Soil conservation measures · In situ and ex situ conservation practices · Soil erosion · Land degradation

24.1 Introduction

Soil and land degradation are worldwide problems (Ferreira et al. 2015; Ali et al. 2017), and these are some of the major threats to the land ecosystem, which affect the society and the economy of a country. Globally, nearly 24 billion tonnes of fertile soil are lost annually through water erosion (FAO 2011). In India, about 5.11 gigatonnes of soil are being eroded annually due to different reasons (Sharda and Ojasvi 2016). Out of which, 34.1% of the total eroded soil is deposited in the reservoirs, 43.0% is displaced within the river basins, and the remaining 22.9 is discharged outside the country mainly to oceans. A recent database on land degradation in India shows that 36.7% of the total arable and nonarable land surface of the country (120.72 million ha) suffers from various forms of degradation. These include soil erosion by water (68.4%), which is a chief contributor to degradation followed by wind erosion (9.6%), acidic soil (15%), alkaline soil (3.0%), saline soil (1.8%), waterlogged lands (1.0%), and mining and industrial wasteland (0.2%) (NAAS 2010; Sharda and Ojasvi 2016). The loss of crop productivity, one of many onsite negative impacts of soil erosion by water and other onsite ill-effects, includes the removal of productive soil top layer; significant loss of agricultural land; deterioration of soil physical, chemical, and biological properties; loss of nutrients, soil organic matter, and soil organic carbon (SOC) by soil transport, and low aggregate stability of the soil; soil loss diminishes soil water storage capacity, nutrient, impacting crop growth, and flood risk and even cropland loss (Lal 2003; WMO 2005; Pimentel 2006). Soil erosion also brings offsite damages, such as fluvial sediment deposition, reservoir sedimentation, channel/stream silting, and surface water quality degradation by agrochemicals and colloid facilitated transport (Cochrane and Flanagan 1999; Mullan 2013). Furthermore, soil erosion has serious consequences for a country's food, livelihood, and environmental securities. These damages can cause significant economic loss (Li and Fang 2016), and annual production loss of major rainfed crops in India suffers 13.4 million tonnes due to water erosion, which amounts to a loss of \$2.51 billion in monetary terms (Sharda et al. 2010).

Majority of the degraded area in India generally falls under the rainfed region which necessitates the adoption of smart soil and water conservation practices for reducing surface runoff and consequently soil erosion for sustaining and stabilizing productivity from these areas. The rainwater conservation and harvesting have been duly emphasized in the National Water Policy as well as the National Agricultural Policy of the Government of India. It has been shown that the adoption of soil and water conservation practices increased crop yield and biomass production and also resulted in drought and flood control, groundwater augmentation, and improvement of socioeconomic conditions of the farmers (Samra et al. 1995). Thus, water harvesting is as relevant for rural as well as urban areas. The conservation practices though initially devised for arid and semiarid regions have now become imperative for subhumid and humid regions also (Verma and Tiwari 1995).

24.2 Conservation Practices

Soil and water conservation practices are usually used to control the movement of water and wind over the soil surface. The aim of the soil and water conservation practice is to reduce runoff by creating a barrier across the water movement and prevent soil loss and land degradation below a thresh hold limit, which permits the natural rate of soil formation to keep pace with the rate of soil erosion while obtaining maximum sustained production level from a given piece of land. A range of conservation technologies have been developed, evaluated, and recommended for different hydro-climatic conditions and degraded land-use systems of India. A choice of appropriate conservation measure would depend on technical feasibility, economic viability, intended land use, community preferences, and long-term sustainability. The conservation practices include in situ and ex situ conservation practices. In situ conservation practices also referred to as water conservation measures include activities in two broad categories, namely, agronomic and engineering measures. The agronomic measures of water conservation include practices like contour cultivation, mulching, deep tillage, contour farming, and ridging, which is suitable for 1–2% slopes. The engineering measures include practices such as bunding (contour and graded bund), marginal bund, conservation ditches, conservation bench terrace system, bench terracing, trenching, and broad bed and furrow system. Agronomic measures are preferred as they involve the least disturbance of the land and are farmer-friendly. However, in situations where agronomic measures are insufficient due to topographic or climatic constraints, mechanical/engineering measures are used to improve soil moisture regime and conserve runoff water, consequently reducing soil loss and improving crop/vegetation yield. Mechanical measures are normally employed in conjunction with agronomical measures. The investment that maximizes conservation practices both the in situ and ex situ conservation practices helps to minimize land degradation and increase the water available for productive uses.

24.3 In Situ Conservation Practices for Natural Resource Conservation and Enhancing Crop Productivity

Tillage practice plays a very crucial role in improving the in situ rainfall receptivity of the fields. This method of conservation practice creates a rough cloddy surface with a miniature ridge and furrow system across the slope, which increases the surface roughness, porosity, infiltration opportunity time, and infiltration capacity, consequently reducing surface runoff and soil loss. Additionally, it helps in

Table 24.1 Effect of tillage methods on soil moisture at sowing and grain yield of chickpea

Tillage practice	Soil water depth (cm)		Grain yield (kg/ha)
	0–15 cm	0–45	
Plowing with Kulpha (blade harrow) during summer and dry spells in monsoon season	3.22	10.93	1088
Plowing with MB (30 cm depth) during summer followed by plowing with cultivator during dry spells (15 cm deep)	2.43	9.09	849

Adopted from Ali et al. (2009)

controlling weeds and pests. Pre-sowing preparatory tillage may commence following pre-monsoon showers. Summer deep plowing with moldboard (MB) or disc plow is usually carried out immediately after the harvest of rabi season crop during the month of early April or May to wipe out and mix the crop root and other organic matter into the soil, improve the soil moisture regime, and control weeds and pests. *Kulpha*, a 30–45-cm-long blade harrow, is traditionally used practice for intercultural operations for effective control of weeds and reduction in surface evaporation by breaking the surface capillary necessary during early crop growth stages. An off-farm evaluation of different tillage practices for black gram, maize, and intercropping of maize and black gram cropping system during *kharif* season showed that mechanized tillage practice conserved 16.2% higher moisture and about 50% less weeds than an indigenous tillage practice (Table 24.1). The yield of black gram, maize, and intercropping of maize and black gram under mechanized tillage increased by 15%, 26%, and 18%, respectively, over indigenous tillage practice, and the corresponding increase in net return was 9%, 34%, and 29%, respectively (Ali et al. 2004). Another study by Ali et al. (2009) for fallow-chickpea cropping during the rabi season indicated that indigenous tillage practice conserved 18.1% higher moisture and increased 22.0% yield of chickpea than the mechanical tillage practice. The water use of chickpea under indigenous tillage practice was 21.4% higher than the mechanical tillage practice. The total cost incurred for the cultivation of chickpea was 16.2% lower, and net return was 64.3% higher under the indigenous than the mechanized tillage practice. In a study on the effect of tillage practices and crop residue recycling on soil moisture, soil properties, and productivity of rainfed sorghum, three tillage depths, *viz*., 10, 15, and 20 cm, and three levels of residue recycling, *viz*., 0, 2.5, and 5 t/ha, were evaluated for rainfed sorghum (Fig. 24.1). The grain yield of sorghum marginally increased with the depth of tillage and the quantity of residue recycling. On average, the grain yield of sorghum increased by 5.9% and 13.1% with 15 and 20 cm deep tillage, respectively, compared to 10 cm deep tillage. Similarly, 2.5 and 5.0 t/ha residue recycling improved the yield by 12.4% and 20.6%, respectively, over control (Singh et al. 2013). This was attributed to a better moisture regime in the root zone of sorghum by deep tillage and residue recycling. Increased level of residue and reduced tillage depth also favored soil organic matter accumulation and pH moderation and improved available

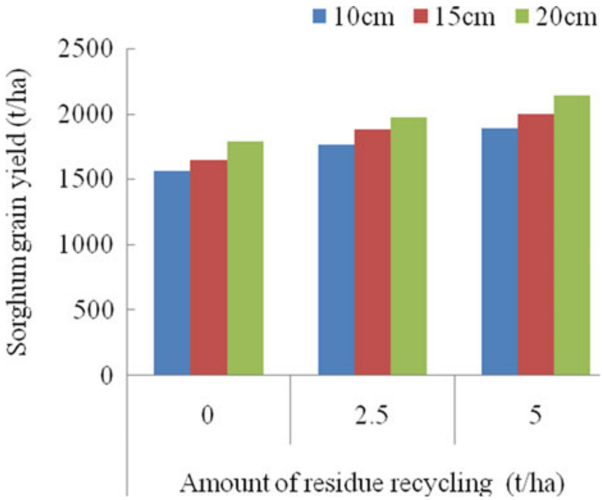

Fig. 24.1 Effect of crop residue recycling and tillage depth on sorghum grain yield. (Adopted and modified: Singh et al. 2013)

N and P status and water-stable aggregates especially when associated with deep tillage treatment.

Contour cultivation is the most basic in situ water conservation practice of plowing, planting, and cultivation on contour, which creates miniature bunds across the slope and promotes infiltration through surface storage of rainwater. The yield of crops like maize is increased by 20–25% with this practice (Sharda and Ojasvi 2005). On a 1% field slope, contour cultivation was found to reduce runoff by about 10% and improved the crop yield by 22–49% (Verma et al. 1990; Prasad et al. 1993).

Bunding is one of the cost-effective mechanical conservation practices in degraded cultivable lands having variable and multidirectional slopes to promote in situ rainwater conservation. The first step usually is to divide uneven and long slopes into smaller field units through bunding and minor inter-bunding leveling. Bunds are the earthen bank, 0.75–1 m wide down across the slope to act as a barrier to runoff, to form a water storage area on the upstream side of bund, and to break up the slope into the segment of shorter length that require to generate overland flow. Contour bunds are earthen embankments constructed along the contour lines at a given vertical interval to intercept the runoff flowing down the slope with a given vertical interval and recommended for mildly sloping lands (6%) and porous soils receiving annual rainfall of less than 600 mm. In the areas having rainfall higher than 600 mm provision or also heavy textured areas with low infiltration rate with rainfall less than 600 mm, safe disposal of excess runoff becomes necessary, and therefore the graded bund is recommended. Conservation efficiency and economic viability of bunding have been evaluated in the degraded Badakheda watershed, Bundi (Rajasthan), and it was found that land treatments with bunding and bunding + inter-bund leveling reduced runoff by 50% and promoted in situ water conservation (Singh et al. 2005). There was much higher soil moisture in the crop root zone (0–60 cm) at 1, 5, 10, and 15 m distance from bunds upstream after the withdrawal of monsoon. At 15 m distance from bunds, about 22–55% higher soil moisture was

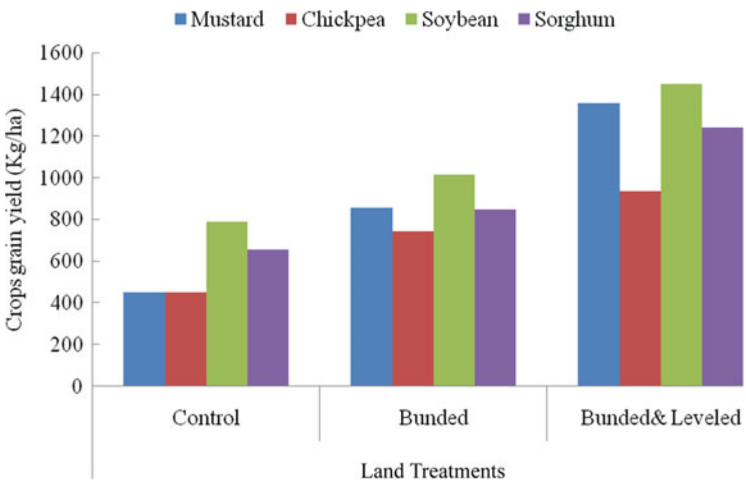

Fig. 24.2 Grain yield of various crops under bunding and minor inter-bunding leveling as well as control. (Adopted and modified: Singh et al. 2005)

found to be in the fields compared to unbunded fields. Bunding + inter-bund leveling treatments further improved in situ moisture conservation by 17% over bunding alone. Bunding alone and bunding + leveling increased mustard seed yield by 89% and 200%, respectively (Fig. 24.2). However, chickpea, soybean, and sorghum were relatively less efficient crops, and the corresponding increase in the seed yield for two land treatments was, respectively, 65% and 108% for chickpea, 29% and 84% for soybean, and 30% and 90% for sorghum. Considering the prevailing market price, mustard cultivation was most remunerative on the treated fields, which recovered 76% of the bunding cost and 64% of the bunding + leveling cost in the first year of land treatment. The other three crops of chickpea, soybean, and sorghum recovered 33–52% of the land treatment cost (Fig. 24.3). In red soil of Bundelkhand region, contour bunding reduced runoff and soil loss by 42% and 97% and considerable reduction in nutrient losses as nitrogen 92%, phosphorus 89%, potassium 81%, and soil organic carbon 89% (Narayan and Tiwari 2014), and runoff reduced by 64% in high-rainfall regions (Sharda and Ojasvi 2005). In black soils of Bijapur, the graded bunds were found more suitable compared to contour bunds in terms of higher safflower (*Carthamus tinctorius L.)* yield. A study at Sholapur revealed that maximum runoff as a percent of rainfall was recorded from flat sowing treatment (21.7%) followed by contour cultivation (17.1%), vegetative barrier (14.5%), and compartmental bunding (4.3%). The studies have shown that bunding in 29% of the sloping area under bun cultivation in red lateritic soils of the northeast region effectively reduced soil loss by 88% and runoff by 18% over non-bunded areas (Sharda 2004).

As an alternative to bunding, vegetative barriers comprising permanent strips of closely spaced grass on contours across the slope have been found to be effective on a gentle slope. Vegetative barriers perform better in conjunction with small

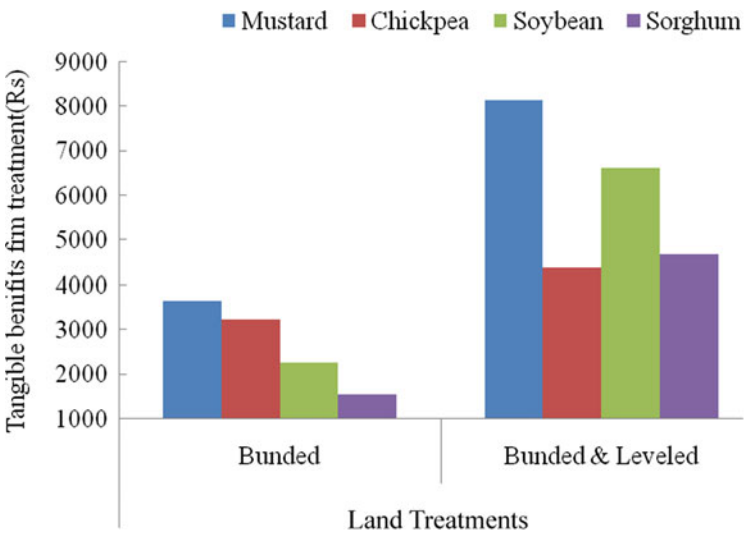

Fig. 24.3 Additional return under bunding and minor inter-bunding leveling (adopted and modified: Singh et al. 2005). Land treatment cost was Rs. 4750/ha for bunding and Rs. 12,800/ha for bunding with leveling

cross-section bunds to reduce runoff velocity; favor infiltration, runoff filtration, and soil deposition; and thereby induce the process of terrace formation. The grass strip is usually 0.6–1 m wide with two lines of grass clumps to provide a dense and sturdy against flowing water. Vegetative barriers are relatively farmer-friendly. The recommended locally available grasses are *Cenchrus ciliaris* and *Dicanthium annulatum* for heavy and non-palatable species such as *Vetiveria ziyanioides and Saccharum munja* for degraded sloppy lands in eastern Rajasthan; *khus* in the semiarid region of central India; khus and bhabhar in Shiwaliks; Pancicum (guinea grass), Napier, and buta in lower Himalayas; khus, guinea, and marvel in the black region; Dhaman, Anjan, and Sewan in arid regions; and pier and Guatemala grasses in southern hill regions. A study at Kota revealed that the four grass species, viz., *Cenchrus ciliaris*, *Dicanthium annulatum*, *Vetiveria ziyanioides*, *and Saccharum munja*, were found equally effective and reduced runoff by 15.5–16.3% and 13.4–13.9% of monsoon rainfall over without barrier for sorghum and soybean crops, respectively. And the corresponding reduction in soil loss was 39.9–54.3% and 46.7–52.2%, respectively (Prasad et al. 2005). Improvement in soil moisture with the barrier in sorghum and soybean crops at sowing, during a dry spell, and during harvesting time ranged from 8.4% to 12.9%, 0.6% to 6.4%, and 1.9% to 5.7%; 7.2% to 25.1%, 8.7% to 21.0%, and 5.5% to 9.9%, respectively. There was an increase in yield by 18.9–20.8% and 19.9–24.4% for sorghum and soybean, respectively, compared to plots without grass barriers (Table 24.2). Additionally, there was a substantial improvement in the fertility status of the soil in the upstream vicinity of vegetative barriers. The vegetative barriers reduced runoff by 18–31% on slopes from 2–8% and higher yields of maize and wheat on conserved moisture by about

Table 24.2 Effect of grass barriers on runoff, soil loss, and crop productivity

Crops	Vegetative barrier	Natural resource conservation		Crop yield(kg/ha)		
		Runoff (% of rainfall)	Soil loss (kg/ha/yr)	Grain	Straw	Air dry forage
Sorghum	No grass barrier	22.0	1898	1140	4106	–
	Cenchrus ciliaris	15.8	1016	1359	4464	495
	Dicanthium annulatum	15.5	1055	1364	4504	442
	Vetiveria ziyanioides	16.2	1148	1377	4468	–
	Saccharum munja	16.3	868	1355	4442	–
Soybean	No grass barrier	20.2	1447	562	1815	–
	Cenchrus ciliaris	13.9	771	697	2041	525
	Dicanthium annulatum	13.7	692	697	2031	498
	Vetiveria ziyanioides	13.6	726	699	2008	–
	Saccharum munja	13.4	704	674	2091	–

Adopted from Prasad et al. (2005)

32% and 10%, respectively. A study at Sholapur revealed the maximum runoff from flat sowing treatment (21.7%) followed by contour cultivation (17.1%), vegetative barrier (14.5%), and compartmental bunding (4.3% of rainfall) (Sharda and Ojasvi 2005).

Contour furrows are earthen channel constructed in interspaces of contour/graded bunds, which often fail on swelling shrinking black soils. This practice is found to be a suitable conservation practice for facilitating in situ rainwater conservation during low-intensity rainfall by creating additional surface storage capacity and facilitate drainage during high-intensity rainfall as well as consecutive heavy rains. It also improved profile moisture and mollified the impact of dry spells. Contour furrows with 0.125 m^2 cross-section (depth 20–25 cm) and spaced at 6 m HI on 1% slope reduced runoff by 20% and 36% in sorghum + pigeon pea intercropping and soybean over control and corresponding soil loss by 23% and 29%, respectively. The contour bund was suited to sorghum + pigeon pea intercropping as well as soybean (Singh et al. 2011). Improvement in average yield of sorghum grain equivalent was 29% and 23% sorghum + pigeon pea intercropping and soybean (Table 24.3). In another study at farmer fields at Kota, Baran, and Bundi, furrows create an additional surface storage capacity of 11.25 mm/ha and reduce runoff by about 22% and soil loss by 1.4 t/ha/year. The net returns under contour furrow treatment are 129% higher than the farmers' practice.

Raised and sunken bed conservation practice has been found suitable particularly in black soils of high-rainfall areas where bunding requires frequent maintenance to

Table 24.3 Conservation and production efficiency of different land treatments

Land treatment	Cropping system	Runoff (%)[a]	Soil loss (t/ha)	SGE[b] (kg/ha)	B:C
Control	Sorghum +P. pea intercropping (1:1)	30.04	26.49	2152	1.31
Contour Furrow	Sorghum +P. pea intercropping (1:1)	24.1	20.39	2779	1.58
	Soybean	19.31	18.68	2644	1.62
Conservation bench terrace (2:1)	Sorghum +P. pea intercropping (1:1) on slope and chick pea on leveled terrace	17.48	15.01	2592	1.47
	Soybean on slope and mustard on the leveled terrace	13.21	12.58	1562	1.09
Raised & Sunken bed	Sorghum +P. pea intercropping (1:1) on a raised bed and chickpea on sunken beds	4.42	1.47	3185	1.62
	Soybean on raised bed and mustard on sunken beds	3.27	1.09	1440	0.63

Adopted from Singh et al. (2011)
[a]Average rainfall during the project period was 589 mm
[b]Sorghum grain equivalent

swelling and shrinkage phenomenon. The practice consists of an alternate strip of raised and sunken beds with a bed width of 6 m and an elevation difference of 15 cm. This system facilitates crop diversification by providing the opportunity to cultivate both *rabi* and *kharif* season crops. The excess rainwater drains off quickly to sunken beds, and suitable tilth is available much earlier after rainfall event for tillage operation in the heavy soils of the region. The raised beds are cultivated during *kharif* season, while *rabi* crops are raised on conserved moisture in sunken beds. Harvested runoff is sunken beds that also benefit crops on the raised bed during dry spells. The possibility of at least a good harvest either in *Kharif* or *rabi* is improved under erratic monsoon conditions. The conservation practice has been evaluated for semiarid south-eastern Rajasthan and found very well suited to prominent rainfed cropping systems of this region, which creates an additional 75 mm surface storage capacity and retains almost the entire rainfall for the benefit of crops and also favors groundwater recharge. The sorghum + pigeon pea on raised bed and chickpea on the sunken beds have improved crop yields by about 32% (Table 24.3). On the broad beds can be cultivated any crop grown in the region, such as cotton (*Gossypium* L.) sorghum, and millet. In black soils, a broad bed system reduced runoff by 48% compared with the traditional flat system. In the high-rainfall black soil region of Indore, treatments comprising flatbed, raised bed, sunken bed, narrow bed and furrow, and broad bed and furrow were studied for their efficiency in reducing runoff. It was inferred that runoff was maximum under a “narrow bed and furrow” system (13.3% of rainfall) followed by flatbed (10.1%), broad-bed furrow (9.5%), and raised-bed (5.3%) (Sharda and Ojasvi 2005). Kaushik and Lal (1998) compared five different water harvesting techniques (flatbed, bed, and furrow on grade, field bunding, and interrow water harvesting) on rainy season crops in a semiarid region.

The higher grain yield, monetary returns, soil moisture use, and moisture use efficiency were obtained by the bed and furrow method in low-rainfall years.

On mild slopes where the bulk of rainfall is lost through surface runoff, the conservation bench terracing (CBT) is an appropriate conservation measure. The practice consists of the leveled field at the lower part of the field to impound surface runoff water called recipient area and donor area, which is left in its natural land slope and produces runoff, which spreads on the level field. The ratio of contributing to collect area depends on the rainfall of the region and varied from 2:1 to 3:1 in the semiarid regions at Bellary and Kota and the subhumid region at Dehradun. In arid and semiarid regions, the slopes of contributing areas are cultivated for *Kharif* crops, while leveled bench at the lower part of the field is cultivated for *rabi* crops. In high-rainfall regions, crops requiring drainage such as maize, sorghum, or pearl millet are retivated on the sloping portion, and paddy is taken on the level portion. CBT is suitable for 2–6% slopes, rainfall zones of 700–1500 mm, and heavy to deep soils. For south-eastern Rajasthan 2:1 ratio of contribution, collecting area is found suitable, and the system created an additional surface storage capacity of 50 mm, which helps in reducing the runoff by about 47%. With sorghum + pigeon pea on slopes and chickpea on benches, CBT has improved crop productivity by about 15% (Table 24.3). In Dehradun, CBT system at 2% slope with 3:1 ratio of donor to recipient area reduced runoff and soil loss by over 80% and 90%, respectively, as compared to the conventional practice of maize-wheat cropping system and was found to be 19% more remunerative in terms of maize equivalent yields over the conventional cultivation system (Sharda et al. 2002). Bench terraces are flatbeds constructed across the slopes along the contours by the process of half-cutting and half-filling to control the velocity of overland flow and check soil erosion, optimize rainwater utilization through increased infiltration, and improve irrigation efficiency. Terracing breaks the slope length and reduces the degree of slope steepness of the lands, thereby eliminating the erosion hazards. On steep sloping and undulating lands, intensive farming can only be adopted after constructing bench terraces, which are one of the most popular soil conservation structural measures adopted by the farmers of hilly regions all over the world. Bench terraces are recommended for slopes up to 33%, but due to socioeconomic compulsions, this practice is being adopted up to 50–60% of land slopes. In the Nilgiris area of Tamil Nady, the runoff was reduced by 50% and soil loss by 98% as compared to up- and down-the-slope cultivation, and increase in potato ranged between 20% and 30%. The gross increase in the yield of potatoes due to bench terracing was found to be 27%. Under Doon Valley conditions in land slope ranging from 2% to 8%, runoff reduced by 85–92% and soil loss by 90–92% by bench terracing. In the north-eastern hilly region, the one-third bench terracing concept had 85% reduction in runoff and 4% in soil loss as compared to shifting cultivation. The yield of paddy and wheat in leveled terraces with just one or two irrigations in farmers' fields increased by two to three times, respectively (Sharda and Juyal 2006).

As an alternative to bunds in deep black soils where bunds do not work successfully, conservation ditching has been recommended. Ditching with 0.6 m base width and 5 m top width has been found effective. Conservation ditching serves the dual

Table 24.4 Reduction in hydrologic variable and yield of *Phyllanthus emblica* fruit, *Cenchrus ciliaris*, and *Dendrocalamus strictus* in ravine land of Chambal River under different trenching densities

Hydrologic variable and yields of the hort-pastoral system	Staggered contour trenching (SCT) densities (trenches/ha)			
	No trench	137	247	417
Reduction in runoff (%)	–	37.7	60.5	86.1
Reduction in soil loss (%)	–	40.0	77.1	124.9
Effective rainfall use efficiency (%)	–	7.5	17.1	47.5
Phylanthus emblica fruit yield (t/ha)	2.5	2.8	3.8	5.7
Cenchrus ciliaris grass (t/ha)	6.7	7.3	8.1	8.6
Dendrocal amusstrictus (culm/ha)	124.0	145.5	168.0	231.5
Phyllanthus emblica equivalent yield (t/ha)				
B:C ratio (−)	1.59	2.22	2.53	3.05

purpose of a terrace and storage structure within the field and retains more than 90% of annual runoff, which can be utilized for supplementary arrogation (Patnaik et al. 1997).

Contour trenching is mainly recommended for rehabilitating degraded lands. This conservation practice involves excavating trenches across the land slope in a continuous or staggered manner. Trenches are usually 30–50 cm in width and 30–50 cm in depth. In case of the continuous trenching, the length is restricted to 10–20 m, and for staggered trenching, the length is generally kept as 2–4 m. The spacing between trench rows may vary from 4 to 6 m depending upon the type of tree/shrub to be planted. In low-rainfall areas, continuous trenches are recommended, whereas in high-rainfall areas, staggered trenches are adopted. A study on quantification of the effects of staggered contour trenching (SCT) densities (i.e., 137, 247, and 417 trenches/ha) on natural resource conservation and yield of the horti-pastoral system in degraded ravine lands of Chambal River using paired watershed approach revealed that at optimally SCT densities (i.e., 417 trenches/ha) with the size of $0.45 \times 0.45 \times 3.0$ m, runoff and soil loss were decreased by 86.1% and 124.9% over without trenching, and the highest effective rainfall use efficiency recorded with SCT densities of 417 trenches/ha was 47.5%. The yields of *Phyllanthus emblica* fruit, *Cenchrus ciliaris* grass, and *Dendrocalamus strictus* were found to be the highest in the 417 trenches/ha over no trench by 126.3%, 28.9%, and 86.9%, respectively, with a B:C ratio of 1:3.05 (Table 24.4). The posttreatment values of soil organic carbon were increased by 0.8–2.2 folds than the pretreatment in all trenching densities. Available NPK content of the posttreatment was also significantly increased by trenching densities (Ali et al. 2017). A reduction in runoff and soil loss by the staggered contour trench ($5 \times 1 \times 0.5$ m) filled with coconut husk was recorded 44.7% and 50.2%, respectively, in cashew plantations on degraded steep slopes in India (Rejani and Yadukumar 2010). Bandhe and Magar (2004) reported that staggered contour trench with a density of 230 trenches/ha and

$4.5 \times 0.60 \times 0.30$ m size reduced runoff and soil loss by 87.6% and 65.1%, respectively, under hilly terrain in lateritic soil of the Konkan region of India.

Micro-catchment conservation practice consists of a distinct catchment area and cultivated area that is adjacent to each other. The distinct advantages of micro-catchments are the high specific runoff yield (runoff per unit area) compared to large catchments, simplicity, inexpensiveness, and easy reproducibility. Various forms of micro-catchments have been used successfully in arid and semiarid regions. A study in Negev desert indicated that micro-catchments yielded 95,000 L of water/ha/year compared to collection efforts from a single large unit at the outlet of a 345 ha watershed which yielded only 24,000 L of water/ha/year (Pandey 2001). Another study by Ojasvi et al. (1999) indicated an increase of 108.5% runoff efficiency of shallow conical micro-catchment lined with various forms of waste material for trees in loose sandy soils. Better growth parameters and increased biomass production of three tree species in the arid region were also reported using the ridge and furrow method (Gupta 1995).

Peripheral bunds are earthen structures constructed along the periphery of the tableland to provide protection from the ingress by surrounding gully systems, and it is also termed as marginal bunds. The peripheral bunds need to be placed at a distance of two to three times of gully depth from the gully head. The runoff water from cultivated fields is allowed along with the upstream of the peripheral bund with a nonerosive velocity before it is conveyed safely into the ravine system through a spillway designed to handle expected peak flow. In low-rainfall areas having light-textured soil where total runoff harvesting is targeted through inwardly sloping terrace and leveled fields, the need for peripheral bunds is eliminated or reduced, as the water gets automatically diverted away from the gully head. A field study in degraded lands of Yamuna ravines of Agra showed a consistent improvement in yields of pearl millet, green gram, and sesame with peripheral bunding in conjunction with minor land leveling by 90%, 164%, and 179%, respectively, over the untreated area with the respective yield of 11.78, 2.24, and 2.58 q/ha. Similarly, an increase in yield of wheat, mustard, and pigeon pea during the rabi season was found to be 281%, 122%, and 188%, respectively, over untreated with the respective yield of 7.14, 7.02, and 2.72 q/ha (Singh et al. 2016).

A gully head often develops where flowing water plunges from the upstream segment to the bottom of the gully. Preventing the gully-head extension through appropriate head stabilization measures as spillways is much easier and less expensive than reclaiming degraded ravine lands. Three types of spillways are generally recommended based on the expected peak runoff volumes and overfall of the gully head, which is the elevation difference between the land above the gully head and gully bed (Table 24.5). Drop spillway is the weir structure generally preferred to control the gully head which is not higher than 3 m, and the drainage area is relatively large. The low straight drop is also advisable for small gully head cuts (1–2 m). This structure can be used only where there is sufficient area of nearly level land on either side to carry the overflows without damage to the land or the crop. Along with the runoff, the spillway catches the sediment from the contributing drainage area which gets deposited on the upstream side of the spillway. This

Table 24.5 Types and suitability of spillways as gully head control structure

Type of spillway	Site suitability		Advantages	Disadvantages
	Overfall (m)	Peak runoff (m^3/s)		
Drop spillway	<3	<2.5	Relatively stable and safe, easy to construct and maintain	Require stable grade on either side, unsuitable for detention storage, the high initial cost
Chute spillway	3–6	<2.5	Relatively low cost	Susceptible to failure due to seepage or rodents activity
Pipe spillway	<3	Any	Suited for upstream detention storage, road culverts, economical, stable and safe	Sensitive to clogging by debris, require careful field execution to avoid channeling along the pipe

helps in leveling the land gradually, and consequently helps in situ moisture conservation. A study conducted at Badakheda watershed, Bundi, revealed that silt retention capacity of the six drop masonry spillways with 2–3 m length and fall 1.5–2.5 m ranged from 42 to 60 t/ha/year with 15–20% higher soil moisture regime at upstream side up to 50 m distance over without spillway. An increase in yield of the soybean, mustard, and chickpea area above the spillways ranged from 45% to 60%, 95% to 212%, and 70% to 120%, respectively.

24.4 Ex Situ Conservation Practices for Natural Resource Conservation

Check dams are constructed in series in between the gully reach to retain runoff and silt load and stabilize the gully bed and banks. Silt retention type check dams are usually recommended in degraded ravine lands and water storage check dams where silt load is minimum. Efficacy of 12 masonry silt retention check dams covers 307 ha watershed area was evaluated in the Badakheda watershed of Chambal ravine system of Bundi district of Rajasthan and found that about 13,533 tonnes of eroded soil retained on the upstream sides of check dams along with 974, 34, and 5908 kg N, P, and K, respectively, having catchment of 307 ha. Therefore, as the cumulative effect, silt retained behind the gully control structure was equivalent to arresting 44.1 t/ha of the eroded soil. It was also observed that check dams constructed in upper reaches retained a greater volume of sediment (1335) than the middle (864) and lower (793 t/structure) reaches of the degraded land. These structures also reclaimed 9.12 ha of severely gullied land and 24.6 ha of moderately degraded land (Table 24.6). The silt retention capacity of gabion and earthen check dames was recorded at 6583 and 4500 tonnes. In another study at Dhoti watershed for water storage check dam, about 55–63% of the runoff harvested in the water storage check dams had been recharge artificially. The runoff over the check dam was recorded highest which ranged between 35% and 40% and evaporation from 10% to 12% of the stored water.

Table 24.6 Silt and nutrient retention in Bhadakheda watershed

		Silt retention (tonnes)	Nutrient retention (kg)		
Gully reaches	Check dams	N	P	K	
Upper	WUP1	1500.2	112.7	4.2	274.9
	WUP2	1243.2	92.3	3.1	251.7
	WUP3	1981.2	148	4.8	3698
	WUP4	673.3	50.6	1.9	123.3
	WUP5	611.9	38.2	1.6	115.3
	WUP6	2668.9	197.8	6.6	514.4
	WUP7	668.4	45.9	1.9	140.8
Middle	WMR1	583.7	43.9	1.4	112.4
	WMR2	1200.5	85.5	2.7	211.6
	WMR3	807.5	55.3	1.7	155.6
Lower	WLR1	739.5	49	1.8	147.9
	WLR2	855.1	54.1	1.9	161.1
Total		13,533	973	34	5907

Another study in degraded land of Badakheda watershed showed a reduction of 47.5% and 78.4% surface runoff by applying mechanical measures alone (<1 m loose boulder/masonry check dam/spillways) and mechanical measures with vegetative (live hedge check dams) measures, respectively, compared to untreated area, and respective reduction in soil loss was of 55.3% and 68.2%. It was also observed that structure located in the upper reach retained greater soil volumes compared to lower reach structure. Impact evaluation of Chhajawa watershed in Baran (Rajasthan) showed that a large amount of silt retained behind the masonry gully control structure, and siltation rates reduced from 15.14 (1986) to 4.12 (1988–1990) in the watershed by the implementation of various soil conservation measures (Prasad et al. 1996). The runoff from this project site was compared with an untreated area having similar topography and catchment area. Three years of average runoff from untreated watershed was 77% against 24.7% from the treated watershed (Prasad et al. 1996).

A recharge pond is one of the artificial groundwater recharging practices to aquifer underneath the recharge pond. A field study on the response of two recharge ponds constructed in Badakhera watershed located in the Bundi district of south-eastern Rajasthan showed that on average, 82.98–90.20% of the accumulated surface runoff in the small recharge ponds contributed to artificial recharge into aquifer underneath ponds (Fig. 24.4). Evaporation losses from ponds varied from 7.72% to 9.18% of the stored runoffs. Surplus flows from the ponds and stored runoffs in the ponds at the end of simulation periods ranged, respectively, from 0% to 8.34% and 0.61% to 0.79% (Ali et al. 2012). In another study at Dhoti watersheds, potential groundwater recharge through three recharge ponds ranged from 93% to 88% with a mean of 83% of accumulated runoffs in the ponds. It was also recorded that the pond's improved depth to groundwater table ranged between 12 and 18 m with a mean of 15 m in the installed observation wells at 15 m away from a pond's

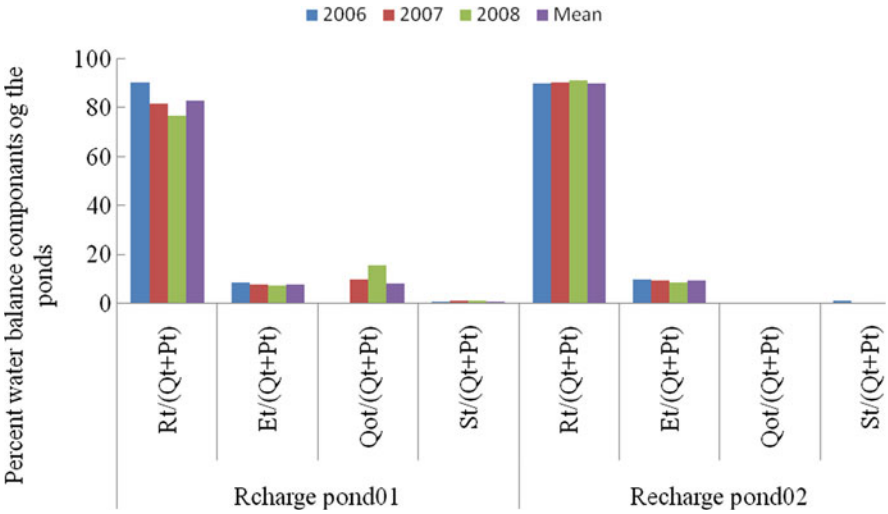

Fig. 24.4 Partition factors of the water balance components (percent) for the ponds during the simulation period (2006–2008). (Adopted and redrawn; Ali et al. 2012)

embankment. A study by Verma et al. (1986) conducted at Kota observed higher seepage/recharge from a farm pond ranged from 42 to 45 cm/day but 25.8 L/m^2/day to 158 L/m^2/day in the ponds in Shiwalik hills (Sharda and Ojasvi 2005).

The $R_t/(Q_t + P_t)$ is the ratio of the total volume of water recharged into the aquifer, R_t, to the total volume of inflows, which is the sum of the volume of runoff into the pond and the volume of rainfall directly over the pond ($Q_t + P_t$); $E_t/(Q_t + P_t)$ is the ratio of the total volume of water loss by evaporation, E_t, to the total volume of inflows; $Q_{ot}/(Q_t + P_t)$ is the ratio of the total volume of outflows from the pond, Q_{ot}, to the total volume of inflows; and $S_t/(Q_t + P_t)$ is the ratio of the total volume of water remained as storage in the pond at the end of the simulation period, S_t, to the total volume of inflows.

The farm pond is an important source of life-saving irrigation water particularly in the arid and semiarid regions. Water requirements for supplementary irrigation are usually greater than for any other purpose of ponds as water for livestock, artificial groundwater recharging, fish production, recreation, wildlife habitats, flood protection, silt retention, and landscape improvement. The irrigated area from the farm pond is limited by the availability of water during the crop-growing season. In southeastern Rajasthan, harvested water is usually available till February depending on the location and soil type of the farm pond. The construction of the farm pond is recommended at the location with clay soil. The capacity of the irrigation pond must be adequate to meet crop water requirements and unavoidable water losses by evaporation and seepage. The capacity of the farm pond mainly depends on the runoff producing potential of the pond's catchment, loss by evaporation and seepage, and water requirement for supplemental irrigation. Studies at Kota recorded the runoff producing potential of Kota soils at 1–2% slope to vary from 6.1% to 21.1%

of rainfall under different land cover conditions (Bhola et al. 1975) and 17% to 47% of rainfall from ravine lands (Mishra and Handa 1977) which can be economically harvested into farm ponds. In the Shiwalik region, runoff ranged from 17% to 48% of monsoon rainfall depending upon size and land over conditions of the watersheds. Studies in the Nilgiris region from 17 watersheds (75.1–33.5 ha) have indicated that runoff varies from 14% to 67.8% of the annual rainfall. However, the runoff from different land uses and topographic conditions in Nilgiris may range from <1% to 43% of the rainfall (Chinnamani 1982). Studies in the outer Himalayan region reported that about 15–20% of runoff is expected under steep and rolling topography (Sastry and Singh 1993). Sharda (2004) reported subsurface runoff is the chief contributor to total flow (89.9–95.8%) and surface runoff accounts for ranged from 4.2% to 10% of rainfall particularly during heavy intensity storms in the monsoon season in middle Himalayan micro-watersheds comprising the forest, mixed, and scrub land-use systems. Studies at Bangalore indicated 20–25% runoff from cultivated land and 7–12% from a Eucalyptus forest watershed. Runoff in the Bundelkhand region ranges from 10% to 70% of rainfall depending upon soils, geography, and land-use conditions, and runoff from cultivated fallow was 35% of the monsoon rainfall (Tiwari and Sharma 1995). Runoff from protected forest and grassland watersheds was 16–17% of rainfall, whereas the protected forest + grass watershed yielded only 3% of runoff. It was estimated that for 0.2 ha m pond, capacity requires 5 ha of the catchment with flatlands and 0.3–0.4 ha m capacity for every 5 ha of the catchment with sloping lands.

24.5 Recycling of Harvested Runoff

The success of any ex situ water conservation practice depends upon the amount of harvested water, its temporal availability, and the way it is used or recycled for economic use at the micro, field, and/or watershed level, which can bring sustainability to the water resources sector and, consequently, increase water availability for multiple services. The main use of harvested runoff is crop production at a small scale benefiting few persons or a limited farm area. In a study conducted at Kota, runoff water harvested from 8 ha agricultural watershed collected in lined dugout pond was utilized for supplemental irrigation at critical growth stages of *rabi* crops (i.e., wheat, gram, and coriander) taken after a uniform *kharif* crop of black gram. The yield of the chickpea, coriander, and wheat was increased by 74%, 78%, and 126% with pre-sowing irrigation only over control (Fig. 24.5). The grain yield of all the crops showed a progressive increase with the number of irrigations; however, wheat (303%) and coriander (299%) recorded a higher improvement in yield than chickpea (181%) with three irrigations. The water use efficiency of wheat was higher than the chickpea and coriander (Fig. 24.6) (Verma et al. 1986). Increase in mean yield of wheat, barley, and gram with one supplemental irrigation was 85%, 32%, and 36%, respectively, and benefit (B):cost(C) ratios of various water harvesting structures have been reported as 1.48–2.71:1 in the north-western Himalayan region (Samra et al. 2002; Sharda et al. 2017). In the Shiwalik region, where a unique

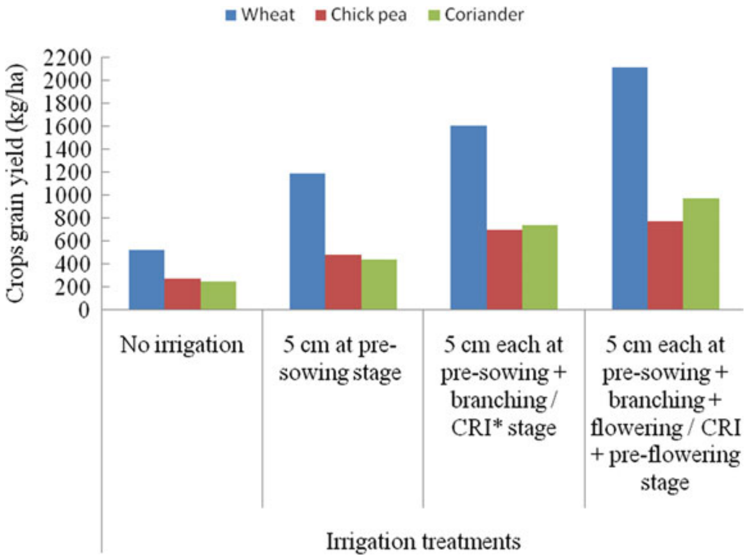

Fig. 24.5 Yield of various crops under different irrigations by harvested runoff water (Adopted and modified; Verma et al. 1986); *CRI: crown root initiation stage

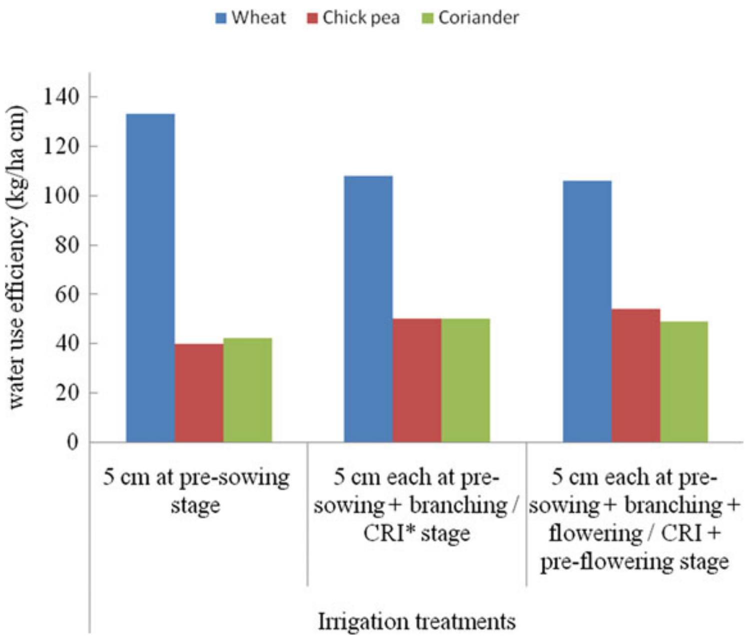

Fig. 24.6 Runoff water use efficiency of various crops under different irrigations (Adopted and modified; Verma et al. 1986); *CRI: crown root initiation stage

system of conveying harvested water through the underground pipeline system is in practice, the B:C ratio of the overall project may range from 1.07 to 2.05:1 (Agnihotri et al. 1989). With this system, supplemental irrigation can be provided to farm areas ranging from 20 to 243 ha depending upon the storage capacity of the earthen dam. At Datia (Bundelkhand region), the mustard crop responds well to one to two irrigations, and the yield of gram can be increased to 60% with one irrigation only (Sharma and Tiwari 1995). In arid areas, the yield of pearl millet increased by 100% by providing one supplemental irrigation of 7.5 cm (Singh 1994). The B:C ratio of farm ponds with crops like hybrid maize, tomato, and mulberry has been reported as 2:1 to 2.4:1 (Havanagi 1980).

24.6 Conclusions

Mankind is utilizing land-ecosystem services at a significantly higher rate than the earth can provide, thus putting enormous pressure on natural resources. The land ecosystem includes soil, water, and biological resources, which are the principal natural resources providing ecosystem services for the nourishment of life. Land degradation of the arable and nonarable land surface of a country suffers from various forms of degradation and has serious consequences for a country's food, livelihood, and environmental securities. Effective rainwater conservation and management practices have the potential to restore the further degradation land ecosystem apart from many environmental benefits such as reduced runoff and soil erosion, improvement in yield of rainfed crops, and overall improvement of the natural resources. The conservation practices include in situ water conservation, micro-catchments, and ex situ water harvesting and storage systems. Summer deep plowing followed by shallow contour tillage during dry spells with contour furrows promotes in situ rainwater conservation and favors better *rabi* harvest. Contour or graded bunding on prevalent gentle to moderate slopes and contour cultivation and contour furrowing in the inter-bunded area are effective and adequate conservation measures to support *kharif* crops. Sunken and raised beds for low-lying flatlands and conservation bench terracing for 1–4% slopes are suitable alternative measures to facilitate crop diversification. Retaining runoff in downstream locations through the construction of rainwater harvesting structures improves surface and groundwater availability for one and/or two irrigations for *rabi* crops, thereby helping to bring stability to the rainfed production system. Conservation technologies are highly location-specific, and practices evolved in a given agroecological region have limited applicability in other regions. Suitable farming systems by integrating horticulture, floriculture, cash crops, and agroforestry systems should also be evolved for increasing rainwater water conservation and productivity in different agroecological regions. Greater emphasis on groundwater recharge is needed through conservation practices and watershed development programs.

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Machinery for Conservation Agriculture: Indian Perspective

25

R. C. Singh

Abstract

In mechanized agriculture, no-tillage (NT) cultivation of crops have been practiced long time ago, but it was not until the advent of modern herbicides that the technique could be put into practice for larger adoption and acceptance. The most significant change from tillage-based farming to conservation agriculture (CA) is in the land preparation and seeding practices. The use of tillage as a standard periodic operation is completely eliminated in a fully functioning CA system and remains only for very specific tasks, such as creating the conditions such as minimum soil disturbances of soil for seeding purpose and maintaining sufficient crop residue cover on the soil surface. Breaking compacted soil may also become necessary within CA system under mechanized agriculture. NT farming offers a way of optimizing productivity and ecosystem services, offering a wide range of economic, environmental, and social benefits to the producer and to the society. At the same time, NT farming has promising option to respond and address some of the global challenges associated with climate change, land and environmental degradation, and increasing cost of food, energy, and production inputs. The wider recognition of NT farming as a truly sustainable system should ensure the spread of the NT technology and the associated practices of organic soil cover and crop rotation, as soon as the barriers to its adoption have been overcome, to areas where adoption currently remains low. NT farming has established itself as a farming practice and a different way of thinking about sustainable agro-ecosystem management that can no longer be ignored by scientists, academics, extension workers, farmers at large as well as equipment and machine manufacturers and politicians. The chapter summarizes the

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equipment available for seeding and planting to place the seed with accuracy into an untilled soil covered with a heavy mulch of crop residues. Equipment for weed and crop residue management directly influences the quality of the subsequent planting operation. It also includes the implements for breaking soil compaction with minimum soil disturbance under mechanized CA farming system, particularly in humid climates.

Keywords

Mechanized agriculture · No-till farming · Zero-tillage adoption · Conservation agriculture · Climate change · Equipment · Implements · Soil compaction

25.1 Introduction

Agricultural sector faces major challenge during the twenty-first century to meet the food requirement for the growing population with limited per capita land availability without environmental degradation. In order to meet these growing demands, improved agronomical practices such as intensive tillage, optimized use of fertilizers, improved crop protection practices, and crop residue management are being adopted. These practices are highly productive but are energy intensive and have contributed to a tenfold increase in the global energy budget since the start of the twentieth century and increase in anthropogenic emissions of greenhouse gas emission (GHG). The increase in energy inputs and GHG emissions in agriculture is mostly due to higher fossil fuel combustion during various farm operations. The growing concern on climate change has focused to reduce GHG emissions in agriculture. Saving in various inputs and increase in energy use efficiency in crop production is mostly needed as energy inputs (direct/indirect) and CO_2 emissions are directly related to each other. Further, increase in energy use efficiency and conservation of natural resources also offer opportunities for mitigation of climate change. Climate change mitigation involves efforts to reduce the emission of GHG with the use of new and energy-efficient technologies, usage of renewable energies, and adoption of good management practices. The shift in the use of efficient technology, combined with the growth of renewable energy sources, shows low-carbon footprint with less emissions. In the current context of energy conservation and growing environmental concerns, conservation agriculture (CA) practices with reduced or zero tillage with residue retention are essential for sustaining soil health and crop production. It would be able to reduce environmental pollution by reducing fossil fuel consumption which in turn reduces energy input and CO_2 emission with reduction in cost of cultivation. In recent years, minimum soil disturbance, residue retention, and crop rotation have emerged as important management strategies to mitigate the GHG emission while maintaining crop productivity (Friedrich et al. 2014).

Conservation agriculture (CA) in the context of sustainable agricultural mechanization is more than just a mechanical technique, such as no-till and direct seeding. It represents a fundamental change in the soil system management and in the cropping system design and management which in turn lead to consequential changes in the required field operations and the related mechanization solutions. When a tillage-based production system is to be transformed into a CA-based system, it involves a shift in the prevailing on-farm mix of mechanical technologies, some of which will remain but with only marginal use in the future, and there will be the development of completely new set of mechanical technologies, changes in farm power requirements, and in land use suitability for sustainable intensification as elaborated in the following sections.

25.2 Manual and Animal-Traction Seeders

Manual and animal-traction seeders are usually small, light-weighted, simple in design and easily manufactured, utilized, and maintained. These seeders are invariably used on small farms and hilly areas. The use of manual equipment is the basic level of mechanization, and improved equipment designs are intended to enhance productivity in respect to energy efficiency and ergonomics. A demand-driven development and an innovation system are necessary for the adoption of improved human- and animal-dragged equipment. Some typical seeders in Asia are given as follows:

25.3 Manual Direct Seeder

Li seeder: Li seeder is a typical manual seeder for no-till seeding of maize and soybean. It can be used on small farms under a wide range of conditions, including wet soils. The operating handle contains the seed, and a shoulder bag carries the fertilizer. Through a chopping action, the seeder can plant one or more seeds simultaneously, while fertilizer can be applied separately, and the amount is adjustable. The total weight of Li seeder is 2.2 kg, and the working efficiency is 0.2–0.3 ha/day/person.

Jab planter: Jab planter is the most common manual planting tool for row crops in no-till areas. It is a handheld tool which enables farmers to plant from a standing position. This machine is able to seed into mulch-covered no-tilled soil effectively. There are two containers in which fertilizer and seed are stored, which are mounted on a wooden frame with two planting tips. To allow fertilizer and seed to drop into the planting hole, the tips are punched firmly into the soil and opened by a manipulator. Seeding rates can be adjusted accordingly. There is a provision to plant one, two, or three seeds per hole (Johansena et al. 2012). The Li and Jab planter are shown in Fig. 25.1.

Fig. 25.1 Li seeder and Jab planter

Fig. 25.2 Animal-drawn seeder developed in China, South Africa, India, and Tanzania

25.4 Animal-Drawn Planters

The planters are multi-crop planter that generally consists of a coulter to cut plant residue and ripper tine to open a small rip-line. Seed and fertilizer are held in two separate hoppers and delivered into the slot by individual drop tubes. A simple lightweight long-beam couples is to draft animals. Mounted behind the tine is a seed and metering device drive wheel which may act as a seed-covering device and press wheel. The operator walks behind the seed drill and controls operation through handlebars. The plant population ranges from 36,000 plants/ha to 53,000 plants/ha for maize. It can seed ~2 ha/day. It is suitable for seed and fertilizer, with the working width of 600 mm and working depth of 30–50 mm. Different animal-drawn no-till seeders/planter are shown in Fig. 25.2. These are commonly used by the small farmers of African countries, Nepal, Bangladesh, India, and China.

25.5 Passive Anti-blocking No-Till Seeders

ACIAR-ROGRO seed drill (ARC Gongli seed drill): This ACIAR-ROGRO seed drill is a no-till multi-crop planter. The tool bars of this machine can be fitted at various points to the frame to adjust bar spacing, and the main frame can also carry tools. Up to four tines can be fitted to the tool bars which can be adjusted vertically and laterally along the bars. The twin seed and fertilizer boxes are mounted on either side of the handle bars of the power tiller to ensure good clearance for the tines and

Fig. 25.3 ACIAR-ROGRO-tined seed drill, ARC GONGLI seed drill, national zero-till multi-crop planter and Knapik 2 WT seed drill

tool bar (Hossain et al. 2009; Esdaile 2011). The front box is fitted with Asian-made dual system fluted roller seed meter, which can meter seed of all sizes and deliver fertilizer at variable rates as required. China Agricultural University redesigned and modified the ACIAR-ROGRO seed drill for 2WT and is now being sold as the ARC Gongli seed drill. The seeder is primarily designed for close drill planting of rice and wheat. Variable tine layouts are available to seed in different soil and residue conditions. Integral fertilizer box allows for accurate fertilizer placement in seed rows. Integral press wheels firm the soil to improve soil-to-seed contact and plant emergence.

National zero-till multi-crop planter: This is a four-row multi-crop planter developed in India. The unit is attached behind a 2WT rotary tiller with the aid of clamps. The existing rotavator (rotary tiller) is retained, and this seed drill is fitted to the rear (not necessarily no till). Four flat inclined plate seed meters are fitted. No press wheels or other seed firming devices are available. Depth control wheels are provided on both sides of the planter.

Knapik 2 WT seed drill: This Brazilian 2 WT seed drill is used to sow maize and beans. A classic seed drill with disc openers for seed and fertilizer application. The front discs sow the seed, and another set of discs applies the fertilizer. Seed metering is by a horizontal flat plate system. Two pairs of paired press wheels are at the rear. The large central steel drive/depth wheel is mounted in the center of the seed drill. Large diameter tractor wheels are fitted for increased traction. The above seeders are shown in Fig. 25.3.

25.6 Active Anti-blocking No-/Minimum-Till Seeders

ACIAR/BARI/CIMMYT-modified 2BG-6A rotary tillage seed drill: This Asian-made seed drill for the soil is prepared by the rotary tillage or strip-till operation. Soil is lightly firmed by an attached steel roller which also acts as depth control. At 1200 mm wide, it can plant up to six rows at 200 mm row spacing. It can provide full rotary tillage or strip tillage and covers 0.14–0.20 ha/h.

2BG-6A: This 2BG-6A planter is primarily designed for one-pass planting of rainfed crops following rice harvest either in full-till or strip-till configurations. This planter is bolted to a Chinese two-wheel tractor in place of the standard rotavator with an attached seed box. Metered seed is delivered to wide profile soil openers through seeding tubes, dropping into the soil prepared by the rotary tillage or strip-

Fig. 25.4 ACIAR-modified 2BG-6A, 2BG-6A planter rotary tillage seed drill, VMP planter and 2BFM (DC) 6 planter

till operation. Soil is lightly firmed by an attached steel roller which also acts as depth control. At 1200 mm wide, it can plant up to six rows at 200 mm row spacing. It can provide full rotary tillage or strip tillage and covers 0.14–0.20 ha/h.

Versatile Multi-planter (VMP): The machine has been developed in Bangladesh for strip-till sowing of spring crops. It has a square section tiller shaft which is bolted on blade holders. There are four tiller blades at each site mounted in blade holders to match the four row seed and fertilizer boxes, and row spacing and tillage options are infinitely adjustable. In order to ensure deep seed placement, an optional set of tine type soil openers can be fixed on a separate tool bar as required in marginal moisture conditions (Haque et al. 2011). The net weight of VMP is 152 kg, and its overall dimensions are length 990 mm, width 1220 mm, and height 840 mm.

2BFM (DC) 6: It has a three-point hitch for the cultivator that is powered by a 22 hp. diesel engine. The planter components are arranged close to the center of mass instead of hanging far off the back, which makes it much easier to lift the machine out of the soil while seated via the bushing/hinge on the cultivator itself. Therefore, the operator can quickly turn in the field without dismounting. It is 1380 mm wide allowing it to plant up to 6 rows and covers 0.13–0.26 ha/h. It is a one-pass strip-till seeder for wheat and maize. This differs from the 2BFG-100 as tines are positioned to deliver all the seeds to the bottom of the tilled layer and into the untilled subsoil if it is required. The steel roller is replaced by a 25 mm axle with press wheels behind seed rows to ensure good seed-soil contact. The row spacing and depth of planting are adjustable to meet different needs. The number of rows that can be planted depends on soil and residue conditions, and the power available from the traction unit. The above-cited seeders are shown in Fig. 25.4.

25.7 No-/Minimum-Till Seeders Powered by Four-Wheel Tractors

CA seeders for four-wheel tractors are suitable for large area and high-horsepower tractors. These incorporate passive anti-blockage no-till systems, such as the John Deere 750 and Great Plain 1. These disc-type seeders are heavy at 800–1000 kg/m and can incorporate row clearance devices and cutting discs to avoid blockages. Most of these are too large and highly unsuitable for Asian farms. In order to suit the smallholder farming system in Asia, smaller passive anti-blocking no-till seeders were developed to handle low-residue cover conditions (wheat or rice residues), and

Fig. 25.5 2BMF-7 no-till wheat seeder, 2BMF-11 no-till wheat seeder, 2BMQF-4 no-till corn seeder, and 2BYCF-3 no-till corn seeder

Fig. 25.6 Strip rotary hoe mini-till seeder, strip chop no-till seeder, happy seeder, turbo happy seeder

Fig. 25.7 Chinese-modified turbo seeder, powered disc mini-till seeder, powered coulter mini-till seeder, powered straight knife mini-till seeder, powered residue throwing finger no-till seeder

some active anti-blocking methods were used for heavy residue cover fields. However, uptake of active anti-blockage CA seeders was less than passive anti-blockage types due to their more complex structure and higher power consumption (Gao et al. 2007). Some typical passive and active anti-blocking no-/minimum-till seeders are shown in Figs. 25.5, 25.6, and 25.7.

25.8 Passive Anti-blocking No-Till Seeders

2BMF-7 no-till wheat seeder: The 2BMF-7 uses the multi-beam structure to achieve anti-blocking. In this design, residue clearance is maximized by mounting three openers on the front, two on the middle, and two on the rear bar of the machine. During seeding, the machine used narrow-point openers and press wheels to place and firm seed and fertilizer at depths of 50 mm and 100 mm, respectively. The machine is set to 160 mm row spacing, commonly used by local farmers, giving an operating width of 1.12 m.

2BMF-11 no-till wheat seeder: The 2BMF-11 was developed by China Agricultural University for a 40 kW tractor. Residue clearance was maximized by mounting

Table 25.1 Comparison of passive anti-blocking no-till seeders powered by four-wheel tractors

Machine	Utility	Power	Seeding rows	Anti-blocking method
2BMF-7	Wheat	Four-wheel tractor	Seven rows	Multi-beam structure
2BMF-11	Wheat	Four-wheel tractor	Eleven rows	Five openers on the front and six on the rear bar
2BMQF-4	Corn	Four-wheel tractor	Four rows	Disc coulter combining with dual-teeth discs
2BYCF-3	Corn	Four-wheel tractor	Three rows	Rotary drum

Ref. He Jin et al. (2014)

five openers on the front and six on the rear bar of the machine. This machine used narrow-point openers and press wheels to place and firm seed and fertilizer at depths of 50 mm and 100 mm, respectively.

2BMQF-4 no-till corn seeder: The seeder uses the disc coulter combining with dual-teeth discs to achieve anti-blocking. The leading disc coulter cuts the residue, and then the following dual teeth discs provide residue clearance from the seeding row; thus, the narrow-point opener can easily complete no-till seeding. Furthermore, the wide row spacing (450–650 mm) for maize assists high trash flow.

The passive anti-blocking no-till seeders powered by four-wheel tractors usually operate on medium-sized farms for planting more than three rows (Table 25.1). They normally utilize a multi-beam structure to ensure trash flow and ground clearance and/or utilize anti-blocking components (rollers) to allow residues to flow through the seed drill, when seeding in both heavy and light residue cover fields (He Jin et al. 2014).

25.9 Active Anti-blocking No-/Minimum-Till Seeders

These machines typically use tractor power to drive devices to cut and/or push aside crop residue, to clear the path for the soil openers. These abovementioned types of seeder are explained as follows.

Strip rotary hoe mini-till seeder: General anti-blocking is achieved by strip rotary tillage with varying levels of soil disturbance depending on the number of blades and their shape. In the operation, the powered rotary blades loosen most of the seedbed, cut off stalks, and break roots, so the broad-profile openers can pass through easily. Normally, in order to reduce blade wear, the rotary hoe cultivator operates at low speed (about 200 rpm). However, to ensure complete effectiveness, the chopper should be operated at higher speed (over 1500 rpm).

Strip chop no-till seeder: The strip chop no-till seeder's power-driven chopper blades mounted beside the opener cut off or push away the stalks caught on the opener. The following disc opener pushes chopped stalks or residue to the side and opens the soil for effective seeding.

Happy seeder: The general ideas for the anti-blocking of earlier designed happy seeder is that in the operation, the straw management unit cuts, lifts, and throws the standing stubble and loose straw caught on the tines onto the sown area behind the seed drill, which sows into near bare soil (Blackwell et al. 2003; Sidhu et al. 2007).

Turbo happy seeder and Chinese-modified turbo seeder: High-speed rotating flails are mounted immediately in front of the non-adjustable inverted T-narrow profile planting tines to have an effect of residue clearance and anti-blockage on the turbo happy seeder. The Chinese-modified turbo seeder is based on the happy seeder designs of Dr. John Blackwell with significant differences of twin forward rotating flail rotors, with the additional rear rotor set further back for inter-row clearing under very heavy residue conditions. Furthermore, the twin forward rotating flail rotors operating at 1400 rpm at the shaft provides superior anti-blocking operations and reduces power requirements as well (Humphreys et al. 2006; Sidhu et al. 2008, 2015).

Powered disc mini-till seeder: The general idea for the anti-blocking of powered disc mini-till seeder is to use a scalloped powered disc, to cut roots and residues. These are followed by shark tooth row clearance devices. The following narrow-point opener opens the slot for the seed and fertilizer.

Powered coulter mini-till seeder: The anti-blocking of powered coulter mini-till seeder uses a powered disc and powered coulter, driven by the tractor, cut the corn root and residue. The following narrow-point opener opens the furrow further and prepares the seedbed for the seeds without residue blockage.

Powered straight knife mini-till seeder: The powered straight knife mini-till seeder utilizes a straight knife to cut the corn roots and residue. The straight knife can open the furrow and produces a seedbed for the seeds without the interference of residue.

Powered residue-throwing finger no-till seeder: The powered residue-throwing finger no-till seeder uses a tractor-driven residue-throwing finger, which throws the straw in front of the tine to either side of the opener, clearing the path from residue for the soil opener.

25.10 Indian Scenario

In India, sowing of wheat with traditional method requires 7–8 days in field preparation that also delays sowing of wheat resulting in decrease in yield and increase in GHG emission. Hence, for timely sowing of wheat, no-till drill, slit-till drill, rotary slit-till drill, and happy seeder (different variants) were developed and used for direct drilling of wheat after paddy (Fig. 25.8). The performance of the machine has been compared with conventional tillage (Table 25.2). The bed former cum seeder forms broad beds of size: top width 1200 mm, bottom width 1500 mm, and bed height 100 mm separated by furrows at an interval of 1500 mm. It is suitable for sowing wheat, chickpea maize, sorghum, oil seeds, and pulses in permanent beds. The CO_2 emission to the atmosphere is 61.5% lower under permanent bed cultivation as compared to conventional flat cultivation system due to saving of fuel (high-speed diesel) in field operation. The saving in irrigation water in permanent bed system for wheat crop was 36% as compared to flat cultivation practice.

Fig. 25.8 Commonly used zero−/no-till drill, strip-till drill, rotary slit-till drill and bed former cum seeder under CA in India

Table 25.2 Comparison of different types of no-tillage seeding machines for sowing of wheat after paddy

Particulars	No-till drill	Strip-till drill	Rotary slit-till drill	Bed former cum seeder/ planter	Conventional seeding (3-ploughing + seed drill)
Operational energy (MJ/ha)	648.96 (67.2)	1001.8 (49.3)	565.0 (71.4)	765.5 (61.3)	1976.62
Cost of operation (Rs/ha)	639.54 (66.4)	979.95 (48.5)	1000.0 (70.6)	754.4 (60.36)	1903.04
CO_2 emission, kg/ha	29.38 (67.36)	46.28 (48.58)	26.0 (71.0)	34.66 (61.5)	90.0

Figures in brackets show % saving over conventional practice

However, to realize the full advantage of zero tillage and to sequester carbon, retention of crop residue especially with controlled traffic measures (permanent furrow and bed planting) may further be beneficial due to reduced soil compaction and increased water infiltration and reduced soil evaporation due to residue mulch and provide more water for plant growth (Singh 2014).

25.11 Conclusions

Conservation agriculture requires adequate and very specific mechanization inputs which could be described as "innovations for sustainable agricultural mechanization." For conservation farming system, a large number of machinery has been developed in America, Australia, Canada, Brazil, South Africa, China, and India. However, large-scale adoption of these technologies will apparently enhance sustainability and profitability of farming and farmers' livelihood status in developing countries and also allows the mechanization sector to develop and prosper in a sustainable way. In many developing countries, especially in Africa, supportive and guiding policies are required to attract the agricultural machinery sector to open up and develop markets for agricultural mechanization in general and for CA equipment in particular and also need to establish the required commercial upscale and services such as custom hiring and incentives to farmers for adopting CA machinery infrastructures. Without this change in the machinery sector, future agriculture development needs of South Asian countries for food security, poverty alleviation, economic growth, and environmental services cannot be achieved.

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Conservation Agriculture Improves Soil Health: Major Research Findings from Bangladesh

26

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Abstract

Agriculture in Bangladesh is subsistence-oriented, with traditional management practices still widespread. More recently, new management options have been introduced which have led to substantial improvements in national food and nutrition security as well as a decline in rural poverty. Globally, Bangladesh is the second largest consumer per capita of rice (about 200 kg year^{-1}). Between

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77% and 80% of the country's arable land is used for rice-based crop production. Depending on local edaphic and hydrologic conditions, rice may be grown over three key cropping periods: *aman* (grown in the wet season and rainfed from monsoon rains); *boro* (grown in winter and fully irrigated); and *aus* (grown in spring largely using pre-monsoon rainfall). To meet the increasing food and nutrition demands of Bangladesh's increasing population, farmers apply high doses of agrochemicals (e.g. fertilizers, pesticides, and herbicides) without realizing the deleterious effect overapplication has in terms of depleting soil organic matter, increasing both macro- and micro-nutrient insufficiencies, increasing water-logging and/or poor drainage, and increases in soil salinity and acidity. In addition, intensive rice cultivation under irrigation is the greatest source of greenhouse gas emissions from cropland. In 2014, global greenhouse gas emissions from rice cultivation were 192 megatons. To mitigate the adverse effects on soil health of traditional intensive crop management, and also to reduce greenhouse gas emissions from food grain production, conservation agriculture has been proposed as a key tool to sustainably maintain or increase agricultural productivity and profitability while preserving or enhancing natural resources and the environment. Conservation agriculture is based on three principle strategies: minimal disturbance of soil; maintaining soil cover through the retention of crop

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residues and/or cover crops; and the use of crop rotations. This chapter explores how, in Bangladesh, conservation agriculture improves soil physical, biochemical and biological health, leading to improved cropping system productivity while minimizing environmental damage. We also examine key challenges and potential solutions to promote the wider expansion of conservation agriculture practices in the intensive rice-based cropping systems of South Asia, in particular in Bangladesh.

Keywords

Conservation agriculture · Soil properties · Bangladesh · Rice · Greenhouse gas

26.1 Introduction

Projections of global population estimate that it will increase from 7.7b in 2019 to 9.7bby 2050 (United Nations 2019). Under this human population growth, and subsequent emerging environmental challenges, the demand for food will also increase, while the availability of natural resources will decline (Page et al. 2020). In Bangladesh, 70% of the total land area (in total around 9.1 mha) is under cultivation. Crop rotations (in general rice-based cropping systems) account for approximately 84.4% of cultivated land; 9.1%is under permanent crops, and approximately 6.5% of the cultivated land is used for livestock pasture, this is declining (World Bank 2017). Under the recent expansion of urban and peri-urban areas, overall agricultural land has reduced in Bangladesh (World Bank 2017). In 1961, the per capita arable land was 0.17 ha; by 2016, this had declined to 0.05 ha per capita (World Bank 2020). Due to ever-increasing population pressure, the average farm size in Bangladesh is now 0.68 ha (Quasem 2011).

To meet the growing food demand of an increasing population, cropping systems have intensified and diversified. Most arable areas in Bangladesh are double-cropped, i.e. they produce two crops in each 12-month period (GoB and FAO 2013; GoB 2015). In some areas, particularly in the north-west where soils are both fertile and well drained and groundwater relatively easy to access, three or even four crops are grown in a year, particularly following the introduction of improved, high-yielding crop cultivars (BBS 2016). Among the food crops grown in Bangladesh, rice is the most common followed by wheat. In Bangladesh, each person consumes annual on average 267 kg of rice and 18.5 kg of wheat; the country as a whole consumes around 2.93 m tons of wheat and 42.2 m tons of rice (FAOSTAT 2020). Most of this is produced domestically; however, this comes with significant environmental costs. The recently introduced high-yielding varieties require more fertilizer, pesticides, and irrigation water than traditional varieties, which has led to inadvertent overuse and misuse of agrochemicals (Mottaleb et al. 2019), degrading both the ecological balance and soil health (Quamruzzzaman 2006). Declining soil health in Bangladesh is already observed to be negatively affecting yields: between 1998 and 2007, the annual growth rate of rice yield was

4.1%; between 2008 and 2018, this had declined to 1.4% (FAO 2020). These negative outcomes of cropping system intensification have also been observed in the widespread rice-wheat and rice-rice cropping systems of India and Nepal, as well as in Bangladesh (Rahman 2003; Hobbs and Morris 2011).

The rice-wheat (RW) cropping system is widespread across the subtropical Indo-Gangetic Plain (IGP) which extends across Bangladesh, India, Nepal, and Pakistan. Growth in RW cropping system productivity has decreased across the IGP (Pittelkow et al. 2015), and agronomic sustainability is threatened by declining soil health, increasing scarcity of irrigation water and labour constraints. These three challenges are a consequence of traditional crop production practices, including the repeated compaction (puddling) before rice cultivation, suboptimal crop and residue management, and unbalanced and poorly timed use of agrochemicals (Gathala et al. 2013; Pittelkow et al. 2015; Islam et al. 2019). Repeated puddling of soils creates a hard layer (i.e. a plough pan) in the crop-root zone which increases soil compaction and reduces soil hydraulic conductivity, macroporosity, and the proportion of water-stable aggregates, all of which adversely affect the productivity of the crop succeeding the rice crop(Hobbs 2007; Hobbs et al. 2008; Singh 2015). The traditional crop management practices for rice-based cropping systems are input- and energy-intensive (Gathala et al. 2016) and emit relatively high levels of greenhouse gases (Soni et al. 2013). Therefore, alternative agronomic practices are needed to sustainably maintain or increase rice-based cropping system productivity. Large-scale uptake of improved crop management practices such as those promoted under conservation agriculture (CA) will contribute significantly to enabling Bangladesh to achieve food security for an increasing population while conserving natural resources. There are three key facets of CA crop management: minimal soil disturbance, maintaining permanent soil cover through crop residues and/or cover crops, and the incorporation of multiple crops in rotation (FAO 2017).

A growing body of literature has demonstrated that CA practices such as zero tillage (ZT) facilitate significant productivity and economic gains for farmers in South Asia while concurrently improving water and soil quality, and thus contributing to improving the environmental footprint of agriculture (Gathala et al. 2013; Busari et al. 2015; Edralin et al. 2017). Aryal et al. (2015) demonstrated that, compared to conventional management practices, ZT reduced cropping system production costs by US $ 79/ha and increased farmers' income by US $ 97.5/ha in the Indian state of Haryana. Similarly, Krishna and Veettil (2014) reported 14% cost savings, 5% productivity increases, and 1% technical efficiencies in RW cropping systems in Haryana under ZT compared to a traditional cropping system baseline. In Bangladesh, much research has demonstrated that ZT combined with residue retention improves soil health and leads to increased agricultural productivity (e.g. Gathala et al. 2016; Islam et al. 2019; Alam et al. 2014, 2016, 2017, 2018, 2020). In this chapter, we examine the ways by which ZT in combination with increased residue retention contributes to improved soil physical, biochemical and biological health, which in turn improves cropping system productivity while reducing environmental degradation. Here we also present key challenges and potential solutions to facilitate the widespread expansion of CA in the intensive rice-wheat cropping systems of South Asia, in particular in Bangladesh.

26.2 Conservation Agriculture Improves Soil Health

26.2.1 Soil Physiological Properties

26.2.1.1 Soil Structure and Aggregation

Soils are comprised of sand, silt and clay particles, in a soil structure which is 'the spatial heterogeneity of the different components or properties of the soil' (Dexter 1988). Good soil structure and structural stability (i.e. soil structure that persists for a long time and is of high quality) are essential for ongoing agriculture or horticulture (Dexter 1988). Soil aggregates, the structural units of any soil, are the larger particles formed from single sand, silt, and clay particles; microaggregates are formed inside macroaggregates (Oades 1984; Angers et al. 1997). Soil aggregates influence organic matter, nutrient cycling, porosity, and aeration within the soil profile, thereby affecting plant and microbial populations, water infiltration, and soil erosion (Chevallier et al. 2004; Bossuyt et al. 2005). Degradation of soil structure is measured by a reduction in aggregate stability (D'Andréa et al. 2002), which is the capacity of cohesive forces between soil particles to resist externally applied destructive forces. Crop management practices employed such as tillage, the removal or incorporation of residues or other organic matter, and the cultivation of crops in a rotationphysically disrupt soil aggregation processes, breaking macroaggregates into microaggregates and ultimately altering the biological and chemical properties of the soil (Barto et al. 2010). Conservation agriculture is a sustainable, cost-effective option for crop management which has numerous benefits in terms of maintaining and/or improving the natural resource base on the agronomic environment (Jat et al. 2019; Somasundaram et al. 2019; Page et al. 2019, 2020). CA facilitates an increase in soil organic matter (SOM), particularly at the soil surface (Lal 2015), which is directly associated with soil aggregate stability and which leads to improve soil physical health (Blanco-Canqui and Ruis 2018; Li et al. 2019). Different arrangements of a soil's micro- and macroaggregates influence its structure. Management practices which improve SOM are key to improving soil health in the rice-based cropping systems of Bangladesh (Islam et al. 2019; Alam et al. 2014, 2016, 2020).

Influence of Tillage

Increasing pre-crop tillage is useful for weed control and timely crop establishment and thus appears initially to increase yields. However, over the long term, intensive tillage degrades soil aggregates and the soil structure itself, ultimately leading to yield reductions. This decline in soil health is further exacerbated by compacting (puddling) a hard layer to grow rice in the rice-based cropping systems which predominate across the in the Indo-Gangetic Plains (Gathala et al. 2014; Pittelkow et al. 2015). Borie et al. (2006) and Curaqueo et al. (2011) demonstrated that under conventional tillage (CT), the soil mycelium network was reduced through the breaking down of soil macroaggregates and through decreases in soil organic matter, microbial biomass, and faunal activities. Chaudhary et al. (2009) report that decreased soil aggregate stability contributed to soil nutrient depletion and soil erosion. Zheng et al. (2018) and Tang et al. (2020a) found a significant difference in soil aggregates under different soil tillage treatments, where each size class of soil aggregates under CT, ridge tillage (RT), and no-tillage (NT) treatments was higher ($P < 0.05$) than rotary tillage without incorporation of crop residue (RTO) treatment. This is likely to be due to the different mechanisms of different factors (e.g. soil microbial activities, soil particles, and soil moisture content) on the soil aggregation of crop residue and soil tillage practices (Lenka et al. 2019). Several studies have reported that macroaggregates are more susceptible than microaggregates to breakdown by tillage practice (e.g. Ashagrie et al. 2007). In an experiment conducted on black soils in northeast China, Zhang et al. (2012) compared the effects of NT, RT and CT on soil aggregation and reported that reduced-tillage practices such as RT and NT are beneficial for soil structure due to the positive effects on soil aggregation.

Alam et al. (2020) demonstrated that in Bangladesh, traditional puddled transplanted rice (PTR) in rice-based cropping systems is the major concern for declines in soil aggregation, soil organic carbon sequestration, and soil health. They also observed that if the upland (predominantly nonirrigated)crops following rice were grown using conservation tillage practices (e.g. NT, RT, zero tillage, strip tillage, or bed planting), soil fertility and soil productivity both increased, increasing cropping system productivity (Alam et al. 2020)).

Influence of Residue Management

The decomposition of organic material remaining after the harvest of a crop releases polysaccharides and organic acids which are important for the stabilization of macroaggregates (Naresh et al. 2016, 2017). These polysaccharide and organic acids do not spread far from the site of their introduction into the soil; freshly added crop residues thus function as nucleation sites for the growth of fungi and other soil microbes (Zhang et al. 2012). As a result, crop residues and soil particulates are bound into macroaggregates in higher proportions in the topsoil layer than in subsurface layers (Benbi and Senapati 2010).

Research has shown that combining no-tillage practice with the retention on the soil surface of crop residues results in higher water-stable macroaggregates than was observed in a treatment where conventional tillage practice was combined with crop residue removal (e.g. Jat et al. 2019; Nandan et al. 2019). For example, Jat et al. (2019) reported that residue retention significantly increased (by 19.4%) the total water-stable aggregates in the topsoil (0–5 cm) and increased by 6.95% the total water-stable aggregates in the soil at 5–15 cm depth. This demonstrates that residue management has the potential to double the presence of water-stable aggregates within the soil, compared to treatments without residue retention. Similarly, Nandan et al. (2019) recorded increased soil aggregation under zero tillage with residue retention compared to treatments where zero tillage was combined with residue removal.

Kushwaha et al. (2001) suggested that the increase in soil organic matter addition resulting from residue retention combined with tillage reduction accelerates the formation of macroaggregates through an increase in the microbial biomass content in the soil. As the most labile fraction of soil organic matter is reflected in the soil microbial biomass, the negative impact of repeated tillage on soil microbial content is one of the reasons for reduced macroaggregation in ploughed soils (Gupta and Germida 1988). Microbial biomass plays an important role in the metabolism of transient-binding organic matter, such as plant and microbially derived polysaccharides, and so increasing microbial biomass positively affects soil aggregation in agroecosystems. Singh et al. (2018) also observed that retaining crop residues increased by 30% the presence of water-stable macroaggregates compared to treatments where residues were removed.

Influence of Crop Rotation

The choice of crops in a rotation influences soil aggregation as there are differences between crops in terms of root distributions through the soil profile, root growth pattern, and in-season crop-litter fall (Zotarelli et al. 2007; Singh et al. 2018). Due to variations in above- and belowground biomass production and hence variability in soil carbon supply, crops have differing effects on soil aggregation and the stabilization of soil aggregates (Holeplass et al. 2004; Wohlenberg et al. 2004), mechanical effect (Silva et al. 2007), the promotion of mycorrhizal associations (Maiti et al. 2006, 2012), and variability in soil aggregate stability over each growing season (Castiglioni et al. 2018). Different crops in a cropping system require different management, including different establishment practices (Alam et al. 2020). Plant roots significantly accelerate the aggregation of soil particles (Govaerts et al. 2008). Jiang et al. (2011) observed improved soil structure and soil fertility as a consequence of including different crops (cereals, legumes, etc.) in a rotation, and also by alternating deep-rooted and shallow-rooted crops. Chu et al. (2016) reported significant changes in soil aggregate distribution at 20–40 cm depth; these were primarily as a result of the presence of plant roots in this zone.

Cereal-dominant cropping systems may have lower soil aggregate binding agents than legume-dominant cropping systems. Singh et al. (2018) reported a positive relationship between soil aggregate stability and glomalin (a microaggregate-binding agent) content; the authors also observed that legume-based cropping systems had approximately 12% higher soil glomalin cropping systems with cereals alone. Kumari et al. (2011) and Nath and Rattan (2017) observed that soil properties such as soil aggregation, organic carbon, beneficial microorganisms, and the overall soil environment were negatively affected by long-term repeated tillage and puddling (i.e. soil compacting) before transplanted rice in the widespread rice-wheat cropping system in South Asia.

26.2.1.2 Soil Porosity

Bulk Density and Total Porosity

Bulk density (BD) is a useful indicator of soil health which influences infiltration, rooting depth, soil water-holding capacity, soil porosity, plant nutrient availability, and soil microbial activity (Chaudhari et al. 2013; USDA 2014; NRCS 2019). While BD is primarily influenced by a soil's inherent qualities, the choice of crop establishment practice affects BD after several cropping seasons. Alam et al. (2014) showed that, for soils in Bangladesh, practices that increase soil organic matter accumulation decrease soil BD. Other research from Bangladesh has demonstrated that reducing soil disturbance by reducing or eliminating tillage and retaining crop residues facilitates the accumulation over time of soil organic matter (Alam et al. 2014, 2016, 2018; Salahin et al. 2017): these practices thus reduce the BD of a soil (Alam et al. 2016, 2020). Zhang et al. (2009) examined the long-term effects of spacing soil tillage (SST), ZT, and CT on soil properties and crop yields in Daxing and Changping, China. After 8 years, they found that soil BD was 0.8–1.5% lower under SST and ZT than under CT at both sites, a result that the authors attributed to higher soil organic matter content and improved soil aggregation in SST and ZT treatments.

In contrast, conventional tillage has also been shown to reduce soil BD (e.g. Motschenbacher et al. 2011), while in an experiment over 20 years, Chang and Lindwall (1989) did not observe changes in soil BD between different tillage and residue retention treatments. Similarly, Carefoot et al. (1990), working in the semiarid regions of Alberta-Canada, reported that BD did not vary between loam and clay soils which had been under ZT for up to 8 years, compared to control treatments with soils under CT. Motschenbacher et al. (2011) evaluated in the USA the effects of tillage (CT and ZT) on soil BD after 10 years of ZT or CT management. Their results indicated that soil BD was greater under ZT than CT in the top 0–10 cm, but there was no significant difference in BD in the 10–20 cm soil layer.

The effects of retaining crop residues on soil BD are more evident when residue retention is combined with no or minimal soil disturbance (e.g. strip tillage, NT, ZT) (Alam et al. 2014, 2016, 2018). Applying mulch to treatments where the soil was minimally disturbed reduced soil BD, as reported by Bautista et al. (1996) and Hobbs et al. (2008). Shaver (2010) and Shaver et al. (2013) observed that the BD of the topsoil (i.e. 0–2.5 cm depth) was directly related to crop residue accumulation over the preceding 12 years in the dryland cropping systems in the western Great Plains, USA. Similarly, Du et al.(2009) and Zhang et al. (2014a, b) in China, Zeleke et al. (2004) in Ethiopia, and Singh et al. (2007) in India reported significant decreases in BD after 3–5 years of crop residue incorporation. The effects of reduced soil disturbance on BD become more evident over time. For example, Li et al. (2007) examined the effect of ZT with residue retention compared to CT with residues removed, in a 15-year field experiment on the loess plateau of northern China. For the first 6 years of the experiment soil, BD was significantly lower in the CT treatment in the topsoil (0–20 cm depth) than in the ZT treatment: this was due to the use of heavy machinery and the lack of regular soil loosening. In the subsequent

5 years, soil BD values were similar between treatments, while in the final 2 years, soil BD was higher in the CT without residue treatment than in the ZT with residue retention treatment.

In Bangladesh, Alam et al. (2018) compared the effects on soil physical properties of strip-tillage (ST), bed planting (BP), and conventional tillage (CT) for upland crops, non-puddled transplanted rice, and puddled transplanted rice in rice-based cropping systems at Alipur and Digram in Rajshahi. They also examined the effect of retaining or removing residues in each tillage treatment. The authors reported that after 5 years of ST or BP, the effect of tillage on the soil BD at both sites varied with residue retention practice. The lowest BD at both sites was in treatments where a high amount of residue was retained; BD further varied by tillage treatment in the following order: BD was lower under ST, then under CT, and highest under BP. The treatment of ST combined with residue retention reduced soil BD by 0.12 g cm^{-3} at both sites relative to the control treatment of CT with residues removed. At Alipur, increasing residue retention in the ST, BP, and CT treatments increased soil porosity values by 4.3%, 2.4%, and 2.3%, respectively, relative to the CT treatment without residue. At Digram, the ST, BP, and CT treatments with retained residues had soil porosity values 4.6%, 2.1%, and 2.6%, respectively, higher than those observed in the CT treatment where residues were removed. Other research has also demonstrated that tillage and residue retention significantly influence soil porosity and pore size distribution. Alam et al. (2014) and Alam et al. (2016) showed that the effects of tillage practices on soil porosity were small but consistently positive after 4to 5 years in clay loam soils under wheat-mung bean-rice cropping systems.

Pore Size Distribution and Pore Continuity

Soil effective porosity, influenced by macropores, is related to a soil's saturated hydraulic conductivity (Ahuja et al. 1989) and also reflects the percentage of total soil pores which are open to infiltration during rain or irrigation. The pores which are 150 mm in diameter or less are those which are the effective pores to facilitate drainage of water freely with gravity (Azooz et al. 1996). In dry soil, the transmission of water across a matric pressure gradient occurs more rapidly through small than large pores. Soil water storage and transmission can, therefore, be altered by affecting the pore size distribution through different tillage management practices. Bhattacharyya et al. (2006) reported that the volume of pores which drain at above 10 kPa is a combination of the transmission pores and the macropores through which water moves freely under gravity. Many studies have indicated that tillage systems significantly affect soil pore size distribution (e.g. Lipiec et al. 2006). He et al. (2009) found that the total soil porosity, macroporosity, and mesoporosity in the topsoil (i.e. 0–15 cm layer) were similar under both CT and zero or minimal tillage. However, significant ($P < 0.05$) differences between tillage treatments have been observed in the 15–30 cm soil layer. In treatments with no or reduced tillage, mesoporosity was increased by 18% over control CT treatments, which coincided with observed changes in soil bulk density at that depth.

Alam et al. (2014) and Shukla et al. (2003) reported that intensive tillage decreased soil porosity and reduced water infiltration into the soil by disrupting soil pores. When the distribution of clay increases at the interface of the puddled (compacted) soil layer and the relatively undisturbed layer below it, a hard plough pan forms, at around 10–20 cm soil depth (Behera et al. 2009). This plough pan is formed where compaction of the topsoil layer disrupts pore sizes and hydraulic conductivity. Initially, soil puddling (i.e. compaction) may decrease the porosity rate (PR); however, over time subsidence and compaction of the puddled soil increase both the BD and the PR, thus decreasing hydraulic conductivity (Behera et al. 2009).

26.2.1.3 Hydraulic Conductivity and Water-Holding Capacity

Soil tillage and residue retention increase affect the hydraulic conductivity and water-holding capacity of a soil. He et al. (2009) reported that the saturated hydraulic conductivity (Ks) of soils increased under no-tillage practice at the 0–30 cm layer. Singh et al. (2014) observed higher Ks values at various soil depths under ZT than under CT in a rice-wheat cropping system. In the topsoil (i.e. 10 cm soil depth), Ks was significantly higher under ZT than under the CT treatment. Ks also varies with soil type: at the topsoil (0–5 cm layer) Ks value was highest in a loam (51%) followed by that observed in a sandy loam (40%) and then a clay loam (38%). Other research has also reported higher Ks under ZT than observed under CT practice (e.g. Castellini and Ventrella 2012). Zhang (2005) observed similar findings and reported that hydraulic conductivity in CT (compacted) soil was 28–36% lower than that observed in a non-compacted loess soil under ZT in Shaanxi province, China. Busari et al. (2015) attributed that the lower Ks observed under CT treatment than under ZT treatment is damaged caused by ploughing to water-stable aggregates and reductions in macropore continuity and numbers. The reduction of Ks in the soil below the plough pan (i.e. below 15–30 cm depth) may be a result of redistributed clay particles filling macropores, and of the deposition of clay particles at the compacted zone. In contrast, higher Ks values were observed under CT practice than under ZT in an experiment conducted on a silty clay loam soil under rice-wheat cropping system in the Terai region of Northern India Sharma et al. (2005).

The water-holding capacity (WHC) of a soil varies with tillage (Abu-Hamdeh 2004; Alam et al. 2014; Busari et al. 2015; Dixit et al. 2019).They reported WHC at field capacity (i.e. saturated soil) to be higher initially under CT, and over time the WHC gradually increased steadily in soils under ZT. Plant-available water capacity (PAWC) also increased in soils under ZT over time. For example, Alam et al. (2014) observed an initial PAWC at the 0–25 cm soil depth which was 36.6% lower in ZT than the PAWC observed in the CT treatment. After four complete rotations of the wheat-mungbean-rice system, differences in PAWC were insignificant between ZT and CT practices. Increasing soil water retention under ZT also facilitated increased water uptake by the crop resulting in a gradual improvement in dry-season crop yield under ZT compared to yields under CT where yields almost remained constant or decreased in some cases. Soils under ZT have greater water storage capacity than soils under CT (Gozubuyuk et al. 2014). Over the longer term, WHC and PAWC are significantly higher in soils under ZT than in soils under CT: this is due to an increase in soil organic matter and other physical characteristics under ZT. As well, infiltration is an important soil feature which influences nutrient leaching and runoff, and crop-water availability (Schwen et al. 2011).

26.2.1.4 Soil Water Balance

Infiltration and Runoff

Reduced soil disturbance and residue retention also improve soil water infiltration and runoff. Singh et al. (2014) reported that ZT practice significantly increased (by 28%) soil water in a clay loam soil compared to soils under CT. Alam et al. (2014) also reported higher soil water infiltration when soils were minimally disturbed; they further noted that retaining 30% of crop residues facilitated water infiltration. Alam et al. (2014) reported that after 4 years, a treatment combining ZT and 30% residue retention increased soil water infiltration by 18.4% compared to a CT treatment without residue retention, while a minimum tillage (MT) treatment increased infiltration by 7.4% compared to the CT baseline. Ehlers (1975) proposed that the entry of water into soil is managed by soil macropores and pore continuity. Govaerts et al. (2007) stated that long-term ZT management improved the macropore network in clay loam soil, leading to improved soil water infiltration. Greater soil water infiltration under CT than NT was due to the relatively high soil organic matter in the topsoil which reduced topsoil 'sealing' which impedes the entry of water into the soil under CT and promotes rapid flow along with interaggregate pores (Lipiec et al. 2006).

The increase in soil water infiltration decreases water runoff due to the improved soil aggregate stability associated with minimal or no-tillage and residue retention (Reeves 1997). Runoff rates varied with tillage practice. Several studies have shown that reduced no tillage resulted in the equal or greater runoff than was observed under CT (Smith et al. 2007), as well runoff has been observed to be higher under ZT treatments than under reduced tillage treatments. In contrast, other studies have demonstrated that no- and minimum-tillage treatments have reduced water runoff volumes (e.g. Truman et al. 2007, 2009). DeLaune and Sij (2012) and DeLaune et al. (2013) showed that conversion from NT to CT increased water runoff volume by 38%.

Applying minimum or no-tillage practices such as strip tillage, ZT, NT, and ZT-based direct-seeding of rice, or the establishment of rice without puddling in combination with the retention of crop residues is likely to reduce and eliminate that compacted plough pan soil layer by increasing the number of macropores and continuous pores in the soil. This result will take some seasons of plant production (and plant root exploration of the former compacted soil layer) to achieve and will lead to a subsequent reduction in runoff of monsoon rain and/or irrigation water, due to the increase of soil water infiltration (Alam et al. 2020). This increased soil water infiltration and decreased runoff of rainwater under reduced tillage and residue retention practices, in turn, has the potential to positively influence groundwater recharge and while reducing nutrient loss from soils.

Evaporation

The goal for judicious crop-water management is to maximize transpiration and water losses such as the evaporation of soil water. Tillage and residue retention greatly influence soil evaporation. Swella et al. (2015)reported that no tillage (NT) combined with residue retention reduced the rate of soil water evaporation during the hot, dry summer season by about 10.2 cm. Converting from CT to NT reduces irrigation water demand as a result of the reduction in soil water evaporation (Hu et al. 2016). In general, the retention of crop residues reduces the evaporation of soil water by increasing soil shading, reducing soil surface temperatures, and exposure to solar radiation and by reducing the effects of wind on the soil surface (van Donk 2010). The evaporation rate from a bare soil after initial wetting is higher than that from the same soil where residues are retained. However, if the soil under residue is not rewetted (e.g. by irrigation or rainfall), evaporation will continue and may, after some days, exceed that from bare soil. This is fairly constant for each wetting event, no matter how light or heavy the wetting event is. Research at Garden City, Kansas (USA), reported a 50% reduction in evaporation over a period of 3 months in summer under NT with retention of nearly 100% of wheat straw or corn stover compared to the evaporation observed on the soil without residue retention (van Donk and Klocke 2012). Galbally et al. (2005) reported low evaporation losses where NT was combined with residue retention: these were as a result of increased soil moisture and increased labile soil organic carbon.

Soil Water Content and Plant Available Water

Soil moisture-retention (SMR) characteristics varied with tillage practice. SMR at field capacity (i.e. saturated soil) was initially higher in treatments with tillage, but over time the SMR of treatments under no or minimal tillage increased (Bescansa et al. 2006); results of plant-available water content were similar to those of SMR at field capacity (Alam et al. 2014). Higher SMR differences were observed in the topsoil layer (0–25 cm) following the completion of the first complete cropping cycle: the available water content (AWC) was significantly lower under ZT than under other tillage treatments (Alam et al. 2014). However, after four cropping cycles, there were insignificant differences in AWC between the different tillage treatments. Increasing SMR under ZT also facilitated increased crop-water uptake, resulting in an improvement over time in dry season crop yield under ZT compared to yields achieved under CT where crop yields remained constant or decreased in some cases. Fernández-Ugalde et al. (2009) also observed that soils under NT have improved SMR capacity compared to those under CT. The authors reported that water-holding capacity at field capacity was significantly higher in NT treatments than in CT treatments; they observed that these variances were predominantly at the soil surface where SMR was 23% lower in the CT treatment than in the NT treatment. In the long term, SMR and AWC were significantly higher in ZT than in CT treatments, largely due to increased build-up of organic matter and other favourable physical characteristics (Schwen et al. 2011).

26.2.1.5 Soil Erosion

Over the last 40 years, soil erosion has permanently damaged about a third of the global total arable land (The Guardian 2015). The FAO-led 'Global Soil Partnership-20' reported that 75 billion tonnes of soil are eroded annually from global arable lands; this results in a financial loss of US$400 b year^{-1} (Borrelli et al. 2017).India experiences a serious soil erosion challenge, experiencing about 18.5% of the total global soil erosion (Bhatt and Khera 2006). In Bangladesh, different types of soil erosion occur, including sheet, rill, and gully erosion, landslides, riverbank erosion, and coastal erosion (Hasan and Alam 2006). Water erosion is the most extensive form of soil degradation, affecting about 25% of the country's agricultural land. It is estimated that 2270 ha of land is lost annually to riverbank erosion (Kamal and Abedin 2019). In the hilly regions of Bangladesh, soil erosion has accelerated and has occurred over approximately 1.7 m ha (Hasnat et al. 2018). A study at the Ramgati (hilly region) station of the Bangladesh Agricultural Research Institute (BARI)reported that every year 2.0–4.7 t ha^{-1}soil is eroded in the region (Banglapedia 2015).

Research has shown that crop residues (and crop canopies) reduce soil detachment and erosion by absorbing the impact of falling raindrops (McCarthy et al. 1993). As well, crop residues may form small dams which retard runoff and create localized puddles which absorb raindrop energy, reducing both the detachment and the transport of soil particles (Nalatwadmath et al. 2006). The frontline defence measures to reduce and stop soil erosion from cultivated fields are the reduction or elimination of tillage combined with the retention of residues and/or the application of mulches (Toure et al. 2011;Alliaume et al. 2014). Bhatt and Arora (2019) reported that treatments under ZT or NT combined with a weed mulch had only 3 Mg ha^{-1}of soil loss, whereas treatments under CT with the weed mulch or under ZT without mulch had 7 and 12 Mg ha^{-1} soil loss, respectively.

26.2.1.6 Soil Temperature

Soil temperature fluctuations are decreased with the retention of crop residues under both minimum tillage and under CT (Li et al. 2013; Almagro et al. 2017; Alam et al. 2018). This decreased rate of temperature change is a result of the increased reflection of incident solar radiation (Li et al. 2013) by the surface residues which also act as an insulating barrier between the soil surface and the warmer (or colder) atmospheric air above (López-Moreno et al. 2009; Chen et al. 2013). The incorporation of tillage affects soil heat capacity, soil thermal conductivity, and therefore soil thermal diffusivity (i.e. the ratio of the thermal conductivity to the heat capacity) by altering soil organic matter, bulk density, interaggregate contact and soil moisture content (Usowicz and Lipiec 2020). Alam et al. (2018) reported increased soil organic carbon, lower BD, and increased soil moisture after 5 years under reduced tillage and with residue retention in Bangladesh. The authors also recorded lower temperatures under strip planting and bed planting over three growing seasons than under conventional crop establishment practices and suggested that these may be due to the retention of crop residues on the soil surface in the strip and bed planting treatments which better reflected solar radiation and insulated the topsoil from fluctuations in atmospheric temperature.

26.2.2 Conservation Agriculture Improves Soil Chemical Properties

26.2.2.1 Soil Organic Carbon

The minimal or no-tillage and retention of residues under conservation agriculture (CA) improve soil organic carbon (SOC) relative to conventional practice. The addition of organic matter to the soil through crop biomass and the losses from the soil through decomposition, leaching as well as erosion, contribute both positively and negatively to the soil organic carbon. In general, higher SOC was observed in soils under minimal or no-tillage than in soils under conventional tillage (CT) (Muchabi et al. 2014).Differences in SOC in soils under CA and CT practices become more pronounced and significant as the experiment length increases(Umar et al. 2011; Muchabi et al. 2014), suggesting that it takes time to accumulate SOC and observe changes within a soil. Dolan et al. (2006) reported higher SOC under CA practices due to the retention of residues without incorporation. Chivenge et al. (2007) studied the long-term effects of reduced tillage and residue retention in contrasting soils and came out with the ideas of maintenance of soil carbon through the management of crop residues for long-term sustainability in coarse-textured soils, whereas in fine-textured soils, fewer tillage operations *vis-à-vis* reduced rate of decomposition of soil organic matter are to be focussed. While studying a rice-wheat system in eastern Indo-Gangetic plains, Sapkota et al. (2017) reported the changes in SOC after 7 years of CA practices. Repeated tillage operations in the soil actually lead to losses of SOC as the soil is exposed for microbial decay, particularly the organic matter present in soil macroaggregates (Six et al. 2000). However, there are also certain instances in which it was seen that the tillage increases the SOC (Zhang et al. 2014a, b).Christopher et al. (2009) reported that poor soil aeration may limit the rate of burial of organic matter in soils which were fully inverted under cool and moist condition.

There was a tremendous role of crop rotation and conservation tillage practices and their interaction which actually significantly influences the soil organic matter (Degu et al. 2019). Complete removal of crop biomass might be one of the most important factors for having the lower values of SOC as reported by Yihenew (2002) from most of the cultivated soil of Ethiopia. Higher organic matter present in surface soil under conservation agriculture was mostly due to the retention of crop residues (Shimeles et al. 2006). After conducting a 5-year CA-maize trial at Nepal, Karki and Shrestha (2015) revealed more organic matter in CA plots over traditionally tilled plots. With an increase in leftover crop residue load under CA practices, a linear increase in SOC stocks was reported by several workers (Virto et al. 2012; Liu et al. 2014). That is the real strength of CA practices through which surface residue retention could increase SOC storage in soil. To positively impact soil organic C, there could be insufficient residue retention under CA particularly under various constraint soils or poor fertile soils (Palm et al. 2014; Lal 2015).

The quantity, quality, as well as periodicity of C inputs in soil may differ from crop to crops grown there, and this variable response may modify the soil in various ways (Huggins et al. 2007).The different sequences of crops followed under conservation and traditional practices may impact SOC and ultimately the crops and the rotations with higher amount of leftover residues are mostly preferred for maintaining a higher carbon reserve in soil (Huggins et al. 2007; Conceição et al. 2013). From a 17-year trial on Brazillian Ferrosol, dos Santos et al. (2011) reported a close association of SOC stocks with plant's leftover roots addition. Choudhary et al. (2018) reported a lesser effect of rice-wheat rotation on SOC over a wheat-maize system in slightly alkaline soils.

However, different agricultural systems based on CA or CT practices exerted various degrees of soil carbon depending on factors like initial values of SOC (Steinbach and Alvarez 2006), management schedule followed for the crops (VandenBygaart et al. 2003) in addition to soil type (Liang et al. 2002) and climate (Ogle et al. 2019). The regions with favourable climatic condition for higher biomass production, CA practices resulted in greater values of soil C than traditionally repeated tillage-based systems. Although there exists a large range in C sequestration rates, CA could be perceived as a better alternative through which potential benefits in soil chemical properties and soil environment be harnessed through better recycling of plant nutrients.

26.2.2.2 Soil pH

Soil pH is the most influential factor affecting chemical and biological processes as well as soil functions (Karlen et al. 2003). Soil pH is highly influenced by conservation agriculture practices. Increase in SOC under CA practices has a direct effect on soil pH. It was reported from a 13 years of residue retention study that pH and SOC related negatively in the top 10 cm soil depth in a nitrogen-fertilized zero-tilled wheat experiment on a vertisol (Dalal 1989). Actually, long-term effects of nitrogen fertilization have a greater impact in reducing the pH of a fine-textured soil (Dalal et al. 1991). In a coarse-textured (sandy and sandy loam) soil with low buffer capacity, especially in a high-rainfall environment, ZT practice may adversely affect soil pH, as found in eastern Gangetic alluvial plains (Guo et al. 2010). Higher accumulation of crop residues, as well as formation of surface acidity through production of organic acids under CA systems, is directly associated with the changes in soil reaction (Franzluebbers and Hons 1996). Root exudates may also have an impact on acidification (Limousin and Tessier 2007). On the contrary, Muchabi et al. (2014) reported that CA practices can reduce soil acidification.

Crop rotation may influence in changing the pH of soil, particularly under CA practices. From a CA system from Southern Brazil, Vieira et al. (2009) found 0.4–1.5 units change in soil pH; there was a higher decrease in soil pH under legume-based crop rotations coupled with mineral N fertilizer application. Taking into account crop rotation x conservation practice effects, 3 years maize and maize-wheat-fababean showed higher pH values, while lower pH values were observed with maize-pepper-pepper and maize-wheat-pepper rotations (Degu et al. 2019) in north-western Ethiopia. In eastern Gangetic alluvial plains, there was a decrease in soil pH under ZT as compared to conventionally tilled plots, pH decreased up to 0.4 units over 4 years' rotation in conventional acidic soils (Sinha et al. 2019). It was also observed in certain studies that conserved and non-conserved farmlands differ considerably in soil pH, and increased mean soil pH was observed across conserved farmlands due to variation in the extent of soil erosion and loss of basic cations through leaching (Birhane et al. 2016; Degu et al. 2019). Again, from a 9 years study on Luvisol in a subtropical semiarid climate in Southern Queensland, Australia, it was found that soil pH was not much affected in top 0–10 cm layer through tillage or stubble treatments, but pH decreased significantly with nitrogenous fertilizer application (Thomas et al. 2007). It is thus clear from various studies that the degree of changes in soil pH actually depends on the factors, viz., soil buffering capacity, changes in organic matter concentrations in soil, climatic features, and overall nitrogen management.

26.2.2.3 Nutrient Availability

Nitrogen

Nitrogen availability is influenced greatly under CA practices. In most of the studies on CA systems, there was an improvement in SOC which in turn have a great influence on the availability of nutrients. The crop residues which were retained as stubble much under CA practices may have high C:N ratio which actually triggers higher rates of immobilization rather than mineralization and makes it less available in initial years (O'Leary and Connor 1997). With the subsequent addition of nitrogen in the system as a part of crop management, this situation is gradually improved, and ultimately after certain years, there would be higher and steady rates of mineralization (Mrabet et al. 2012; Soane et al. 2012).

For maintaining the sustainability of CA-based cropping systems, monitoring on availability of nutrients are very important as we have to maintain a steady yield level with not much depletion of soil nutrients. Further, it's the availability of plant N (along with P and K also) which actually affects the crop productivity as well as the sustainability of the farming system (Wanjari et al. 2004). Sometimes higher yields in CA system are also coupled with higher uptake of nutrients from the soil (Mitra et al. 2014) and removal from grain which results in nutrient depletion (Wanjari et al. 2004; Surekha and Satishkumar 2014).

In CA systems, more specifically under a complete no-till system in arid regions where soil drying is quite common, there were no chances of soil mixing; it may result into the stratification of immobile nutrients (Mrabet et al. 2012; Dang et al. 2015). In areas where conservation tillage leads to lower air-filled pore spaces, denitrification may be observed (Rochette 2008). Again, soils having higher infiltration rate may also prone to N leaching, making N unavailable (Turpin et al. 1998). Considering all the aspects, scientists are more interested in analysing nitrogen use efficiency under CA systems. Karki and Shrestha (2015) observed 15–25% higher use efficiency of nutrients by crops under CA systems. Higher N use efficiency with increased apparent N recovery was also noticed under CA-based management (Mitra et al. 2019).

Phosphorus

Under CA system with higher yields and greater residue retention, soil P availability improves mostly due to increased organic matter addition (Zhao et al. 2017; Sithole and Magwaza 2019; Sinha et al. 2019). However, in the long run, there might be decline in the availability of soil P as reported by Muchabi et al. (2014). Shitumbanuma and Banda (2004) also found a decline in P much below the optimum level after 16 years of cropping. Actually, CA practices are not considered to be an option through which soil P could be improved to a significant extent. Increasing the availability of P through CA practices is really problematic in acid soils having low native soil P stocks. Studies conducted on acid soils of Kenya reflected more Fe and Al-hydroxide-driven P-fixation under acid soils for which CA has not been considered for P improvement of the soil. In Western Kenya, P remains a big challenge for getting increased agricultural productivity for this reason (Nziguheba et al. 2015). In weathered soils, phosphorus cycling through organic pools may be considered as an important factor for meeting the demand of the crop (Oberson et al. 2006, 2011). P fixation may be reduced through residue retention and reduced tillage under CA systems with increased labile P and its further mineralization through phosphatase enzyme in weathered soils. Less number of tillage operations and retaining the organic matter under CA systems improved soil aggregate formation which was very congenial for P availability in weathered soil (Wei et al. 2014).

From a study in eastern Gangetic alluvial plains over 3 years, it was seen that the tillage practice did not influence available P to a great extent except in sites with higher pH where ZT plots showed higher available P over CT plots probably due to lower phosphatic fertilizer dissolution in higher pH (Sinha et al. 2019). Slight improvement in soil P status was reported from ZT-wheat plots as compared to CT plots in eastern sub-Himalayan plains (Mitra et al. 2019; Mondal et al. 2018). Mitra and Patra (2019) also reported an improved P status in soils under DSR-surface-seeded wheat and unpuddled transplanted rice-ZT wheat sequence.

Potassium and Secondary Nutrients

In long-run CA practices, the distribution of potassium in soils showed vertical stratification in ridge-till plant or flat no-till systems, and due to positional variability of nutrient concentration, while high concentrations in interrow zones, yield-limiting problems could develop (Robbins and Voss 1991). In eastern sub-Himalayan plains soils with low potassium (K), it was seen that under rice-wheat cropping, the soil K was gradually reduced both under CA practices and under conventional tillage practices; however, the degree of reduction was much lesser in CA-based treatments (Mitra et al. 2019; Mitra and Patra 2019). Negative partial nutrient balance for K (up to 90 kg ha^{-1}) was reported in eastern Gangetic alluvial plains under both tillage practices, more so under zero-tillage practices despite retention of crop residues (Sinha et al. 2019). While assessing the soil properties under cereal-based cropping in reclaimed sodic soil of North-West India, it was observed that CA practices increased the availability of K due to additions of a higher quantity of residues having high concentrations of potassium (Jat et al. 2018). We apprehend that K nutrition and its management in crops under CA is not so focussed unlike N and

P. There is an urgent need to give more emphasis on K management in cropping under CA systems keeping in view the ever-decreasing status of the soil.

There were only a few studies available targeting the influence of CA practices on the availability of secondary nutrient elements. In farmlands having conservation practices, there were higher concentrations exchangeable Mg^{++} and Ca^{++} farmlands devoid of conservation practices (Degu et al. 2019). Improved practices relating to soil and water conservation helped to reduce the degree of soil erosion for which exchangeable cations were not leached out (Behailu et al. 2016). Considering the interaction effect of conservation practices and crop rotations, higher exchangeable Ca^{2+} and Mg^{2+} were observed under the rotation comprising maize-fababean-pepper under conservation tillage practices. Crop rotation, as well as conservation tillage, brought about a significant effect in exchangeable K^{+} and relatively high availability of these ions helped to displace Na + from the soil clay complex (Degu et al. 2019).

Micronutrients

There are very limited works on how the availability of micronutrients is influenced by CA practices. Most of the researches have targeted the response of macronutrients, more specifically N, P, and K. In present-day agriculture, micronutrients are playing a vital role in the overall maintenance of sustainability of the system. Climate change and elevated CO_2 concentration in present-day farming may affect food nutrient content and decreasing zinc and iron concentrations in reported particularly in some legumes and cereals (Myers et al. 2014). Under CA practices, altering organic matter content as well as soil reactions may play a crucial role in the availability of various micronutrients also.

Soil copper and zinc did not affect to a significant extent due to variation in tillage practices (Hickman 2002). Again, there were greater concentrations of Zn and Mg under zero-tillage plots in comparison to traditionally tilled plots (Follett and Peterson 1988). Due to low soil pH and increased organic matter, there was a faster rate of conversion of iron and manganese oxides to their exchangeable forms (Shuman and Hargrove 1988). There was a significant reduction in extractable-zinc noted in top 10 cm soil under zero tillage treatment compared to undisturbed grass pasture; though the Mehlich III extractable boron, manganese, zinc, copper, and the iron did not differ with tillage methods (Shiwakoti et al. 2019).The long-term impact of tillage methods on the dynamics of micronutrients are to be studied in detail considering the nutritional aspects of micronutrients in crop-human-livestock systems. The detailed study on changes of nutrient dynamics (both macro- and micronutrients) may reflect the actual feasibility of CA systems in the long run.

26.2.2.4 Cation Exchange Capacity

Cation exchange capacity (CEC) is an inherent soil characteristic of a soil impacts pH buffering capacity, soil fertility, and structural stability capacity, and thus any changes to soil pH or organic matter may influence CEC to a great extent (McBride 1994). Being a character dependent on clay-mineralogy of the soil, CA practices have no direct role in influencing CEC.

Variable changes in CEC due to CA practices have been reported in various studies throughout the globe. In some cases, the CEC is higher due to more organic matter present under CA practices which increase the negative charges (Sa et al. 2009). Ramos et al. (2018) reported that soil organic matter doubles the CEC of tropical soil under no-till farming in Brazil. Again, lower CEC values under CA practices are reported from those soils having a decrease in pH which in turn resulted in lowering of the exchange sites of cation which depends on pH (Sithole and Magwaza 2019). There have been also reports of no change in CEC under CA practices. Crop rotation also has a great role in influencing CEC under CA (Degu et al. 2019).

26.2.2.5 Salinity and Sodicity

The problem of soil salinization can be reduced through CA practices. Minimum traffic in agricultural operations coupled with retention of residues limits the salt movement from lower layers to surface. It is the moderating effect of soil organic carbon added through crop residues in one hand, and in other hand, loss of accumulated carbon is not allowed to get lost through decomposition—these twin effects reduce the electrical conductivity. Again, recycling organic residues reduces the pH through the production of various acids during decomposition which lowers the pH. Devkota et al. (2015) described the management of salinity in soils through bed planting in irrigated production systems of Central Asia. Govaerts et al. (2007) also opined that permanent bed planting reduces sodicity under rainfed conditions with reduced Na^+ in 0–5 cm and 5–20 cm soil layers. Planting in beds provides a better opportunity for salts to get leach down (Bakkar et al. 2010), though Choudhary et al. (2008) reported higher salt accumulation on the top of the beds due to capillary rise. Retention of crop residues as surface mulch may control soil salinity through its effect on evaporation and regulation of salt movement (Qiao et al. 2006).Sayre et al. (2005) emphasized on partial or full retention of crop residues under permanent raised beds in saline tracts. On the contrary, Wilson et al. (2000) reported higher salt accumulation near the surface under zero tillage in rice.

Actually, there are different findings of soil electrical conductivity under various tillage operations as well as under various soil depths. Irrespective of tillage practices, extractable Na increased with soil depth (Franzluebbers and Hons 1996); on the contrary, Du Preez et al. (2001) reported that tillage operations did not have a great impact in altering Na concentrations. This aspect needs to be captured under long-term CA practices to see the actual changes in electrical conductivity as well as Na concentrations.

26.2.3 Conservation Agriculture Influences Soil Microbial Activity

Intensive agricultural practices are essential in developing countries like Bangladesh where agriculture contributes around 13% in the gross domestic product (GDP) of the country. These practices alter soil physicochemical and biological properties for enhancement of productivity from the unit area in a cropping year. Intensive agriculture imposes repeated tillage before the commencement of sowing a crop in each season and thus manipulates soil properties and negatively impacts soil quality (Allen et al. 2011). But it is known that healthy soil is prerequisite to sustainable farm productivity (Rojas et al. 2016; Tahat et al. 2020). Deep ploughing is required after few years in the rice-based cropping system, which is very common in Bangladesh, for breaking off the hard-plough pan (Chivenge et al. 2020), and deep tillage disturbs soil health (Setboonsarng and Gregorio 2017). On the other side, CA with reduced tillage and crop diversification enhances soil quality by improving physical, chemical, and biological properties (Kumar and Babalad 2018). Earlier studies revealed that organic agriculture and strip tillage increased population of soil microbes in watermelon (*Citrullus lanatus*) (Leskovar et al. 2016) and globe artichoke (*Cynara cardunculus*) (Leskovar and Othman 2018). In general, sustainable agricultural system nurtures a complex biological system in which soil flora and fauna interact with plants and maintain healthy ecosystem services. Interestingly, CA improved farmers' livelihood in Bangladesh (Uddin and Dhar 2016).

26.2.3.1 Soil Micro-Fauna and Micro-Flora

Each soil is unique because of its parent material and geomorphological past, living organisms' diversity, and land use pattern (Aislabie and Deslippe 2013). Soils support a diverse range of micro-flora and micro-fauna and shelters 360,000 species of animals (Decaëns et al. 2006). The complex communities of flora and fauna are together commonly also known as soil microbial biomass (SMB). SMB performs various activities favouring different natural cycles, moderation of GHGs emission, ecosystem services, agricultural productivity, and human sustainability (Robinson et al. 2013; FAO and ITPS 2015). Among SBM, mainly bacteria and fungi play a major role in the transformation of nutrients, nutrient uptake by plants, the release of growth promoters, plant health, and crop productivity. Earlier studies revealed that bacteria, *Arbuscular mycorrhizal* fungi (AMF), and beneficial nematodes played a crucial role in improving soil fertility and crop health (Leskovar and Othman 2018; Leskovar et al. 2016). In South African dryland conditions, CA resulted in the maximum activity of microorganisms with richness in terms of diversity (Habig and Swanepoel 2015). CA in Jilin Province of China and noted the presence of more microbial organisms on topsoil of 5 cm depth with no tillage and incorporation of crop residues in black soil; however, microbial metabolic activity was more up to a soil depth of 20 cm (Sun et al. 2016). A study conducted at Indo-Gangetic plains in India revealed that CA-based management with zero tillage in maize-wheat-green gram cropping system recorded enhanced microbial activities in terms of increased SOC, microbial biomass C and N, phosphatase, and β-glucosidase activities compared to conventional tillage (Choudhary et al. 2018a, 2018b). Under the present scenario of climate change, the beneficial role of soil microorganisms should be relooked into for a healthy and sustainable agroecosystem.

Microbial Community Structure

Among SMB, bacteria including Actinomycetes, fungi, algae, and protozoa are plenty in soil and show higher metabolic activities (Verhulst et al. 2010). Each 10 g of soil contains about 1010 bacterial cells (Gans et al. 2005). Another estimate suggested per gram of soil may contain 2000–18,000 number of species of bacteria (Aislabie and Deslippe 2013). Saprotrophic fungi produce enzymes (amylases, proteases, lipases, and phosphatases) and decompose organic matters in soil. Also, saprotrophic fungi take part in the carbon cycle. Mycorrhizal fungi establish symbiotic associations with a wide range of plant roots (Aislabie and Deslippe 2013). Actinomycetes are gram-positive bacteria known to produce different lignocellulolytic enzymes which decompose lignocellulose, the most abundant renewable plant waste biomass present in the soil as crop residue (Bettache et al. 2018). Fungi may attack different soil microorganisms, but generally, mites, nematodes, and larger soil organisms feed on fungi (Stirling et al. 2017). Filamentous saprotrophic fungi decompose organic matter present in soil (Smith and Wan 2019) and nutrient cycling (Averill et al. 2019, Yu et al. 2019). Arbuscular mycorrhizal fungi (AMF) are vital endosymbionts and play an important role because of its symbiotic association with about 90% of plants (Begum et al. 2019). AMF fungi provide support to plants against different biotic and abiotic stresses (Abdel-Salam et al. 2018) and enhance growth (Begum et al. 2019). AMF absorb low mobile nutrients like P, Cu, and Zn and share with plants. Extra radical hyphae of AMF conserve soil and help in the improvement of soil health by aggregation (Posta and Duc 2019). AMF hyphae can accelerate the breakdown of soil organic matter (Paterson et al. 2016). Furthermore, AMF may affect atmospheric CO_2 fixation by host plants (Begum et al. 2019). Crop residues are the energy source for SMB (Hellequin et al. 2018) and in conservation tillage addition of crop residues as organic mulch increase microbial activity on topsoil (Das et al. 2020; Saikia et al. 2020). Due to higher microbial activity, yield of wheat was enhanced with conservation tillage along with more soil microbial biomass carbon and soil dehydrogenase in New Delhi, India (Sharma et al. 2011). Incorporation of wheat straw and green manuring in RW cropping system increased microbial biomass carbon (MBC) under CA in the Indo-Gangetic plains in north-western India (Saikia et al. 2020). In a study, Das et al. (2020) observed that conservation tillage enhanced more available N, P, and K than conventional tillage in upland rice-rapeseed system in the subtropical eastern Himalayas of India. They further commented that conservation tillage along with combined application/adoption of green manuring/weed biomass/in situ rice residue retention enhanced system productivity and soil fertility in terms of SOC, microbial biomass carbon (MBC), availability of nutrients, and dehydrogenase activity (DHA).

In pearl millet-mustard crop rotation under rainfed condition in the semiarid region, zero-tillage and residue retention resulted in higher soil macroaggregate, SOC, and MBC (Choudhary et al. 2018b). A study conducted in the Eastern Ganga Alluvial plains in two districts each of Nepal, Bangladesh, and Bihar and West Bengal in India on CA-based sustainable intensification revealed that zero-tillage crop residue retention and crop rotation enhanced soil organic matter content, SOC, and N content in soil compared to conventional tillage (Sinha et al. 2019). CA practices with zerotillage and minimum tillage were evaluated in the red-brown terrace soil of Bangladesh, and the study revealed that minimum tillage was environment-friendly for maize cultivation (Sayed et al. 2020). Hossain (2019) suggested that for achieving agricultural sustainability in Bangladesh, management of SOM should be considered with top priority in which growing of cover crops, crop rotation, reduced tillage, and conservation of crop residues are to be adopted which are actually CA practices.

Fungal-feeding nematodes are found abundant in top-soil of zero-tilled field (Treonis et al. 2010, 2018). A higher population of nematode is observed under reduced tillage than conventional tillage (Naab et al. 2017; Mashavakure et al. 2018). Beneficial free-living and harmful plant-parasitic nematodes are more in the field where CA practices are adopted including residue management, reduced tillage, and crop rotation (Mashavakure et al. 2018). Inclusion of green manuring or application of manure and organic residues is suggested as a tool against plant-parasitic nematode management because of increase in the population of non-pathogenic free-living nematodes along with other benefits of the organic amendment (Thoden et al. 2011). But CA practices like cover cropping and suitable crop rotation with rich amounts of bioactivity can manage plant-parasitic nematodes (Ntalli et al. 2020).

Microbial Biomass

The SMB ensures a high turnover of soil organic matter, cycling of C, N, P, and S (Ramesh et al. 2019; Cheng 2020) and aggregate stabilization (Wu 2020; Zhou et al. 2020). The corn-soybean and fallow-soybean rotations enhanced soil macroaggregates with greater aggregate suitability and enhancement of SOC on black soils of Northeast China (Zhou et al. 2020). Prommer et al. (2020) mentioned that crop diversity increased soil microbial growth and turnover, crop yield, SMB, and SOC. The SMB gets energy from SOC derived from the decomposition of organic residues (Kallenbach et al. 2016). CA with residue retention increases SMB-C and N in the topsoil layer (Li et al. 2020). A continuous, uniform supply of C from crop residues serves as an energy source for microorganisms (Cherubin et al. 2018). Different soil-borne pathogens are suppressed due to the presence of beneficial SMB (Panth et al. 2020). The beneficial microbes like, *Trichoderma* and *Pseudomonas* species produce growth regulators and phenols which suppress the harmful pathogen population in the soil (Welke 2005). Some of the CA practices are useful for the management of plant pathogen of which crop rotation is well known (Umaerus et al. 1989). Wang et al. (2020) mentioned that sweet potato→winter wheat→summer maize and spring peanut→winter wheat→summer maize resulted in yield and soil quality improvement over the common practice of winter wheat→summer maize crop rotation. They noted the inclusion of either sweet potato or spring peanut in crop rotation increased SOC, total nitrogen, available phosphorus, alkaline phosphatase, and urease activity after 2 years of crop rotation. Balota et al. (2003) revealed that a greater quantity of C immobilized in microbial biomass under zero tillage than conventional tillage. But residue management had a greater impact than reduced tillage in terms of SMB carbon and nitrogen levels in the topsoil layer of 0–10 cm in maize-based cropping system (Spedding et al. 2004); however, Alvear et al. (2005) observed in zero tillage more of SMB-C and N at a soil depth of 0–20 cm compared to conventional tillage in ultisols of southern Chile.

Functional Diversity

Functional diversity is the sign of healthy soil assuring better ecosystem services (Coker et al. 2019) and soil organisms interact with the biological, atmospheric, and hydrological systems (FAO 2015). CA practices with residue retention on soil enhanced functional diversity (Tang et al. 2020b); however, conventional tillage reduced it (Capelle et al. 2012). Tang et al. (2013) demonstrated that crop residue inclusion increased diversity of soil microbial activities in maize-winter wheat-soybean cropping system at Loess Plateau in Western China. However, Tang et al. (2020b) noted that rice-based cropping system, the combination of zero tillage, and retention of crop residue increased microbes community functional diversity. SMB shows sensitivity to tillage and no-tillage enhanced microbial activity and metabolic functional diversity in southwest China; however, conventional tillage deteriorated suitable micro-environment for microbes and reduced SMB (Xiao et al. 2019). A long-term trial in temperate Switzerland clearly revealed that reduced tillage increased SOC in topsoil and SMB compared to conventional ploughing (Krauss et al. 2020).

Enzyme Activity

Soil enzymes have a significant role in facilitating the decomposition of organic matters and cycling of nutrients (Heidari et al. 2016). CA practices like crop rotation and cover crop, residue management, and tillage positively impact on activities of soil enzymes (Hinojosa and Strauss 2020; Niewiadomska et al. 2020). Mangalassery et al. (2015) observed that zero tillage enhanced 9% more soil C and higher microbial enzyme activities than tilled soils because of the presence of more organic residue, and they observed that enzymes like cellulose, β-glucosidase, dehydrogenase, peroxidase, and oxidase were more with zero-tilled soil in the temperate region. Soil enzymatic activities are closely related to COC and no tillage favoured the building of SMB and SOC which enhanced enzymatic activities under soybean-based cropping system in Iran (Heidari et al. 2016). Roldán et al. (2007) observed greater activities of dehydrogenase and phosphatase in the topsoil layer with zero tillage on a Vertisol. Similarly, Niewiadomska et al. (2020) observed that different soil enzymatic activities were increased with reduced tillage options with cover cropping in wheat and dehydrogenase, and phosphatase activities were enhanced by 90% and 32% over conventional tillage. But Janušauskaite et al. (2013) reported that tillage intensity enhanced urease activity, however, negatively influenced dehydrogenase activity. Ji et al. (2014) noted that SMB and enzymatic activities were reduced with increase in depth of soil tillage, and returning of straw enhanced both the SMB (0–30 cm) and activities of enzymes (0–40) cm soil depth in Henan Province, China.

Soil-Borne Diseases

Tillage has a great impact on soil-borne pathogens that create diseases and tillage influence soil-borne pathogen dynamics in various ways. In CA, residue retention further causes a suitable environment for soil microbiome inclusive of beneficial organisms and harmful pests. Residues are considered as food material by pathogen, and they infect the next crop. Formation of different fungal spores is very common on partially decayed organic residues. Under residue retention and followed by zero-tillage conditions, these pathogens infect the roots of the next crop in a cropping system very easily (Cook 2006). The common root pathogens are by *Gaeumannomyces graminis*, *Rhizoctonia solani*, *Pythium* sp., *Fusarium* sp., *Bipolaris sorokiniana*, and so on. *Rhizoctonia solani* Kühn causes establishment and yield losses in many field crops including wheat (*Triticum aestivum*), oilseed rape (*Brassica napus*), field pea (*Pisum sativum*), potato (*Solanum tuberosum*), and rice (*Oryza sativa*) (Nadarajahet al. 2014; Sturrock et al. 2015). Disease caused by *Pythium* is commonly known as root rot or damping off, and seedlings of different crops, mainly flowers and vegetables, are largely affected in the nursery or at the seedling stage. The symptoms are quite diverse based on age and host plants. Generally, wet lesions of brownish colour appear on roots which may reach to stem base and cause decay. The affected plants wilt and die quickly (Blancard 2012). Disease caused by *Gaeumannomyces graminis* is commonly known as a take-all disease which is a pernicious pathogen of wheat. The common symptoms of the take-all disease are root rot with black or chocolate-coloured lesion, yellowing, stunted growth, and nutrient deficiency, and when the stem is infected, water flow is disturbed causing plant death (Kwak and Weller 2013). *Fusarium* sp. attacks several plants including cereals (Chetouhi et al. 2016), fruits (Thangavelu et al. 2004), and vegetables (Coleman 2016; Askun 2018). The disease symptoms appear as per the species and host specificity. The pathogen *Bipolaris sorokiniana* affects mainly wheat and barley (Gangwar et al. 2018) and causing seedling blight, root rot, black point, head blight, and leaf spot.

Some contradictory results were noted in favour and against of reduced tillage in the expression of soil-borne diseases. Diseases of wheat like *Rhizoctonia* and *Pythium* root rot and take-all incidence were more in reduced tillage (Schroeder and Paulitz 2006). Similarly, Moore and Cook (1984) earlier mentioned that there are more incidences of *Gaeumannomyces graminis* with zero tillage compared to conventional tillage, but Bailey et al. (2001) reported low occurrence of take-all disease under zero tillage. *Rhizoctonia* incidence in wheat was associated with zero tillage as mentioned by Smiley et al. (1996), but Schillinger et al. (1999) stated that there was no difference between tillage methods in infection of *Rhizoctonia*. Later results also suggest that *Rhizoctonia* incidence was not influenced by tillage differences (Sharma-Poudyal et al. 2017). There are beneficial microorganisms in soil which can suppress the population of disease-causing pathogens (Panth et al. 2020), and CA increases SMB inclusive of beneficial organisms that control pathogens biologically (Jacoby et al. 2017). *Pseudomonas poae*, *Pseudomonas putida*, *Pseudomonas syringae*, and *Pseudomonas vranovensisare* are known to suppress diseases like *Rhizoctonia oryzae* and *Pythium irregular* (Mavrodi et al.

2012). Different soil-borne *Actinomycetes* produce metabolites useful in the production of antibiotics (Vurukonda et al. 2018). There are beneficial fungi that can control harmful soil organisms (Panth et al. 2020). Further, CA with reduced tillage, cover crops, and organic amendments enhance the population of natural enemies of plant-parasitic nematodes (Timper 2014), and the presence of sufficient free-living nematodes are considered as indicators for healthy soil (Gebremikael et al. 2016). *Trichoderma* species can control root-knot nematodes (*Meloidogyne* spp.) efficiently (Sharon et al. 2011). Some important biennial microorganisms in suppressing soil-borne diseases are listed below (Table 26.1).

26.2.3.2 Soil Meso-Fauna and Macro-Fauna

Soil meso-fauna are comprised of micro-arthropods, micro-fauna, and other invertebrates. In soil, they feed on organic materials by facilitating the decomposition of organic residues in the soil. Macro-fauna are vertebrates and invertebrates inclusive of mainly snails, soil arthropods, and earthworms and the feed on soil litter helping decomposition of organic wastes, cycling of nutrients, and SOM dynamics in the agricultural and natural system. The most important soil meso- and macro-fauna are springtails, mites, epigeic worms and earthworms, millipedes, isopods, myriapods, and insect larvae to take part in soil biological activities and influencing soil biological properties (Sofo et al. 2020). In CA, soils are less disturbed, and crop residues are managed; therefore, soil meso- and macro-fauna get suitable habitat (Bedano and Domínguez 2016). They generally convert soil litter and influence soil aggregation and structure.

Meso-Fauna

In a multi-locational trial conducted in Kenya, Ayuke et al. (2019) observed different types of results of CA. At Kakamega site, they noted *Collembolan* group of meso-fauna population was higher in the CA compared to conventional practices, and at Nyabeda, *Symphyla* group was more. But at Embu, there was no significant impact of CA practices like tillage, organic residue application, and crop management on soil meso-fauna. Studies showed that *Springtails* population was reduced by tillage disturbances (Miyazawa et al. 2002); however, some studies revealed that opposite or no effect of tillage (Reeleder et al. 2006). Pfingstmann et al. (2019) reported contrasting results of spider density with tillage variations in Austria. They noted unaffected spider activity with a less family diversity of spiders under periodically disturbed soils; however, springtail diversity remained unchanged by tillage. Some researchers noted periodic soil tillage increased spider diversity (Roger-Estrade et al. 2010). Further, Pfingstmann et al. (2019) stated that under permanent green cover, springtail was also higher. Tillage operations had great negative impact on some soil mites as the reduced population of mesostigmatid, prostrigmatic, and cryptostigmatid mites was mentioned by Verhulst et al. (2010). Another important soil meso-fauna is enchytraeids, and the population of this worm is either inhibited or stimulated by tillage operations (Sylvain and Wall 2011; Mccormack et al. 2013).

Table 26.1 Beneficial soil-borne microorganisms used as bioagents for controlling soil-borne pathogen (Adopted from Khan et al. 2019, Panth et al. 2020 and other sources listed)

Beneficial microorganism as bioagent	Pathogen	References
Glomous species (*Glomus mosseae*, *G. monosporum*, *G. etunicatum*, *G. aggregatum*, *G. intraradices*)	*Meloidogyne hapla* *Fusarium oxysporum* *Pythium delicense* *Fusarium lycopersici*	Cooper and Grandisons (1986), Reddy and Locke (1998), Pozo et al. (1999), Matsubara et al. (2002), Leta and Selvaraj (2013), Shukla et al. (2015), Al-Hmoud and Al-Momany (2015)
Gigaspora margarita and *G. fasciculatum*	*Fusarium oxysporum*	Matsubara et al. (2001)
G. mosseae	*Phytophthora capsici*	Ozgonen and Erkilic (2007)
G. aggregatum and *T. harzianum*	*S. cepivorum*	Leta and Selvaraj (2013)
Funneliformis mosseae	*Alternaria solani*	Song et al. (2015)
F. mosseae	*Fusarium oxysporum f.* sp. *Ciceris*	Shukla et al. (2015)
R. irregularis	*Fusarium oxysporum f.* sp. *Ciceris*	Shukla et al. (2015)
Bacillus spp. (*B. subtilis*, *B. amyloliquefaciens*, *B. firmus* and *B. pumilus*)	*Pythium* spp., *Fusarium* spp., *Rhizoctonia solani*, *Aspergillus flavus*	Pertot et al. (2015) Shafi et al. (2017)
Coniothyrium minitans	*Sclerotinia sclerotiorum* and *S. trifoliorum*	Pertot et al. (2015)
Gliocladium catenulatum	*Species of Rhizoctonia*, *Pythium*, *Phytophthora*, *Fusarium*, *Didymella*, *Botrytis*, *Verticillium*, *Alternaria*, *Cladosporium*, *Elminthosporium*, *Penicillium*, and *Plicaria*	Pertot et al. (2015)
Phlebiopsis gigantea	*Heterobasidion annosum*	Pertot et al. (2015)
Purpureocillium lilacinum QLP 12 (previously Paecilomyces lilacinus)	*Verticillium dahliae*, *R. solani* and *nematodes*	Lan et al. (2017)
Pseudomonas spp.	*Pythium* spp. *R. solani*	Pertot et al. (2015)
Pythium oligandrum	*Species of Alternaria*, *Botrytis*, *Fusarium*, *Gaeumannonyces*, *Ophistoma*, *Phoma*, *Pseudocercosporella*, *Pythium*, *Sclerotinia*, and *Sclerotium*	Pertot et al. (2015)

(continued)

Table 26.1 (continued)

Beneficial microorganism as bioagent	Pathogen	References
Streptomyces spp.	*Species of Fusarium*, *Rhizoctonia*, *Phytophthora*, *Pythium*, *Phytomatotricum*, *Aphanomyces*, *Monosprascus*, *Armillaria*, *Sclerotinia*, *Verticillium*, *Geotrichum*	Pertot et al. (2015)
Trichoderma spp. (*T. atroviride*, *T. asperellum*, *T. harzianum*, *T. viridae*, *T. gamsii* and *T. polysporum*)	*Trichoderma* spp. (*T. atroviride*, *T. asperellum*, *T. harzianum*, *T. viridae*, *T. gamsii*, and *T. polysporum*)	Pertotet al. (2015)

Macro-Fauna

Soil macro-fauna are highly delicate to agroecosystem management, and CA plays a great role in population dynamics of the large organism (Ayuke et al. 2019; Sofo et al. 2020). Conventional tillage destructs favourable habitat of macro-fauna, and the population is reduced (da Silva et al. 2016). However, reduced or no tillage with residue management help in building up the population of soil macro-fauna due to greater biomass incorporation (Yadav et al. 2017; Page et al. 2020). In the case of earthworms, functional diversity, as well as abundance, is enriched by CA (Castellanos-Navarrete et al. 2012). Earthworms create burrows modifying soil structure, infiltration, and drainage of water, mix organic matter, form humus, and modify nutrient dynamics, decrease erosion, and favour microbial activity (Yadav et al. 2017). Adoption of CA practices resulted in earthworm activity in the soil leading to agricultural sustainability (Bertrand et al. 2015). Not only tillage but also residue management and mulching plays a great role in population build-up of earthworms in the soil, because earthworms prefer enough moisture (Verhulst et al. 2010). Termites and ants are also important macro-fauna in soil transformation. Evans et al. (2011) observed that ants and termites increased crop yield in a dry climate in Australia by enhancing water infiltration and mineral N in the soil.

26.3 Challenges for Expansion of Conservation Agriculture in Bangladesh

Conservation agriculture (CA) is a part of good agricultural practices (GAPs) worldwide which is being adopted on more than 147 million ha area (Kassam et al. 2015). CA is an approach to managing agroecosystems for improved and sustained productivity, increased profits, and food security. CA is not a prescriptive approach and business as usual but is a scientific response to the questions of sustainability that agriculture is facing today. The major countries practicing CA are the USA, Brazil, Argentina, Canada, and Australia and sharing about 90% of its areas. Although the importance of CA has been increasingly recognized, the adoption rate in South Asia including Bangladesh is less. South Asian countries cover around 5.0 million ha under conservation tillage mostly in the rice-wheat system. Although the adoption rate of CA is low in Bangladesh, however, farmers are accepting the concept of CA-based tillage technologies considering the advantages of the reduced cost of tillage operation, saving irrigation water, and minimum turnaround time between the crops (Hossain et al. 2015). In Bangladesh, Barma et al. (2014) revealed that rice, wheat, maize, pulses, oilseeds, and jute can be established and grown successfully using CA technology. Furthermore, as Bangladesh having a network of 320 rivers, soil erosion in their command catchments represents a threat to food security. In this direction, CA is one of the most important ways forward to address the emerging issues and future challenge of climate change and resultant effects of floods, droughts, salinity, and acidity. Bangladesh is dominated by rice-based cropping systems, the most predominant of which are rice-rice, rice-wheat, rice-maize, and rice-lentil. The traditional farming mindset, small farm-holdings, non-availability of suitable machinery, policy and institutional barriers, socioeconomic conditions, weed and residue management, and lack of sufficient skilled manpower on CA are key challenges to the low adoption of CA practices in Bangladesh.

26.3.1 Mind Set-Up and Social Barriers

Mindset is one of the major possible reasons in the adoption of conservation agriculture by farmers. CA systems are much more complex than conventional systems and require additional management skills. Farmers may often fear lower crop yields and/or economic returns, negative attitudes or perceptions such as lack of knowledge, challenges in weed and crop residue management, retention of crop residue invites pests and diseases, the money required for residue clearing, etc. (Lal 2007). Farmers often prefer to neat and clean fields vis-a-vis untilled shabby-looking fields. Furthermore, pest infestation, particularly termites and rodents, under residue-retained CA fields are a major farmer concern. In addition, high agricultural officials are not much favour on CA technologies, and research–extension−farmers' linkage is not well established about these technologies transfer. The barrier of mental change remains the main obstacle to the diffusion of this new approach in agricultural practices.

26.3.2 Small Farm-Holding

Farm size has been an important determinant to adopt many agricultural practices including CA. In Bangladesh, more than 80% farmers are smallholders having land less than 1.0 ha. In order to feed the increasing population of Bangladesh, priority is given to produce more food through intensification of land usage (Akteruzzaman et al. 2012). It is very difficult to operate CA machinery to small-size lands which are fragmented by many dykes. Besides, smallholder farmers always give priority to grow their staple foods, e.g. in Bangladesh, farmers always prefer to grow rice because of the food demand of their family; therefore, crop diversification is difficult here.

26.3.3 Suitable Machinery

One of the major constraints to adoption of CA is the availability of suitable cost-effective machinery affordable by farmers (Lal 2007). The machinery for sowing, transplanting, fertilizer application, and harvesting that require least soil disturbance and manage crop residue well under different soil conditions is the key to the success of CA. The available CA implements like turbo seeder, happy seeder, laser land leveller, etc., which are useful for CA practices, need high-horsepower (>50 hp) tractors for better functioning in field conditions. Also, these implements are very complex as well as expensive for a farmer to purchase. Hence these are not suitable for small and marginal farmers with small landholdings as they cannot afford to procure such equipment. Available machineries for RCTs are expensive and not available locally, and low prices of agricultural produce discourage investments in agriculture, including machines and tools. Furthermore, many times farmers lack skills to operate the implements, local artisans, and machinery manufacturers for repairing and maintenance are not available. Quality machinery is also important, farmers started to adopt zero-till wheat or strip-till wheat and direct-seeded rice using PTOS in Bangladesh, but this machine does not work smoothly in the field; therefore, farmers and LSPs are becoming demotivated from the PTOS as a seeding purpose.

26.3.4 Site Specificity and Land Suitability

Adapting strategies for CA systems are greatly site specific. It is not possible to apply all CA principles in all sites, e.g. some rice-rice cropping systems in Bangladesh rice residue retention is possible even sometimes when the field remains wet during rice harvesting time, farmers keep some extent of residue in the field. From these fields, non-puddled rice is possible, but crop rotation or diversification is difficult. The land is suitable for non-rice crops especially wheat, lentil, mustard, maize in rabi season, and rice (*aus* rice) in karif-1 season, and rice (*aman* rice) in kharif-II may be more suitable for CA practices. In Bangladesh, currently, there is no specific cropping zone; therefore, farmers frequently change the rabi crops based on the prevailing market price of the crops. Farmers usually don't do this to maintain one of the principles of CA (crop rotation), but this is happening in some areas automatically. In Bangladesh, current growing areas of wheat, maize, lentil, and mustard are highly suitable for CA practice but need to consider them appropriate crop zones.

26.3.5 Policy, Extension Systems, and Institutional Barriers

The policymakers of Bangladesh often are not aware of the relevance of CA as a basis for sustainable intensification; hence, many existing policies work against the adoption of CA (FAO 2001). There is no policy support available for scaling out of CA in the country. Appropriate policies for technology adoption, production, and supply of machineries/equipment and institutional support are prerequisites for promotion of CA practices across different agroecologies. For example, organic farming v/s CA, zero tillage v/s rotavator misleads the policymakers even for farmers. Policymakers should understand the advantages of CA to enable them to frame supportive policies and specific strategies with action plans for the promotion of CA. There are cases where countries have legislation in place which supports CA as part of the programme for sustainable agriculture. Poor extension systems and limited capacity and weak public-private partnership and poor coordination between research, extension, and private sector are also the reason for its low adoption.

26.3.6 Level Land

A properly levelled land with the required inclination based on the irrigation method is required for getting the actual benefit of CA practices. In traditional farming practices in Bangladesh, the methods of levelling land by eyesight are not precise particularly on larger plots and lead to undulating land and inefficient water use and poor crop stand if grown in CA practice (especially direct-seeded rice). The recent development of laser levelling, the levelling off the field, is done up to ±2 cm, resulting in better water application, distribution efficiency, improved water productivity, better fertilizer efficiency, and reduced weed pressure. Hence the laser-guided equipment for the levelling of surface-irrigated fields is more economically feasible. In this method, there is saving of water up to 50% and 68% in wheat and rice, respectively (Jat et al. 2009). Laser land levellers are not available in Bangladesh which can help to accelerate the CA practices by providing the full irrigation savings in these systems.

26.3.7 Weed Problem and Yield Reduction

The high weed infestation is the major challenge of large-scale adoption of CA practices and poor weed control is one of the major reasons resulting in lower yields in these systems. Weed management is one of the main bottlenecks in CA systems reported from the many previous studies (Chauhan et al. 2012; Ahmed et al. 2014). In conventional systems, fine tillage operations help to suppress weeds; therefore, weed pressure is usually less. However, under CA, weed pressure starts at the very beginning of the crops and is largely controlled by chemical methods using herbicides (Chauhan et al. 2012; Ahmed and Chauhan 2014). Herbicides are the low cost and very efficient weed management tools in the current agriculture practice where labour is no longer available for manual weeding or need to pay a higher cost. Although herbicides are must in a CA system but its judicial use is important otherwise, the development of herbicide-resistant weed species and weed shift by continuous application of herbicides are the major challenges in adoption of CA. Therefore, herbicide-based integrated weed management is important for CA systems. Some studies show that eliminating tillage sometimes increases weed pressure in the early years of CA adoption, but weeds decrease over time if controlled well. During the transition phase of CA, there is a fear of loss of productivity in the initial years. CA practices, e.g. no-tillage and surface-maintained crop residues, result in resource improvement only gradually, and benefits come about only with time. Indeed in many situations, benefits in terms of yield increase may not come in the early years of evaluating the impact of CA practices. Therefore, research in CA must have longer-term perspectives which are another challenge to adoption in Bangladesh.

26.3.8 Crop Residue Management

Residue retention is also an important component of CA; however, rice, wheat, and maize straw are usually removed from fields in Bangladesh at harvest for use as fodder, fuel, and building materials. Although sowing of crops in the presence of residues is a problem, special types of seeder machine such as zero-till seed-cum-fertilizer drill/planters such as happy seeder, turbo seeder, rotary-disc drill are needed. In dryland ecosystems, where only a single crop is grown in a year, it is possible to grow a second crop with residual soil moisture in the profile under conservation agriculture with soil cover with crop residues, but with the intensive cropping systems in Bangladesh, it is difficult to maintain. In Bangladesh, crop and livestock productions are closely integrated with mixed farming systems. A crop residue, particularly cereal stover, provides high-value fodder for livestock here. Indeed, the feed is often in critically short supply; the majority of farmers in Bangladesh used to remove a portion of crop residues for animal feed or household fuel and also burn the surplus crop residues for preparing fields for the succeeding crop (Sarkar et al. 2018). In addition, the lack of appropriate crop harvesting with residues maintained on the soil surface is also a challenge for retaining crop residue.

26.3.9 Skilled Manpower on Conservation Agriculture

CA is complex, knowledge-intensive, and a relatively new concept; therefore, problems can arise for which locally based experience and knowledge do not exist. In Bangladesh, adequate skilled scientists and trained extension workers in CA are not sufficient to strengthen this technology. To train farmers on this knowledge-intensive technology, extension workers need new skills and management strategies. Growing more weeds in case of zero and/or minimum tillage and lack of available information about weed management especially herbicide at block level are the major problems hindering conservation agriculture practice. The academic curriculum, especially in agricultural universities and the CA courses, is not adequately developed.

26.4 How to Overcome the Challenges of CA for Sustainable Crop Production System?

- Capacity building and training: Creating awareness of CA among all the stakeholders; the researcher and extension workers must work with farmers to popularize the technologies for mass-scale adoption.
- CA needs to be implemented through a community approach, and each community consists of at least 20–30 farmers. Large plot demonstrations should be conducted in CA.
- Identify major cropping systems and crop rotations which could be best matched for conservation agriculture in different agroecological zones.
- Dry-direct-seeded rice for aus and aman, non-puddled transplanted rice for all three seasons, zero-till or strip-till wheat, zero-till maize, relay mustard, relay wheat, zero-till lentil, and mung bean may be promoted as a CA practice.
- To encourage private sector investment scaling up these technologies for the end users.
- Development, standardization, and adoption of farm machinery suitable for CA.
- Supplying machineries for CA on subsidized rates, promoting custom hiring systems and providing soft loans to marginal and small farmers and local service providers for purchase of implements would swiftly expedite the adoption of CA technologies.
- Farm machinery manufacturers should be given credit at a low-interest rate and without custom duties on raw materials. Provision should be made for subsidies on machinery purchase by the farmers. The government should give priority to promote agricultural mechanization to address the high production cost and labour scarcity. Farm mechanization with power tiller for small landholders should be promoted. Laser land levelling should be promoted on a large scale.
- Service centres, spare parts, repairs, etc. locally should be developed and generate a database of the network of local service providers and build their capacity.
- Developing gender-friendly multi-task machinery suitable for low-horsepower tractor capable of sowing, harvesting, chopping, windrowing, and spreading of straw for uniform distribution of crop residues.
- Government policies to support the spread of these research results and to support widespread access to machinery and appropriate training are important for adoption of these technologies. In addition, there is a need for strong policy for existing crop residue burning problems at farms, it is better to have a partnership with the agencies who advocate biochar technology.
- It is essential to review the present land use policy with the relevant experts, professionals, and farmer's representatives and update it based on their comments and suggestions.

- There should be a strong policy for existing crop residue burning problems at farms, it is better to have a partnership with the agencies who advocate biochar technology.
- Developing suitable crop varieties for CA systems, e.g. anaerobic rice cultivars for direct-seeded rice, drought-resistant varieties, etc.
- Yield reduction can be overcome if pest and weed infestation is monitored and managed effectively using integrated pest management along with residue retention and crop rotation.
- A core group of scientists, farmers, extension workers, and other stakeholders working in partnership mode will, therefore, be critical in developing and promoting new technologies.
- Relay cropping of mung bean in wheat and mustard and wheat in aman rice in waterlogged areas need to be increased.
- Where competition for crop residue use is strong, intercropping with grain legumes can be a viable strategy to achieve surface cover because the legume will cover the area between rows of the main crop and help conserve moisture.
- Using cover crops like sesbania, dhancha, etc. to suppress weed growth and subsequently killed those using selective herbicides.

26.5 Conclusion

In this chapter, we have shown that in order to meet the growing food security of an increasing population, farmers rely on the imbalanced use of chemical fertilizers and pesticides which degrade the ecological balance and soil fertility, particularly in rice-based cropping systems in South Asia. In rice production, the traditional repeated compaction (puddling) prior to transplanting creates a hard layer (i.e. a plough pan) in the root zone of crops which increases soil compaction and reduces hydraulic conductivity, macroporosity, and the proportion of water-stable aggregates in the soil, all of which impede the growth and yield potential of subsequent crops. Practices such as conservation agriculture, which are climate-smart, have the potential to sustainably increase cropping system productivity and profitability, enabling farmers to use the wealth of natural resources in South Asia while preserving the environment. Here we have highlighted the important consequences of and prospects for CA in rice-wheat cropping systems in the Eastern Gangetic plains region of South Asia. We have demonstrated that CA options must be targeted to farmers' specific socioeconomic and agroecological conditions and must be flexible and adaptive. The major limitation of conservation agriculture is a lack of nuance, and options need to be tailored to be location-specific, community-specific, and agroecological-specific. The success or failure of the uptake of conservation agriculture depends greatly on the flexibility and creativity of the extension and research services of a region in their approach to enabling farmers to take up the practices. Further CA research should include the development of multi-disciplinary multi-stakeholder partnerships to better facilitate CA adoption and dissemination. A strong collaborative network is needed between scientists, extension workers, farmers, and policymakers to tailor CA technologies according to local conditions.

Conflict of Interest Authors declare no conflict of interest.

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27

Conservation Agriculture-Based Sustainable Intensification to Achieve Food, Water and Energy Security While Reducing Farmers' Environmental Footprint in the Eastern Gangetic Plains of South Asia

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Abstract

Traditional rice-based crop production in the Eastern Gangetic Plains (EGP) region of South Asia are energy, water, and labor intensive and inefficient, with relatively low productivity and profitability. Additionally, crop management in these systems typically does not consider the emission of CO_2-equivalent greenhouse gases, which is often relatively high. The EGP is currently a highly impoverished region, but it has natural resources sufficient to become a leading food-producing region in South Asia. Conservation agriculture-based sustainable intensification (CASI) crop management practices improve crop productivity and profitability while reducing energy, water and labor requirements, and

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greenhouse gas emissions. The introduction of CASI practices within villages and districts of the EGP provides opportunities for farming households to sustainably diversify and/or intensify their crop production. It also enables the micro-entrepreneurship and employment opportunities within rural communities.

In on-farm experiments, we compared the performance of traditional and improved management practices in rice-based cropping systems. We found that CASI management practices improved crop grain yields by up to 10% and reduced labor demand by up to 50%, while increasing water productivity (up to 19%) and energy productivity (up to 26%). Combined, these results reduced the cost of crop production under CASI by up to 22% compared to traditional practice, and increased gross margins in general by 12–32%. Concurrently, CO_2-equivalent emissions from CASI management were lower than those from traditional management by between 10% and 17%.

The method of implementing and testing CASI management practices was important: this participatory research was embedded within existing farmer support groups, which served as hubs to support collaborative participatory research and to connect farmers and researchers with other important stakeholders as needed. An actively enabling policy environment was necessary to support CASI uptake and to facilitate outscaling at scale outside research areas.

Keywords

Cropping systems · Eastern Gangetic Plains · On-fam participatory trials · Zero-tillage · Systems crop, water and energy productivity · Trans-national boundaries · Community based business models · Capacity building

27.1 Introduction

The Eastern Gangetic Plain (EGP) region in South Asia includes much of Bangladesh, the eastern Nepali Terai region, and the Indian states of Bihar and parts of West Bengal, Assam and Uttar Pradesh. This region is home to almost half a billion people and has the world's highest density of rural poverty (Ericksen et al. 2011). While current agricultural production under traditional management methods is relatively low, the EGP has the edaphic, climatic, and hydrologic capacity to become a major food-producing region within South Asia (Timsina et al. 2010).

Traditional practice in the EGP is to produce two crops annually: a predominantly rainfed wet season rice crop followed by an irrigated dry season crop, usually of wheat or rice or perhaps lentil or oilseeds. Recently, farmers have become more willing to cultivate maize, which is newly emerging as a profitable crop and a viable alternative to irrigated dry season rice and, to some extent, to wheat and pulses in the EGP. In both seasons, prior to sowing, the soil is tilled multiple times, before rice crops are also puddled. Rice seedlings are manually transplanted, while other crops are largely established through broadcasting or manual dibbling. Weed management is largely through land cultivation and manual removal; standing water is also used to suppress weeds in rice crops. Irrigated rice requires high amounts of water: both rice and wheat crops are energy intensive, needing diesel or electricity for land preparation and, in the dry season, to pump water. These crop production methods are also labor intensive, particularly transplanted rice, and maize which is manually dibbled. Wheat grown in the EGP is vulnerable to late-season heat stress, particularly if sowing is delayed following the late finish of a rice crop whose establishment depends on the timely (or not) arrival of monsoonal rains.

Alternative crop establishment practices which promote minimal or no tillage are likely to improve soil structure and health, reduce crop energy and water demands, and reduce greenhouse gas emissions (Alam et al. 2015; Gathala et al. 2013, 2016; Hossen et al. 2018; Laik et al. 2014). Conservation agriculture-based sustainable intensification (CASI) encourages, as far as possible for smallholder farmers, the adoption of no or minimum tillage, combined with mechanized crop establishment, maintenance of ground cover, crop rotations and diversification, improved nutrition management, and reduces the demand for human labor (Kassam et al. 2018). Across the EGP and South Asia, more generally previous research has demonstrated the benefits of reduced/no-tillage crop establishment in terms of cropping system productivity, energy and water efficiency, and economic profitability (Ladha et al. 2015; Padre et al. 2016; Kumar et al. 2018; Hossen et al. 2018; Islam et al. 2013; Alam et al. 2015; Gathala et al. 2016; Laik et al. 2014). However there has been little large-scale research to date about the potential benefits of CASI itself across the greater EGP region.

As well as improving cropping system productivity and profitability, CASI provides additional benefits which boost rural households' economic growth while respecting local social and cultural norms (Fig. 27.1). The improved agronomic

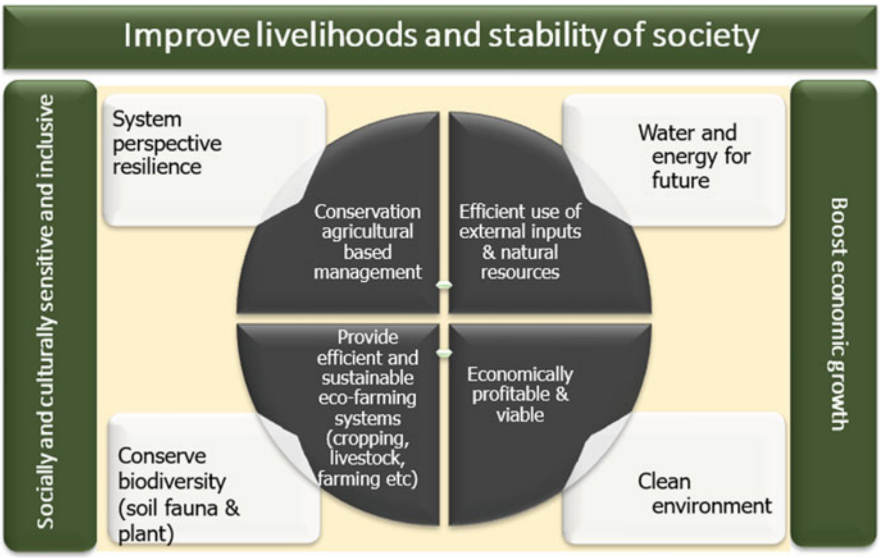

Fig. 27.1 The widespread benefits of conservation agriculture-based sustainable intensification

management practices increase cropping system resilience and ability to withstand climatic shocks, while more efficient use of energy and water resources and nutrients reduces waste and contributes to a healthier environment, with reductions in greenhouse gas emissions from agriculture (Gathala et al. 2018, 2020a; Padre et al. 2016; Ladha et al. 2015). CASI also contributes to improve soil health and to improve biodiversity and sustainable agricultural ecosystems (Choudhary et al. 2018a, b; Jat et al. 2018a, b; Jat et al. 2019a, b). These benefits from CASI improve rural households' livelihoods and contribute to stable societies (Gathala et al. 2018; Aryal et al. 2016). Implementation of CASI within communities provides opportunities for micro-entrepreneurs and emerging small businesses to deliver agrochemicals and mechanization-based agricultural services in their local communities.

Under CASI, crops are established under mechanization without prior tillage: rice is either direct seeded (DSR) or transplanted unpuddled (UPTR), while other crops are directly sown into the soil. This research compared the effects of CASI crop management against conventional tillage (CT) practices in eight districts across the EGP in the common rice-wheat (RW) and rice-lentil (RL) cropping systems, and to a lesser extent in rice-rice (RR) systems. We also examined the effects of CASI in the emerging rice-maize (RM) cropping system and in two systems intensifying the RW system: rice-wheat-jute (RWJ) and rice-wheat-mungbean (RWMb). We hypothesized that the CASI management practices of crop establishment, management, diversification, and intensification would outperform CT crop management practices in terms of cropping system productivity, water, energy and labor usage, production economics, and CO_2-equivalent greenhouse gas emissions.

Here we summarize the results of field trials conducted on over 430 farms at 8 distinct regions throughout the EGP. We report the effects of CASI practice in terms of cropping system productivity and profitability, and in terms of food, energy, and labor requirements, compared to a conventional practice baseline. We examine the benefits for cropping systems which are widespread and common currently across the EGP, and for those cropping systems which enable farmers to intensify and/or diversify their crop production. We report on capacity-building activities undertaken as part of the research and summarize our learnings, including the conditions necessary to facilitate the widespread uptake of CASI practices across the EGP, including key support required by policymakers. The learnings from this study are not only relevant to the EGP but also demonstrate the potential value of CASI crop management in many emerging-economy countries worldwide.

27.2 Materials and Methods

27.2.1 On-Farm Trials Across the EGP

We conducted on-farm trials in RW, RM, and RL cropping systems over 3 years between 2015 and 2018. Trials were conducted across the EGP in eight districts across three countries: Coochbehar and Malda in West Bengal and Madhubani and

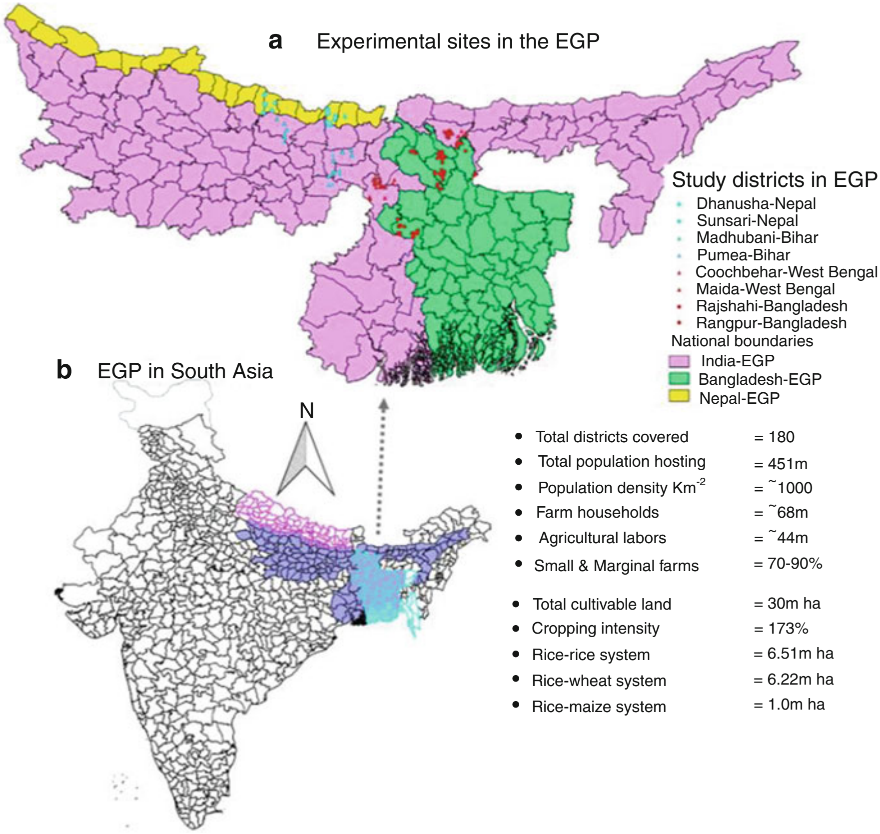

Fig. 27.2 (**b**) An approximation of South Asia (**b**) showing the boundaries of India (light gray), Nepal (pink), and Bangladesh (aqua blue) with the EGP (light purple); (**a**) the EGP showing experimental sites in Bihar (blue triangles), West Bengal (red triangles), Nepal (blue circles), and Bangladesh (red circles). Derived from Gathala et al. (2020b)

Purnea in Bihar, India; Rangpur and Rajshahi in north-western Bangladesh; and Dhanusha and Sunsari in Nepali Terai (Fig. 27.2). Weather, soil, and hydrological characteristics for the trial sites are shown in Islam et al. (2019), as is a detailed description of the experiments, which are here summarized.

Two-hundred and thirteen (213) farmers participated in RW system trials, which were conducted in all 8 research districts, while RM trials were conducted with 129 farmers in 6 districts, and RL trials with 44 farmers in 4 districts. The large numbers of participants in these trials mean that statistical analysis of the output data has great strength and rigor. We also conducted a small number of trials whose results are indicative only: 24 farmers conducted RWJ trials in 2 districts, while 23 farmers conducted RWMb trials in 2 districts, and 3 farmers conducted RR trials in 1 district.

Experimental trials compared traditional conventional tillage (CT) practice to partial and full CASI management practices. In CT practice, rice is transplanted into tilled and puddled fields; this is followed by further tillage and then broadcast wheat or lentil crop, or a manually sown maize crop. In partial CASI, rice is established under CT practice and followed by a machine-sown wheat, maize, or lentil crop with zero tillage (ZT). Under full CASI, rice was established without tillage by either mechanized direct sowing or by mechanized transplanting, and the wheat, maize, or lentil crop was planted as in the partial CASI treatment. Crops were managed by farmers with support and oversight from local and international research partners; best management practices were followed.

27.2.2 Data Collection and Analysis

We recorded data on all cropping system inputs (e.g., fertilizers, seeds, irrigation water, agrochemicals, fuel, human labor) and outputs (i.e., grain and straw). Results were standardized to facilitate comparisons across different cropping systems, countries, and currencies (e.g., all grain yields are reported as rice-equivalent yields, all economic data are reported in Australian dollars (AUD) as the research funder was an Australian agency). We examined the data across ten key metrics which directly relate to the food-energy-water nexus:

I. System rice-equivalent yield (SREY).
II. Irrigation water applied.
III. Total in-crop water (the combined irrigation water and rainfall received during the growing season).
IV. Water productivity (a measure of the efficiency of converting total in-crop water to grain).
V. Total energy (the total energy used in grain production).
VI. Energy productivity (quantifying the efficiency of converting total in-crop energy to grain).
VII. Labor.
VIII. CO_2-equivalent emissions (produced from diesel and agrochemicals used during crop production.
IX. Cost of production.
X. Gross margin.

A detailed synopsis of data collection, calculations, and analytical methods is contained in Islam et al. (2019) for yield and water productivity data; in Gathala et al. (2020a) for energy and CO_2-equivalent emission data; in Gathala et al. (2021) for labor and economic data; and in Gathala et al. (2020b) for explanation of a meta-analysis of all ten metrics together.

27.2.3 Community-Focused Business Models

A key tenet of this research was to embed the introduction of CASI practices into existing farmer-support groups, to better support farmers as they tested new machinery and crop management practices. We identified Farmers' Clubs in West Bengal, Farmers' Clubs, Schools or Federations in Bangladesh, and self-help groups (e.g., JEEViKA) in Bihar. These groups took responsibility for crop establishment and other agricultural machinery, promoted CASI practices locally and were hubs for CASI training. Through engagement with the farmer groups, we build trust with local partners and communities and developed positive relationships with village and community leaders.

27.3 Results and Discussion

27.3.1 Performance of CASI and CT

A synthesis of all results across three countries in the EGP demonstrates the benefits of the total CASI package which includes farmer-adapted (i.e., practical and feasible for local agronomic conditions) conservation agriculture management, improved crop management, and crop diversification and intensification. The multidimensional benefits of CASI are clearly shown by increased system productivity of up to 10% and reductions in irrigation water usage of up to −17%. CASI also reduced energy usage and CO2-equivalent emissions by up to −62% and −16%, respectively, which contributes to increases in gross margins of between 16% and 56%, and to reductions in labor requirements of between −26% and −46% (Fig. 27.3).

A meta-analysis of the ten assessment metrics combined demonstrated that, across all cropping systems and study districts, CT consistently performed worst and the full CASI options performed best (Fig. 27.3). This was due to general higher productivity and lower input requirements in the full CASI treatments than in the CT treatment. The partial CASI treatment performed better than CT but not as well as the full CASI options.

In terms of cropping system rice-equivalent yield (SREY) productivity, CT yielded 11.25 Mg ha^{-1}, which was significantly ($p = 0.05$) less than the SREY obtained for both full CASI options (around 11.70 Mg ha^{-1}) and less than the SREY for the partial CASI option (11.62 Mg ha^{-1}). The meta-analysis shows that, compared to a CT baseline, SREY was 2.6% higher under partial CASI and 4.0% higher under full CASI (Fig. 27.4a). Rice production was comparable under CT and CASI practice, while the productivity of dry season crops increased under CASI (Islam et al. 2019). The increase in yield in dry-season crops was due in part to improved crop establishment under mechanized sowing than under broadcast seed; this result was particularly observed in wheat and lentil crops. An additional factor which contributed to improved crop establishment was the improved soil structure under CASI (as soil compaction prior to transplanting no longer occurred) which reduced the waterlogging of seeds and seedlings, thus improving seed germination rates and

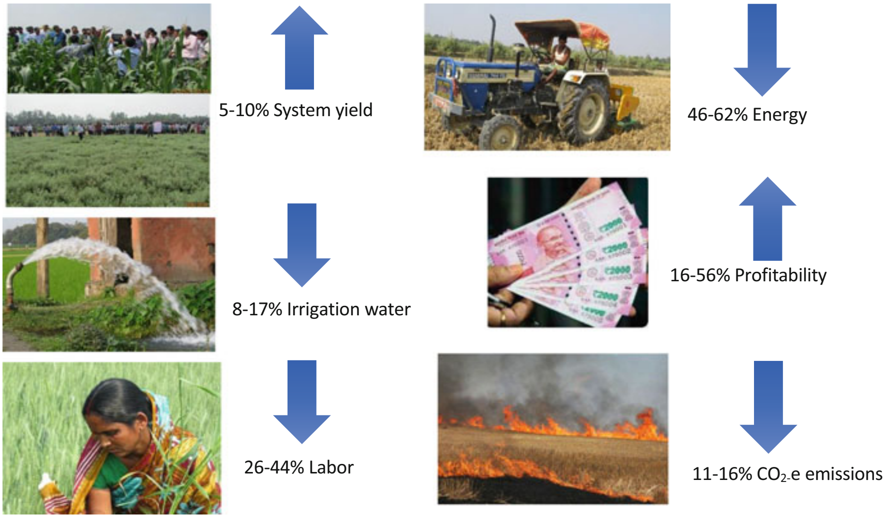

Fig. 27.3 Multidimensional benefits of conservation agriculture-based sustainable intensification on smallholder farmers across the EGP of South Asia

plant root development, and also led to improved soil water retention through the growing season. As well, a more favorable root-zone microenvironment improved soil temperature, increased soil microbial activity, and facilitated greater plant water use efficiency due to greater soil-root contact. For all crops fertilizer use efficiency was greater under CASI than under CT. These results have been previously observed in smaller studies in the EGP and in South Asia (Kumar et al. 2018; Gathala et al. 2011, 2013; Jat et al. 2019a, b; Patra et al. 2019).

Irrigation water usage was greatest under CT (35.11 ha-cm) and comparable and lower under all CASI treatments (ranging from 29.75 to 30.12 ha-cm). Correspondingly, the total water (irrigation and rainfall) used in crop production was highest under CT (148.34 ha-cm) and lower and comparable under all CASI treatments (ranging between 141.46 and 132.40 ha-cm). Water productivity was significantly ($p = 0.05$) lower under CT (0.84 kg grain m^{-3}) than under any CASI practice (all approximately 0.91 kg grain m^{-3}).

The meta-analysis shows that reductions in irrigation water use (Fig. 27.4b) from the CT baseline ranged from −16.3% under full CASI to −37.5% under partial CASI, while total in-crop water use (Fig. 27.4c) decreased, relative to CT, by between −3.0% under full CASI and −7.3% under partial CASI. Water productivity (Fig. 27.4d) increased over CT by 5.3% under partial CASI and by 7.2–8.3% under full CASI. The partial and full CASI treatments used CASI practices in the dry season, which is when the majority of irrigation events occurred: thus, the water-saving effects of CASI are evident in the partial CASI as well as in full CASI treatments. Water savings were achieved under CASI in irrigated dry-season crops but not in (rainfed) wet-season crops. In full or partial CASI treatments, less water was required at the first irrigation than in the CT treatment because pre-sowing

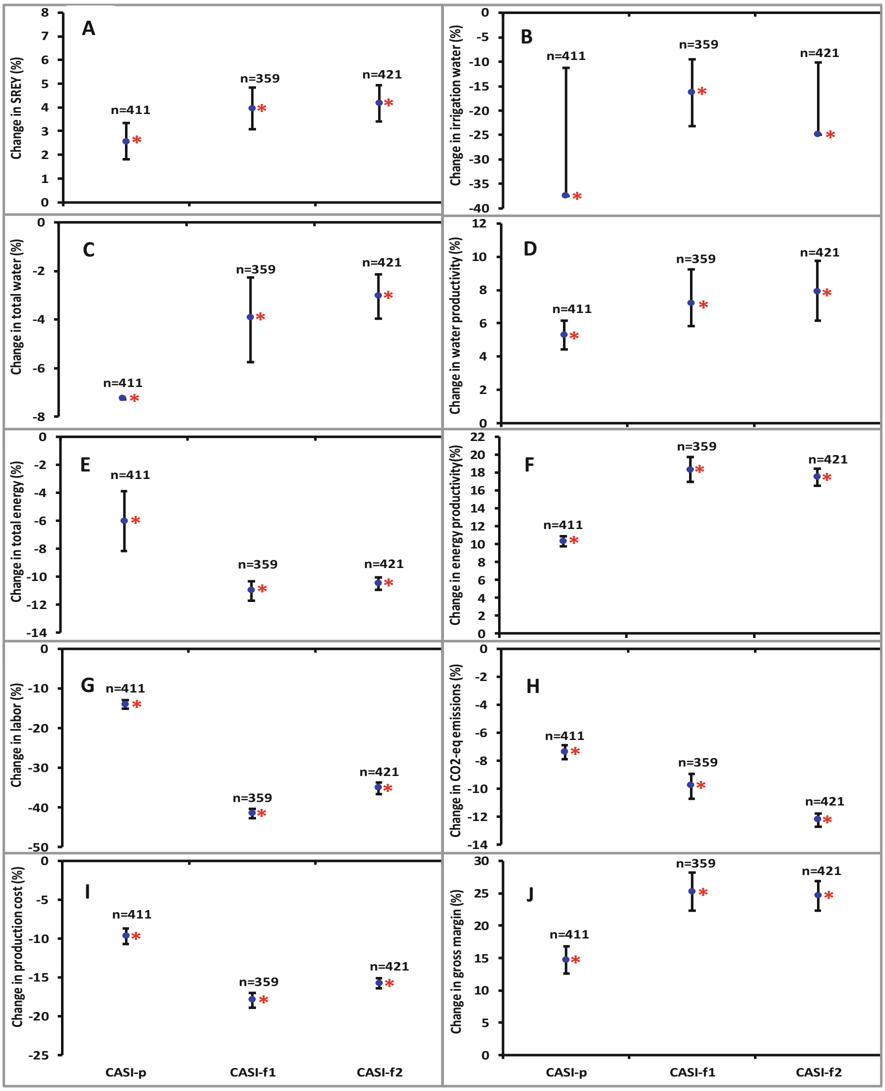

Fig. 27.4 Meta-analysis of on-farm trials showing the percentage change for partial (CASI-p) and full (CASI-f1, DSR and CASI-f2, UPTR) CASI treatments over the conventional tillage (CT) baseline in terms of: (**a**) system rice-equivalent yield (SREY); (**b**) irrigation water; (**c**) total water used; (**d**) water productivity; (**e**) total energy; (**f**) energy productivity; (**g**) labor; (**h**) CO_2-equivalent emissions; (**i**) production cost; and (**j**) gross margins, across all cropping systems in the EGP. *Denotes significance at $p = 0.05$ over CT. Error bars show 95% confidence intervals: if they do not overlap treatment results differ significantly. Derived from Gathala et al. (2020b)

tillages under CT loosened the topsoil and provided a rougher surface over which water flowed more slowly, requiring more water to be applied to sufficiently wet an equivalent area. As well, crop residues retained under CASI practices reduced evaporation and improved soil moisture: consequently, less irrigation water was required through the crop-growing season under CASI (Kumar et al. 2018; Gathala et al. 2016).

Total energy use was significantly ($p = 0.05$) higher under CT (33,757 MJ ha^{-1}) than under partial CASI (32,939 MJ ha^{-1}). Total energy use under partial CASI was again significantly higher than under full CASI (average 30,253 MJ ha^{-1}). In turn, the energy productivity, or amount of grain produced per unit of energy, was significantly lower under CT (0.28 kg grain MJ^{-1}) than under partial CASI (0.31 kg grain MJ^{-1}) which was itself significantly lower than under full CASI (0.33 kg grain MJ^{-1}). Meta-analysis shows that, relative to CT, total energy use (Fig. 27.4e) decreased by −6.1% under partial CASI and by around −10.5% under full CASI, while energy productivity (Fig. 27.4f) increased over CT by 10.3% under partial CASI and by around 17.5% under full CASI. Energy requirements under CT were considerably higher due to the higher energy demands of tillage and (in rice) manual crop establishment. The higher irrigation demands under CT than under partial or full CASI resulted in higher energy demands to run pumps (Gathala et al. 2020a). Partial and full CASI practice had higher usage of agrochemicals (e.g., herbicides) than CT, but this component of total energy used was relatively small.

Significantly ($p = 0.05$) more labor was used under CT (152.66 person days ha^{-1}) than under partial CASI (129.61 person days ha^{-1}). In turn, significantly less labor was required under full (average 99.1 person days ha^{-1}) than under partial CASI. The meta-analysis showed that the reduction in labor from the CT baseline was −14.1% under partial CASI and −35.2% to −41.6% under full CASI (Fig. 27.4g). The most labor-intensive tasks in the production of any crop are pre-sowing tillage operations and, in rice, transplanting (Islam et al. 2019). Under full CASI, there were no tillage operations, and transplanting was either not needed (for direct sowing) or mechanized, thus significantly reducing labor requirements (Gathala et al. 2021). In partial CASI practice, the soil was tilled only before the (wet season) rice crop, while in CT, the soil was tilled before each crop, and rice transplanting was a fully manual operation.

Reflecting the above differences in system grain yield, water and energy productivity and labor demand, the cost of production was highest under CT (1819 AUD ha^{-1}), significantly ($p = 0.05$) lower under partial CASI (1647 AUD ha^{-1}) and significantly lower again under full CASI (average 1520 AUD ha^{-1}). Gross margins were also significantly different between treatments: they were lowest under CT (1920 AUD ha^{-1}), higher under partial CASI (2205 AUD ha^{-1}), and highest under full CASI (average 2379 AUD ha^{-1}). The meta-analysis shows that compared to CT, production costs (Fig. 27.4i) decreased by −9.7% under partial CASI and by around −16% under full CASI, while gross margins (Fig. 27.4j) were higher by 14.7% under partial CASI and by around 25% under full CASI.

CO_2-equivalent emissions were highest under CT (1.75 Mg ha^{-1}), significantly ($p = 0.05$) lower under partial CASI (1.61 Mg ha^{-1}), and significantly lower again under full CASI (average 1.54 Mg ha^{-1}). The meta-analysis showed that CO_2-equivalent emissions reduced from the CT baseline by −7.4% under partial CASI and by −9.8% to −12.2% under full CASI (Fig. 27.4h). The lower CO_2-equivalent emissions under full and partial CASI are a direct result of the lower energy usage in these systems compared to CT.

27.3.2 Performance of Different Cropping Systems

27.3.2.1 Cropping System Productivity, Energy Usage, CO_2-Equivalent Emissions and Economics

Of the double cropping systems tested, RM (12.3 t ha^{-1}) and RL (12.6 t ha^{-1}) had the highest average cropping system yields (Fig. 27.5); the RM system is slightly less variable (i.e., a smaller interquartile range; IQR) than the RL system. The RR system had an average yield of 10.9 t ha^{-1}, while the average RW system yield was 8.6 t ha^{-1}. Variability, as shown by the IQR, is least in the RR system, which reflects the stability of fully irrigated yields in the dry-season crop in particular. Variability is high in the RW and RL systems: in the RW system, crops may be affected by terminal heat stress associated with late planting, often as a result of late sowing of the (rain-dependent) rice crop (Jat et al. 2019a, b). In RL systems, the rainfed lentil crops may be adversely affected by poorly timed rainfall events leading to

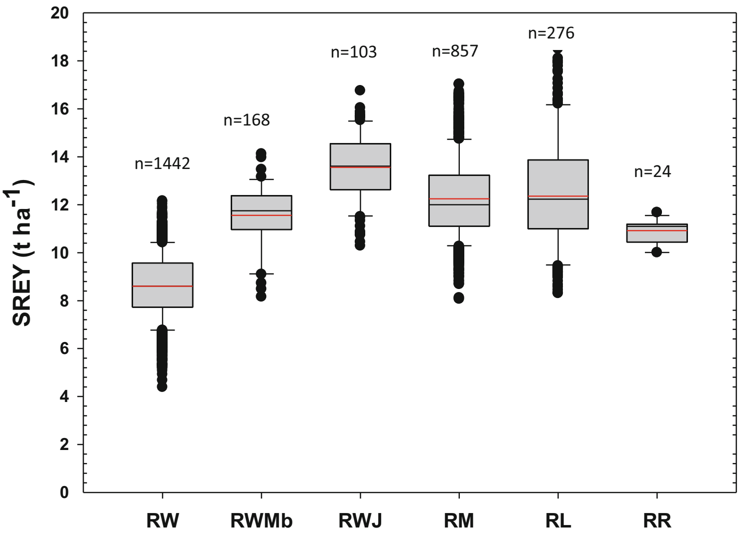

Fig. 27.5 System rice equivalent yield (SREY) for different cropping systems under CASI and CT combined across eight districts of the EGP, South Asia. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *RWJ* rice-wheat-jute, *RM* rice-maize, *RL* rice-lentil, *RR* rice-rice. Derived from Islam et al. (2019)

waterlogging and increasing the variability of system productivity (Islam et al. 2019; Singh et al. 2014).

Intensifying the RW system by including a third crop increased the mean system yield by 3.1 t ha^{-1} in a RWMb system and by 5.0 t ha^{-1} in a RWJ system. Average yields were higher in RWJ than in RM and RL, which were slightly higher than average yields in the RWMb system. The IQR was lower in the tripled cropped systems than in the RM or RL systems.

The average total energy used was significantly ($p = 0.05$) highest in the RR (38,731 MJ ha^{-1}) and RWMb (35,568 MJ ha^{-1}) systems, next highest in the RM (34,025 MJ ha^{-1}), RWJ (32,986 MJ ha^{-1}), and RW (28,070 MJ ha^{-1}) systems, while the RL system (20,449 MJ ha^{-1}) used significantly the least total energy (Fig. 27.6a). The high total energy in the RR system, independent of crop management practice, is a result of the high water demand of dry-season rice. Pumping sufficient water to irrigate this dry-season rice crop requires large amounts of energy in diesel or electricity. Lentil crops are low or no input crops, with minimal irrigation or fertilizer applications, and thus the RL system has considerably lower energy demands than other cropping systems.

There was a significant ($p = 0.05$) difference in CO_2-equivalent emissions between all cropping systems: these differences corresponded to the differences in energy requirements between systems (Fig. 27.6b). CO_2-equivalent emissions were highest in the RR system (2.17 Mg ha^{-1}) and lowest in the RL system (0.96 Mg ha^{-1}). Emissions from the RM system were 1.72 Mg ha^{-1}, and from the RW system, they were 1.41 Mg ha^{-1}, while from the triple cropping systems, CO_2-equivalent emissions were 1.77 Mg ha^{-1} from the RWMb system and 1.62 Mg ha^{-1} from the RWJ system.

Average costs of production were highest in the RR (2018 AUD ha^{-1}) and the RWMb (1878 AUD ha^{-1}) systems: these costs were significantly ($p = 0.05$) higher than for other cropping systems (Fig. 27.7a). Costs in the RWJ system were 1819 AUD ha^{-1}, while in the RM system, they were 1516 AUD ha^{-1} and in the RW system they were 1354 AUD ha^{-1}. Production costs were significantly least in the RL system (1131 AUD ha^{-1}). These differences in production costs reflect the energy, water, and labor demands for each cropping system (water and labor data are not shown here: they are available in Islam et al. (2019) for water and Gathala et al. (2020b) for labor).

In contrast to production costs, average gross margins were significantly highest in the RWJ (2851 AUD ha^{-1}) and RM (2762 AUD ha^{-1}) cropping systems (Fig. 27.7b). While costs in both these systems are reasonably high, the yields of crop products (grains and jute fiber) are also reasonably high, leading to the high gross margins. RL gross margins are also reasonably high (2145 AUD ha^{-1}), reflecting the low system production costs, followed by the RR (2181 AUD ha^{-1}) and RWMb (1846 AUD ha^{-1}) systems which have both high production costs and reasonably high system yields. Gross margins are significantly least in the RW system (1539 AUD ha^{-1}), reflecting the low productivity of these systems.

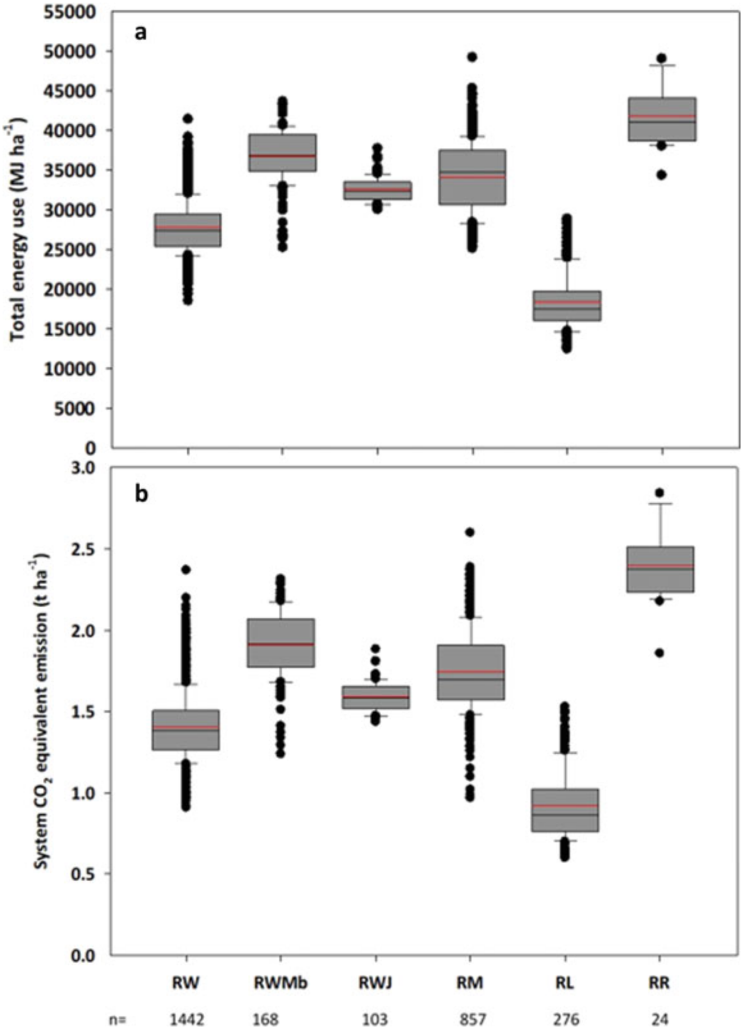

Fig. 27.6 Total energy use and CO_2-equivalent emissions for different cropping systems under CASI and CT combined across eight districts of the EGP, South Asia. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *RWJ* rice-wheat-jute, *RM* rice-maize, *RL* rice-lentil, *RR* rice-rice. n = total data points in each cropping system. Derived from Gathala et al. (2020a)

27.3.2.2 Association Between Cropping System Yields, Net Incomes and CO_2-Equivalent Emissions

Both the system rice-equivalent yields (SREY) and system gross margins were negatively correlated with CO_2-equivalent emissions for RW, RM, and RL cropping systems (Fig. 27.8). These data indicate that high SREY and high gross margins are achievable with reduced CO_2-equivalent emissions across a range of agronomic environments. The relationships between SREY or gross margins and CO_2-

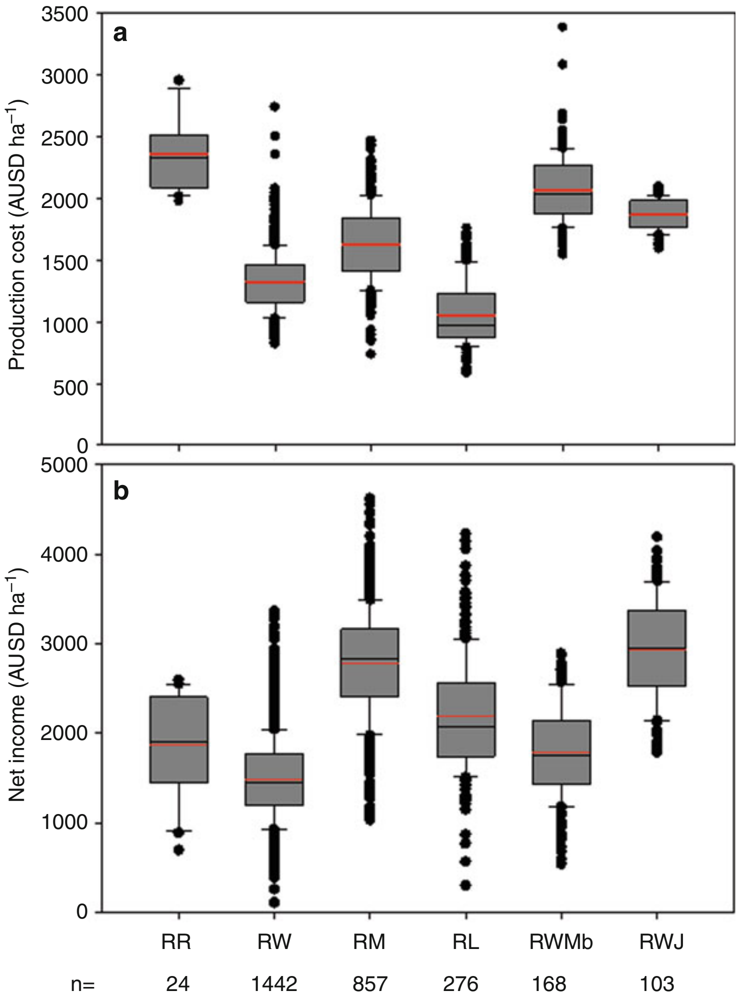

Fig. 27.7 Production cost and gross margin (net income) for different cropping systems under CASI and CT combined in the EGP, South Asia. *RR* rice-rice, *RW* rice-wheat, *RM* rice-maize, *RL* rice-lentil, *RWMb* rice-wheat-mungbean, *RWJ* rice = wheat-jute. *n* = total data points in each cropping system. Derived from Gathala et al. (2021)

equivalent emissions were stronger and more significantly correlated in the RM and RW systems, where more data were available and weaker but still significant in the RL system. The RL system is more variable due to less reliable in-crop water in rainfed and waterlogging-intolerant lentil crops, which also had reduced inputs and higher incidences of pests or disease (Islam et al. 2019).

Most of the data at lower values on the X-axes in Fig. 27.7 represent full or partial CASI management (treatment data not shown): high SREY and high gross margins

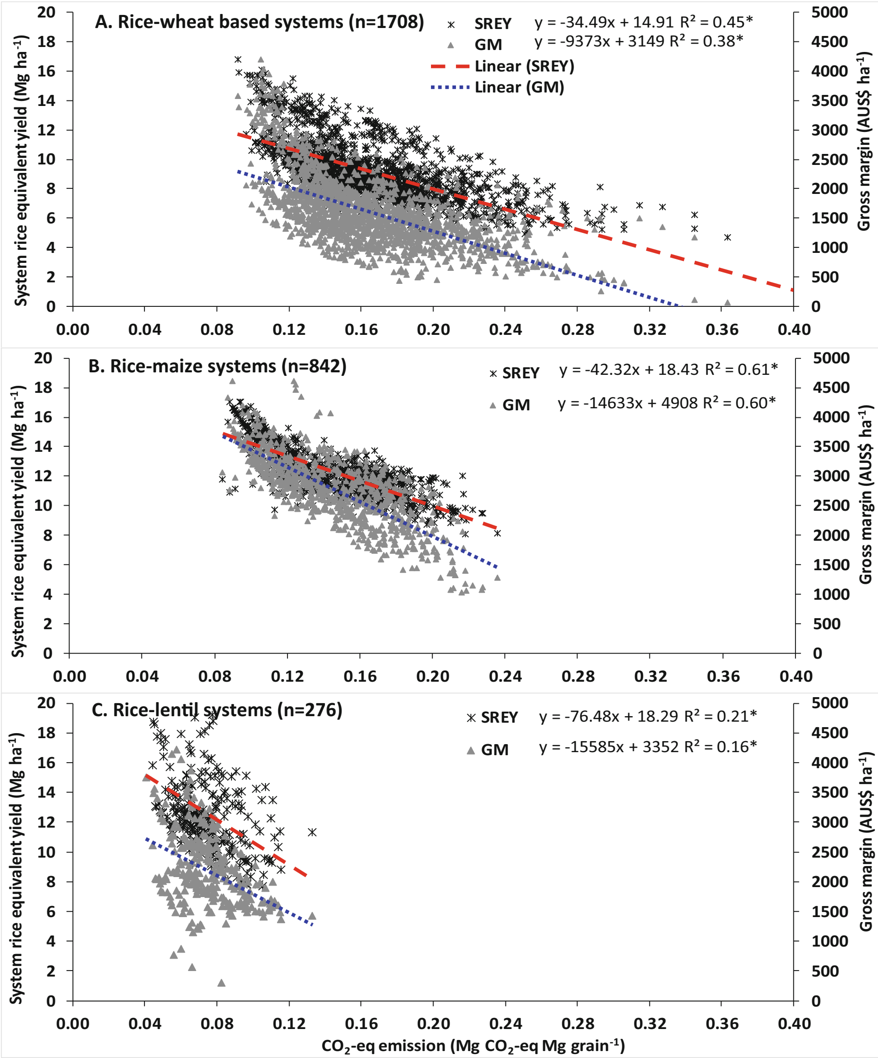

Fig. 27.8 System rice equivalent yield (SREY) and gross margin (GM) plotted against system CO_2-equivalent yields for different cropping systems in the EGP under CASI and CT treatments combined: (**a**) rice-wheat based systems; (**b**) rice-maize systems; (**c**) rice-lentil systems. Values in parentheses show the total number (*n*) of data points. Derived from Gathala et al. (2020b)

were achieved under CASI management for CO_2-equivalent emissions lower than about 0.16 t CO_2-eq t grain^{-1}. Data at the higher end of the X-axes represent CT management practices where lower SREY and lower gross margins are achieved for higher CO_2-eq emissions (treatment data not shown).

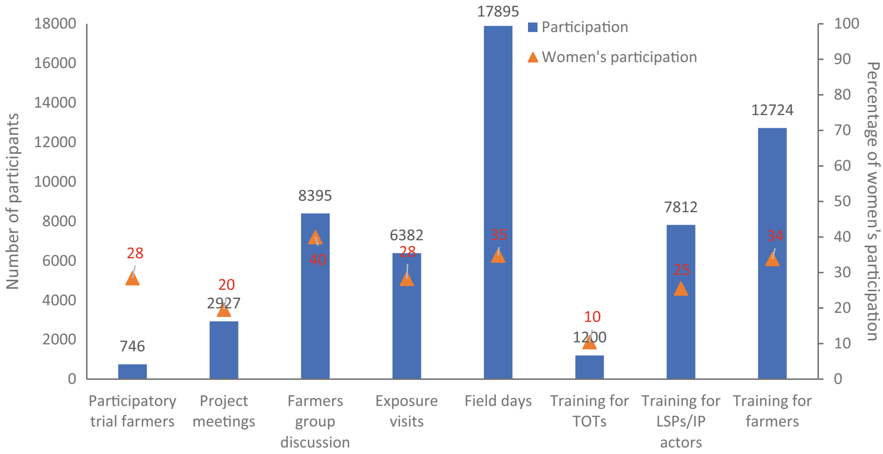

Fig. 27.9 Awareness and capacity building conducted under the research project. *TOT* training of trainers, *LSP* local service provider, *IP* innovation platform

27.3.3 Capacity Building

Significant resources were invested in building capacity across the areas where research was conducted; this took many forms (Fig. 27.9). Over 746 farmers who participated in the field trials received early training in CASI, with follow-up capacity building provided according to their existing skill and ongoing interest. Of these participatory farmers, almost a third (28%) were women. To support the field trials, training was provided to train 1200 trainers (10% women) across the EGP in aspects of CASI practice. Another 7812 actors (25% women) necessary to the uptake of CASI (such as fertilizer and other agrochemical suppliers, machinery use and maintenance, etc.) received training to enable them to facilitate components of CASI practice. In addition to the farmers participating in the field trials, another 12,724 (34% women) received training in CASI, and 17,895 (35% women) attended field days. Exposure visits by 6382 (28% women) people facilitated interested farmers to view existing field trials and interrogate farmers about the new management practices and at the same time provided an opportunity for policymakers, external researchers, and other stakeholders to learn directly from the research practices adopted in this project. Over 8000 farmers (40% women) participated in farmer group discussions, through which both farmers and researchers increased their understanding of local adoption of CASI practices. Finally, almost 3000 research participants (20% women) received training and capacity building at formal project meeting events: this group included junior researchers who increased their scientific research skills and extended their knowledge into new domains (such as cropping system modeling) they might otherwise not have opportunity to learn.

27.3.4 Community-Focused Business Models

The implementation of CASI research activities was achieved through engagement with existing farmer support groups (Fig. 27.10). Without the engagement with and support of these groups, research activities would have been harder to test on farmers' fields, and the recognition and scale-out potential of CASI practices would have been considerably reduced. Farmer-support groups connected and facilitated engagement between many different stakeholder groups, including (a) governments and policymakers, (b) development and extension agencies who promoted CASI and provided training and technical backstopping, (c) researchers and scientists who contributed to CASI training and dissemination of CASI, (d) financial institutions who supported farmer group investments through micro-loans, and (e) agro-industries who provided seeds, fertilizers, and other agrochemicals to the farmer groups. As well, the farmer-support groups linked with external agencies (e.g., certification bodies, financial institutions, agrochemical and fertilizer companies, machinery manufacturers) to provide information, improve commercial viability, ensure access to machinery, and identify and exploit market opportunities. Farmer-support groups also linked farming communities with public extension officers and with higher level public-sector stakeholders.

The success of farmer-support groups, particularly in West Bengal and Bangladesh, enabled the development of additional support groups to facilitate further outscaling and uptake of CASI practices outside the original research districts. Farmers recognized the value of these support groups and were keen to reinvigorate existing groups to ensure that those who were interested in the outscaling and wider uptake of CASI practices were supported and to mitigate risk. For example, in West Bengal, three Farmers' Clubs were involved with initial research activities which commenced in 2013. By 2019, 65 Farmers' Clubs across the north of the state had been introduced to CASI practices and were providing support and facilitation assistance to farmers outside the original research villages.

The model of farmer-support groups supporting the implementation and uptake of CASI practices in villages was flexible and readily adaptable to different social or cultural contexts. It enabled the engagement with different stakeholders at different times according to local community requirements. The flexibility and adaptability of this engagement model were key to its strength and to the ultimate success of the testing and taking up of CASI practices in and beyond research villages.

27.3.5 Extending CASI: Enabling Policy Environment Required

The demonstration of the benefits of CASI relative to CT over a range of cropping systems was achieved through bottom-up farmer- and researcher-driven experiments which were most successful when the social and policy environment enabled innovation and supported (limited) risk taking and the exploration of new crop management practices. Recognition of the value of CASI and provision of wide-spread support within institutional frameworks were facilitated by community

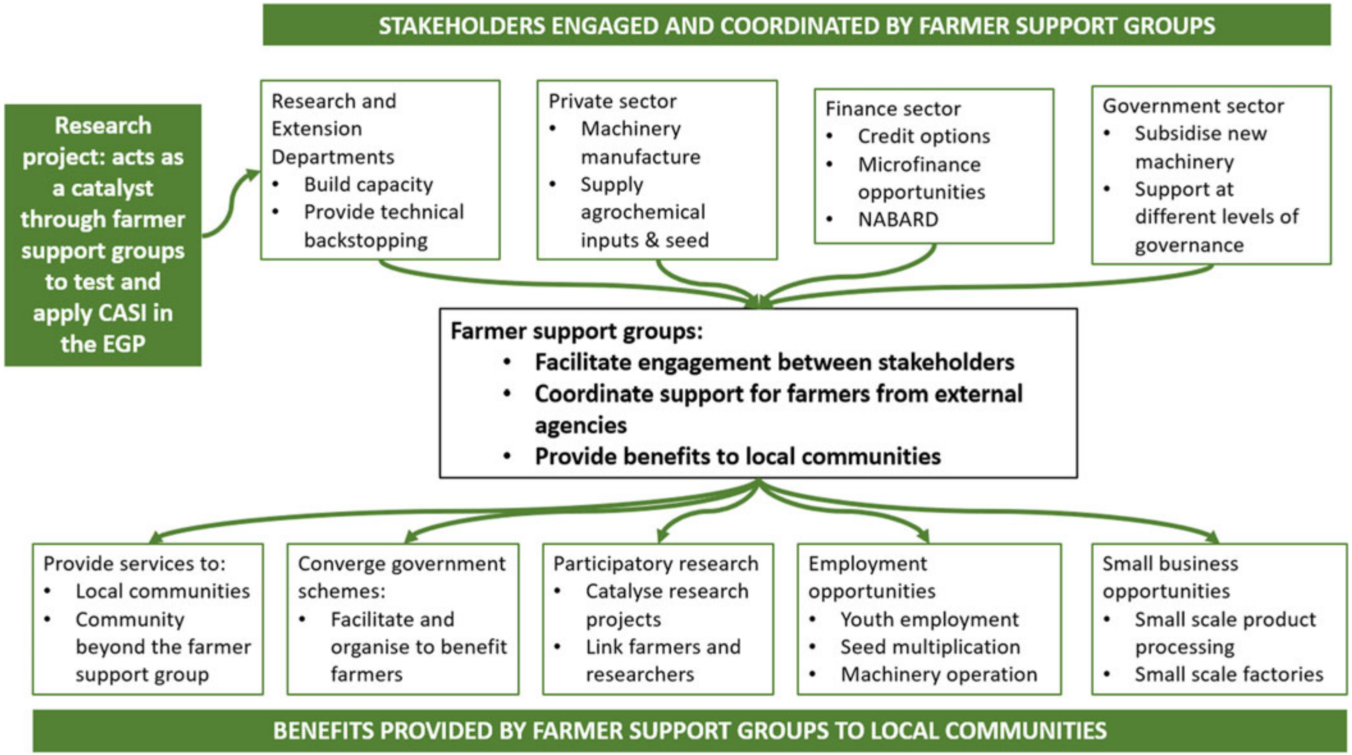

Fig. 27.10 CASI research activities were tested under the aegis of farmer support groups in villages, through which CAIS achieved greater recognition and scale-out than if the project had been run independently of existing in-village farmer support structures

leaders and governments at village, district, and state/regional scales. Robust bottom-up field trials were necessary to demonstrate the effectiveness and applicability of CASI across the EGP and to give credence to top-down policy support for greater implementation through regional outscaling.

Agricultural mechanization is a key component of CASI: increasing mechanization reduces energy, water, labor, and CO_2-equivalent emissions from cropping systems and also underpins the sustainable intensification of crops for food production. Governments can assist farmers to prioritize the use of sustainable agricultural machinery by providing capital subsidies targeted toward machinery that promotes resource conservation, such as the direct seeding and unpuddled transplanting machines used in CASI practices.

In order to further widen the reach of CASI, ongoing support from governments is required to make better linkages between institutions and facilitate capacity building. The benefits to legislators of increasing the adoption of CASI-based practices are many: CASI practices enable farmers to sustainably intensify their production systems, producing more crop product while conserving energy and water resources and reducing the demand for agricultural labor. As well, CASI practices contribute to reductions in agricultural greenhouse gas emissions, contributing to national and regional efforts to address climate change (Ladha et al. 2015; Padre et al. 2016; Kumar et al. 2018). Government policies which support the purchase, maintenance, and the use of CASI machinery will be crucial to its uptake in the EGP, in South Asia, and in many other emerging-economy countries globally.

Linking agricultural development programs with rural development programs is important. It is through agricultural development programs that improved agricultural management practices, such as CASI, are tested and implemented and linkages with rural development programs will facilitate their wider adoption and uptake through more extensive development opportunities across the EGP and other target regions of agricultural development. Linking these programs will encourage and assist farming communities to take local ownership of improved agricultural management practices and to further tailor them to local conditions, and will also provide additional employment opportunities within rural communities.

27.4 Conclusions

From extensive field trials in 6 cropping systems, conducted on over 400 farmers' fields across 3 countries in the EGP, we have demonstrated that CASI practices increase the productivity and profitability of rice-based cropping systems in the EGP. CASI practices also reduce water, energy, and labor requirements and CO_2-equivalent emissions. These benefits are observed under partial (dry season) CASI and are more extensive under full CASI. Traditional RR systems are heavily water intensive, while productivity in RW and RL systems is at risk of terminal heat stress or poorly timed rainfall events, respectively. Diversifying RR, RW, or RL systems into more profitable RM systems has potential across the study regions within the EGP. Intensifying unprofitable RW systems into triple-cropped RWJ or RWMb systems significantly increases the profitability and sustainability of these productions systems: intensification options depend on local climate and soil conditions, with RWJ being more attractive in higher-rainfall areas and RWMb in drier areas within the EGP.

Testing CASI practices under the aegis of existing farmer support groups ensured that the new management practices were well supported within villages. Through farmer support groups, farmers were linked to other stakeholders who assisted in the uptake and eventual outscaling of CASI, first to nearby villages, then within research districts, and ultimately across regions within the EGP.

Implementation and uptake of CASI are strongest when bottom-up farmer-led research activities are complemented by top-down support from policymakers and other stakeholders. With community and governance support, CASI is a feasible and realistic option for smallholder farmers in many countries to sustainably improve cropping system productivity, profitability, and the food-energy-water nexus while reducing labor demands and CO_2-equivalent emissions from agriculture.

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Conservation Agriculture: Next-Generation, Climate Resilient Crop Management Practices for Food Security and Environmental Health

28

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Abstract

The global population is projected to increase to between 8.9 billion (b) and 10.6 b by 2050, from a population of 7.7 b in 2019. To meet the increasing food demand of this growing population, an additional 59–110% more food will need to be produced by 2050. Therefore, improved agricultural management practices must be used by farmers to improve productivity. The next-generation practices including high-yielding crop cultivars require higher inputs, while lack of knowledge about how to correctly use these crop inputs has resulted in their imbalanced use which has contributed to ecological imbalances and deteriorating land productivity. Additionally, traditional rice cultivation in Eastern and South Asia results in the formation of a layer of low soil permeability in the plant root zone which increases soil compaction and reduces hydraulic conductivity, macroporosity, and the proportion of water-stable aggregates in the soil, all of which adversely affect the productivity of the crop following rice. Declining soil fertility and environmental pollution as consequences of traditional crop cultivation are already well reported across Asia. In contrast, conservation agriculture (CA) practices have the potential to maintain or improve the productivity and profitability of rice-based cropping systems, by managing the natural resource base (i.e. soil, water, energy) in an ecologically and environmentally sustainable manner. CA is based on the following three key principles: (1) minimal soil disturbance, (2) maintenance of permanent residues or crop cover, and (3) diversification of crops within rotational sequences and/or plant associations. This chapter highlights the concepts and prospects of CA as an emerging and climate-resilient agricultural technology for food and environmental security in Asia in the modern era of changing climate.

Keywords

Conservation agriculture · Food · Environment · Security · Rice-based cropping systems · Asia

28.1 Introduction

By 2050, the global population is projected to increase to between 8.9 b and 10.6 b (United Nations 2019), from a current estimate of 7.7 b in 2019 (World Bank 2020). In 2019, 56% of the total global population lived in urban areas (World Bank 2020), and this share is projected to increase to 68% by 2050 (World Bank 2020). In 2019, the per capita GDP of the world was US $ 11,435, which is also projected to increase to US $ 13,956 by 2031 (USDA 2020). These demographic and income changes will generate enormous pressure on food supply and food security across the world (Alexandratos and Bruinsma 2012).

As a primary consequence, the demand for agricultural products, in particular the demand for cereals, will increase substantially as a result of the increases in population, income, and rapid urbanization (FAO 2009a; Tilman et al. 2011; Godfray et al. 2010; Ray et al. 2013). Currently, 690 m people in the world experience food insecurity; to ensure food security of the growing population, it will be necessary to produce an additional 59–110% more food by 2050 (The Royal Society 2009; Tilman et al. 2011; Nelson et al. 2014; Valin et al. 2014). While the need to produce more food is undisputed, natural resources are rapidly declining, in part due to pressures from an increasing population. In 1961, the global arable land per capita was 0.37 ha; this had decreased by 2016 to 0.19 ha (World Bank 2020), and, during the same period, global renewable freshwater resources per capita declined from 13,403 m^3 to 5933 m^3 (World Bank 2020).

To meet the growing food demands of an increasing global population, higher-intensity agricultural management practices have been introduced into traditional farming methods (Nhamo and Lungu 2017). Among these next-generation practices, high-yielding crop cultivars (HYV) have been key to increasing farmers' productivity and profitability. However, HYV require more fertilizer, pesticides, and irrigation than traditional crop cultivars (Sarkar et al. 2012; Nhamo and Lungu 2017). As a consequence of this increased crop demand and, frequently, lack of knowledge by farmers about optimal crop-management practices, imbalances in the application and use chemical fertilizers and pesticides have resulted in ecological hazards and decreasing land productivity (Pingali 2001; Wilson and Tisdell 2001). Across eastern and South Asia, rice-wheat or rice-rice rotations are the major cropping systems for food production. The rice crop is traditionally transplanted after repeated puddling (compacting) of the soil: over the longer term, this puddling creates a hard layer in the soil at the plant zone (Jun Cao et al. 2017). This hard layer results in increased soil compaction and decreased soil hydraulic conductivity and macroporosity; it also reduces the proportion of water-stable aggregates in the soil which adversely affects cropping system productivity (Bertolino et al. 2010; Podder et al. 2012). Declining soil fertility and increasing environmental pollution as a result of the intensive cultivation of rice-wheat and rice-rice cropping systems have been widely reported (Jun Cao et al. 2017; Wencai et al. 2019).

Conservation agriculture (CA) management practices have the potential to maintain or increase the productivity and profitability of rice-based cropping systems by facilitating the management of the natural resource base (soil, water, energy) in an ecologically and environmentally sustainable manner (Kassam et al. 2014; Hossain et al. 2015). CA is defined by three principles: minimal soil disturbance; the maintenance of a permanent residue or crop cover; and diversified crop rotations and/or plant associations (Scopel et al. 2013; Farooq and Siddique 2014). The adoption of CA in rice-based cropping systems has great potential to sustainably increase cropping system productivity globally (Pittelkow et al. 2015; Ward et al. 2018). In a global meta-analysis, Keil et al. (2015) reported that CA in the form of zero tillage with or without crop residue retention enhanced wheat yield by 498 kg/ha or 19% compared to conventional crop management across various global agroecological zones. Furthermore, Keil et al. (2015) reported a 6% increase in total income from both savings in the costs of crop production and increased crop yields under zero-tillage practices in wheat cultivation in the Indian state of Bihar. In an experimental study, Edralin et al. (2017) demonstrated that CA practice in Cambodia increased yields and reduced manual weeding costs significantly compared to the conventional tillage. Other studies have also reported that CA practice reduces labour costs (FAO 2016). Importantly, CA practices conserve water and restore soil organic matter, thereby increasing soil fertility over the longer term (Sapkota et al. 2012; Belay et al. 2019). This chapter summarizes the concepts and prospects of CA, as a next-generation and climate-resilient agricultural technology for food and environmental security in the modern era of changing climate.

28.2 Concept and Prospects of Conservation Agriculture in the Changing Climate

Historical crop establishment is thought to have been done by farmers making furrows in soil using pointed sticks, following rudimentary ploughing with oxen. Seeds were then placed within these furrows. Soil quality and loss was minimal due to the few, light-tillage operations on agricultural soils (Derpsch 1998). After the South Asian green revolution of the 1960s, food grain production has increased globally to ensure food security for an ever-growing population; this included the introduction of chemical fertilizers (Timsina 2018). Chemical inputs have resulted in a marked increase in food grain production but concurrent with this has come numerous harmful effects on the environment as well as on human health also. Indiscriminate use of these chemicals (often by farmers unaware of best practices and/or chasing higher crop productivity) along with alterations to the soil profile deteriorate soil quality and reduce its suitability for crop production (Bhan and Behera 2014).

The green revolution has been the basis for sustained food security, rural development, and poverty alleviation across South Asia for almost five decades (Meena and Lal 2018). It has played a leading role in making this region self-sufficient in terms of food grain, in particular by boosting the productivity of the rice-wheat system, which is the most popular cropping system of the Indo-Gangetic Plains (IGP), through the introduction of high-yielding varieties and complementary technologies such as improved irrigation and fertilizer management, and plant protection chemicals (Brahmachari et al. 2019). The increase of food grain production in IGP as part of the green revolution not only increased the region's food security but also enabled agricultural development to increase the economic growth of nations within South Asia and lessened poverty in the countries (Sapkota et al. 2015). However, the green revolution also resulted in environmental degradation and negative consequences for humans (Saha et al. 2016).

Climate change has become a global existential challenge (IPCC 2013; Sánchez-Lugo et al. 2018; NOAA 2020). The relatively rapid increases in greenhouse gas emissions (GHG), largely through industrial development, deforestation, pollution, and the burning of fossil fuels, are the principal causes of climate change and global warming (IPCC 2020). Some of the global consequences of increased greenhouse gas emissions include increased temperatures; changing patterns of rainfall frequency, intensity, and distribution; and sea-level rise as a result of melting of polar ice caps and glaciers. The global mean surface temperature has increased by 0.76 °C since 1880 (IPCC 2020). The densely populated Southeast Asia is the global region most vulnerable to climate change (Weiss 2009). According to the report of IPCC in (2007), the mean temperature of Southeast Asia has increased by 0.1–0.3 °C per decade, while mean annual rainfall has decreased by 1–3 mm/year. The mean surface air temperature in Southeast Asia is projected to increase by between 0.75 °C and 0.87 °C by 2039, by 1.32 °C and 2.01 °C by 2069, and by 1.96 °C and 3.77 °C by 2100, over a 1990 base temperature (Calzadilla et al. 2013; Kabir et al. 2017). Mean precipitation in Southeast Asia is projected to increase from 1% to 2.25% by 2050 relative to a 1990 baseline (IPCC 2007). While overall rainfall is projected to increase, the number of rainy days is anticipated to decline, indicating an increase in rainfall intensity and a potential decrease in rainfall effectiveness. The productivity of major cropping systems are, in consequence, likely to be significantly reduced (Gaydon et al. 2012; Manivannan et al. 2017; Liu et al. 2019). The growing threat of food insecurity and poverty in the IGP due to an expanding population is exacerbated by the risk of climate change and increasing variability in agricultural production (Sapkota et al. 2015). Thus, there is an increasing need for efficient crop production practices to sustainably increase food production while reducing negative environmental impacts.

Conservation agriculture is a complex and sophisticated agricultural management system. To summarize, it can be described as management practices which increase the sustainability of an agricultural production system and which include agronomic practices targeted to the crop and local conditions of a region. CA-recommended soil cultivation techniques and crop management processes will improve soil quality and conserve natural resources while enriching soil biodiversity and protecting the soil from erosion and degradation, without reducing the cropping system productivity. The positive and negative effects of the green revolution are evident across South Asia, and to improve on these, farmers need to adopt CA practices by conserving, improving, and increasing the efficiency of natural resource use through the integrated management of soil, water, and biological resources combined with external inputs (Fig. 28.1).

Conservation agriculture was developed in the 1930s to combat the problems then-modern intensive agriculture practices were causing in the Midwest United States in terms of severe soil erosion (FAO 2019). In 2012, it was estimated that 9% of the world's cropland area was farmed under CA (Kassam et al. 2019) with the largest areas in South America. CA aims at. By improving soil health, CA improves the farmed environment as well as enhancing and sustaining agricultural productivity.

Crop diversification is a key part of CA and is of paramount importance in mitigating environmental problems arising out of monoculture production. Modern agricultural production can be sustainably intensified by effective management of the soil-crop-nutrient-water-landscape system, through CA (Bahri et al. 2019). The adoption of CA has been estimated to increase cropping system productivity by between 20% and 120%, compared to system yields achieved under conventional

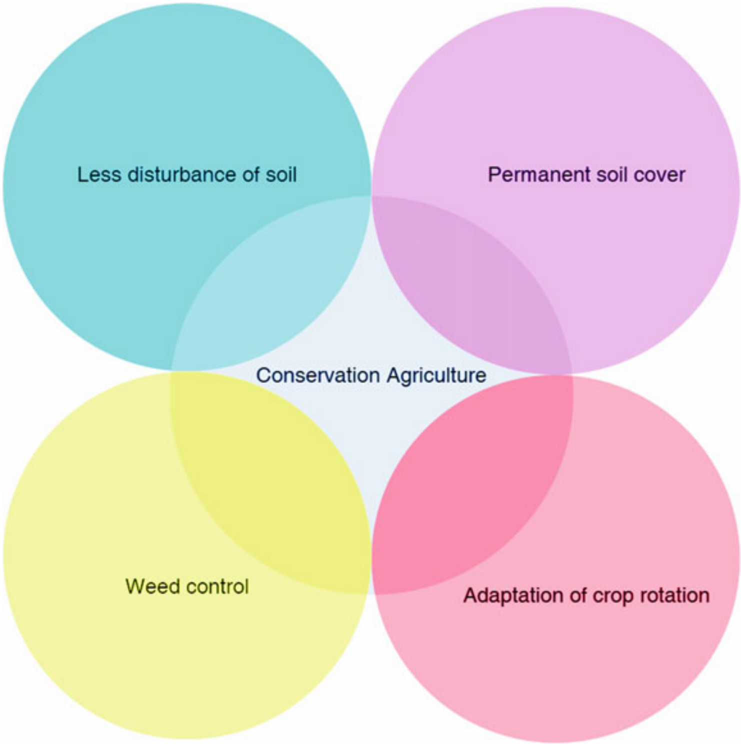

Fig. 28.1 Key elements of conservation agriculture for the sustainability of crop production system

management. Over time, CA maximizes resource-use efficiency by increasing soil health, thus reducing the amount of fertilizer required by lowering the runoff, thus reducing the amount of irrigation water required; by increasing crop resilience to pests and diseases, thus reducing the amount of herbicide and pesticides required for crop cultivation (Alam et al. 2017).

Reduced tillage and residue retention within fields are key components of CA. Under reduced tillage, at least 30% of crop residues are left in the field to reduce soil erosion and soil water loss while increasing soil health and insulating the soil from temperature extremes (Gupta and Seth 2007; Alam et al. 2017). CA tillage practices encompass not only reduced tillage but also zero tillage, mulch tillage, strip tillage, and ridge tillage. Under zero-tillage (or no tillage) crops are established without any prior soil disturbance. Zero tillage has been implemented over more than 100 million hectares worldwide (Farooq and Siddique 2015).

Despite having considerable potential in terms of maximizing cropping system productivity and profitability, increasing the sustainability of land use, reducing the labour and drudgery of crop management, and delivering ecosystem services, the global adoption CA is not uniform. Socioeconomic and geopolitical factors primarily influence the uptake of CA. Ongoing government support and detailed planning of locally relevant CA implementation strategies are critical to ensure the widespread adoption and promotion of CA both in rainfed and irrigated cropping systems of SA to mitigate the negative impact of climate changes.

28.3 Conservation Agriculture Enhances Soil Fertility and Productivity

28.3.1 Conservation Agriculture Improves Soil Physical Properties

Traditional rice cultivation in South Asia negatively affects soil aggregation, the sequestration of soil organic carbon, and overall soil health (Alam et al. 2020). Ongoing, repeated tillage events under traditional crop cultivation increase rice yield (although not the overall yield of rice-based cropping systems) while degrading soil aggregates and the soil structure. This soil degradation is enhanced when the soil is compacted (puddled) to grow traditional transplanted rice. Borie et al. (2006) showed that traditional crop management reduced the soil mycelium network by mechanically breaking down soil macroaggregates, and decreased soil organic matter, microbial biomass, and faunal activity (Sainju et al. 2009; Curaqueo et al. 2011). Borie et al. (2006) reported that decreases in soil aggregate stability contributed to soil nutrient depletion and soil erosion. This is mainly due to loss of the labile organic matter (i.e. microbial biomass) which is responsible for the formation of macroaggregates. Six et al. (1999) showed that tillage accelerated the renewal rate of macroaggregates, which was not conducive to the formation of microaggregates within macroaggregates (Zhou et al. 2020). The reduction of tillage disturbance increased the stability of soil aggregates (Du et al. 2015), because frequent tillage destroys the soil particle structure, increases the soil aeration, and deteriorates the protection of soil particles, resulting in loose soil structure and increased damage to the soil structure (Su et al. 2017). SOC is an essential factor in soil aggregate formation and crop residue management, which is fundamental to the accumulation of soil organic matter in agricultural soils, and regulates the development of the soil structure and its stability (Verhulst et al. 2010). Application of SOC in the form of crop residues, combined with conservation tillage practices, improves the formation of water-stable aggregates resulting in an increase of macroaggregates compared to microaggregates (Dey et al. 2020). Nandan et al. (2019) observed increased soil aggregation in residue retention practice under zero-tillage-based crop establishment practices. Kushwaha et al. (2001) suggested that the organic matter addition to the soil as a result of residue retention along with tillage reduction accelerated the formation of macroaggregates through an increase in the microbial biomass content in the soil. Applying rice residues enhanced soil organic carbon content and had both direct and indirect beneficial effects on soil properties and processes (Dey et al. 2020).

The long-term adverse impact of tillage-intensive, rice-wheat cropping systems where the soil was compacted (puddled) under rice production, in terms of soil aggregation, organic carbon, beneficial microorganisms, and overall soil heal, have been reported in South Asia (Nath et al. 2017, 2019). One of the principal ideas underpinning CA, that of growing crops in rotation on the same soil, positively influences soil aggregation as different crops in the rotation will vary in terms of root distribution at different depths, root growth, and in-season litterfall. Due to variations in biomass production and root systems, different crops differently promote soil aggregation and stabilization due to changes in the soil carbon supply (Wohlenberg et al. 2004). Balota et al. (2003) and Govaerts et al. (2008) observed improved soil structure and fertility resulting from the cultivation of different crop types in sequential seasons (i.e. the crop rotation), and also by alternating deep-rooted and shallow-rooted crops. Cereal-dominant cropping systems may have lower aggregate-binding agents than legume-dominant cropping systems. Singh et al. (2018) reported that legume-based cropping had ~12% higher soil glomalin (a soil microaggregate-binding agent) than cereal-cereal systems and that there was a positive relationship between soil aggregate stability and glomalin content. Legume-based cropping sequences accumulate soil organic carbon, increase soil nitrogen content, and improve soil aggregation which can be attributed to symbiotic fixation of nitrogen within the soil and the return of leaf litter and nitrogen-rich roots to the soil (Bhattacharyya et al. 2009; Ghosh et al. 2012) which lead to residual benefits for the subsequent crop. There is a need to understand for a specific agricultural region how soil organic carbon and soil aggregate dynamics are influenced by post-rainy season tillage, residue management, and crop diversification with legumes (Palm et al. 2014; Gathala et al. 2015).

Bulk density is a useful indicator of soil health which influences infiltration, plant-rooting depth, water-holding capacity, soil porosity, plant nutrient availability, and soil microbial activity. Over the longer term, crop establishment practices alter soil bulk densities, although bulk density is also always associated with the soil's inherent qualities. Alam et al. (2014) showed that practices which increase soil organic matter accumulation decrease soil bulk density. As CA practices such as the minimum disturbance of soil and residue retention increasingly accumulate soil organic matter over time (Alam et al. 2014, 2016, 2018; Salahin et al. 2017), they have also been shown to reduce soil bulk density over time (Alam et al. 2016, 2020). Zhang et al. (2009) examined the long-term effects of subsoil-tillage, zero-tillage, and traditional cultivation on soil properties and crop yields in Daxing and Changping, China. They found after 8 years that soil bulk density was 0.8–1.5% lower in systems with subsoil tillage and zero tillage than in systems with traditional crop cultivation, a result that could be attributed to higher soil organic matter and better aggregation in the non-traditional treatments.

Many studies have shown that tillage system and residue retention significantly influence soil porosity and pore size distribution (Lipiec et al. 2006; Głąb and Kulig 2008; Gao et al. 2019; Li et al. 2019). The altered porosity and pore size distribution under CA have implications for soil-water storage and transmission and also for gaseous exchanges between soil and atmosphere. Macropores are responsible for soil effective porosity, which is related to its saturated hydraulic conductivity (Ahuja et al. 1989, 1998; Bhattacharyya et al. 2006). Tillage systems significantly affect soil pore size distribution (Lipiec et al. 2006). He et al. (2009) found that the total porosity, macroporosity, and mesoporosity in the 0–15 cm layer were similar under both traditional and CA system. However, significant ($P < 0.05$) differences were observed in the 15–30 cm soil layer. Compared with traditional crop cultivation, CA practices increased mesoporosity by 18%, which coincided with the changes in soil bulk density observed in the 15–30 cm soil depth. Similar findings were also reported by Zhang and Song (2004) who demonstrated that no tillage increased mesoporosity. As compaction increased, soil-water retention decreased, as the large pores which are strongly affected by structure at low suctions (0–100 kPa) are reduced.

The minimum disturbance of soil and residue retention under CA increases its hydraulic conductivity and water-holding capacity (e.g., Castellini and Ventrella 2012; Busari et al. 2015). He et al. (2009) recorded that the saturated hydraulic conductivity (Ks) of soil increased under zero tillage in the topsoil (0–30 cm soil layer). Zhang (2005) also recorded similar findings and demonstrated that hydraulic conductivity in a conventionally tilled and compacted loess soil was 28–36% of that in a non-compacted loess soil (CA system) in Shaanxi province, China. Singh et al. (2014) recorded higher hydraulic conductivity at different soil depths under zero tillage in rice-wheat cropping systems. They also reported an increase in hydraulic conductivity values due to the accumulation of soil organic carbon and minimal soil disturbance under zero tillage. The accumulation of soil organic carbon and macropore increase are likely to lead to higher water transmission in soils under zero tillage compared to those under conventional, tilled, and compacted soils.

Water runoff from agriculture systems, and the resulting soil erosion, is a consequence of limitations in soil water infiltration potential and compacted subsoil layers caused by hardpans and/or reduced macropores (Callebaut et al. 1985). As with other soil physical properties, CA practices in combination with residue retention also improve infiltration and decrease runoff by improving soil aggregate stability (Reeves 1997). However, runoff rates varied among conservation tillage practice. Several studies have shown that reduced till or no till resulted in equal or greater runoff than conventional tilled crop production systems (Smith et al. 2007). Singh et al. (2014) demonstrated that zero tillage increases soil water infiltration compared to conventional tillage practices by 28% in a clay loam soil. Alam et al. (2014) recorded higher soil water infiltration under soils which were minimally disturbed and with 30% of residues retained: after 4 years, zero tillage increased water infiltration by 18.4%, followed by minimum tillage (MT) which increased infiltration by 7.35% relative to a baseline cropping system with conventional tillage and full residue removal. Govaerts et al. (2007) observed that long-term CA management improved macropore networking in clay loam soil which directly enhanced soil infiltration.

Soil moisture-retentive (SWR) characteristics are also linked to tillage practice. Over an experiment, SWR at field capacity (−33 kPa) was initially higher in soil under conventional tillage practice, but SWR gradually increased in soil under zero tillage (Bescansa et al. 2006; Govaerts et al. 2009; Alam et al. 2014). Soils under zero tillage have greater water storage capacity than comparable tilled soils

(Fernández-Ugalde et al. 2009). Over the medium term, soil-water-holding capacity at field capacity was significantly higher in under zero tillage than under conventional tillage management, particularly in the topsoil where water retention is up to 23% lower under conventional tillage than under zero tillage (Fernández-Ugalde 2002; Alam et al. 2014).

28.3.2 Conservation Agriculture Enhances Nutrients Status and Availability

Globally, CA practice has been observed to improve the soil physicochemical properties which in turn support the long-term productivity of cropping systems (Corbeels et al. 2015; Sinha et al. 2019). Organic matter greatly affects soil chemical properties as it affects both sources and sinks of key nutrients and their transformations (Gathala et al. 2017). Under CA, the reduction in tillage, retention of crop residues, and targeted fertilizer applications increase soil organic carbon by influencing the quality and placement of organic matter inputs, as well as the rate of decomposition of organic matter, which ultimately resulted in soil higher organic matter concentrations under reduced till or no till treatments when compared to a conventionally tilled control (Dalal et al. 2011; Somasundaram et al. 2017). Crop residue load may be further increased by intensifying the cropping system, as well-retained crop residues will conserve soil moisture and facilitate additional crop production (Wilhelm et al. 2007). At the same time, increased crop residues increase soil organic carbon, thereby improving soil structures, bulk density, and cation exchange capacity (CEC) as well as soil water retention.

Early CA research demonstrated that it influences soil pH (Dalal et al. 1991; Guo et al. 2010). Over a 13-year study on the effects of nitrogen fertilizer on wheat, Dalal (1989) demonstrated that pH and SOC in the top 10 cm of a Vertosol were negatively affected under ZT. Another long-term study on a Luvisol in a subtropical semiarid climate in Southern Queensland, Australia, found that over 9 years, soil pH was not much affected in top 0–10 cm layer by tillage or stubble retention treatments, but that pH decreased significantly with the application of nitrogen fertilizer (Thomas et al. 2007).

The higher availability to plants of nitrogen under CA management is primarily achieved through greater residue retention which acts as a nitrogen store (Thomas et al. 2007; Page et al. 2019; Sithole and Magwaza 2019). While the high biomass addition from crop residues in CA systems increases the total store of soil nitrogen, in the initial years of CA implementation, reduced plant nitrogen availability is often observed as the additional nitrogen is not immediately present in a plant-available form (O'Leary and Connor 1997). The addition of nitrogen fertilizers is required to maintain yields (Mrabet et al. 2012; Sithole and Magwaza 2019). In weathered soils, enhanced organic phosphorus storage in macroaggregates (Fonte et al. 2014; Nesper et al. 2015) indicates the effects of crop management on soil aggregation and may result from alterations in the availability of phosphorus through means other than soil phosphorus fixation. Tillage practices and crop residue management influence phosphatase enzymes which facilitate phosphate mineralization (Nannipieri et al. 2011). Increased availability of soil potassium has been reported from several CA studies (Zhao et al. 2017; Sithole and Magwaza 2019) and is mostly attributed to higher additions of organic matter through residue retention.

Little information is available on the influence of CA management on the availability of soil micronutrients, as most research has targeted the response to CA of macronutrients, in particular of nitrogen, phosphorus, and potassium (Jat et al. 2011; Margenot et al. 2017). Under CA, the practices which affect SOC content as well as in-soil reactions of macronutrients may play a crucial role in the availability of various micronutrients also (Verhulst et al. 2010; Jat et al. 2018). Variability in soil CEC under CA has been reported by several earlier findings, who reported that in some cases, CEC was higher due to more SOC being present under CA practices which increased negative charges (Duiker and Beegle 2006; Sa et al. 2009).

28.3.3 Conservation Agriculture Enhances the Activity of Beneficial Living Organisms in the Soil

Under CA, soil disturbance is reduced and crop diversification increased, including the growing of cover crops to improve soil health and sustainable increase cropping system productivity (Corsi and Muminjanov 2019). The capacity of a soil to sustain all living organisms, cycle water, carbon, gasses, and nutrients properly, maintain its structure, and promote human livelihoods is known as its ‘soil health’ (Kibblewhite et al. 2008). Soil health is an integrative property that quantifies the capacity of the soil to support sustainable agricultural practices (Frąc et al. 2018; Hou et al. 2020). Sustainable crop productivity depends to a great extent on the physicochemical and biological properties of the soil and the related soil biodiversity (Huera-Lucero et al. 2020; Lehman et al. 2015). Different living organisms play a pivotal role in breaking down organic matter by processes of comminution and chemical mineralization. The released nutrients are taken up and used by crops; however, some inert organic substance, known as soil organic matter (SOM), remains unchanged. SOM increases the water-holding capacity of a soil, facilitates edaphic life, and sequesters atmospheric carbon to increase the soil organic carbon. Maintaining or increasing ecosystem services and sustainable agricultural productivity are great challenges for today’s farmers globally. Sustainable soil management, including CA practices, plays a key part.

The complex communities of flora and fauna in soils are commonly known as the soil microbial biomass (SMB). SMB includes bacteria, cyanobacteria, algae, yeast, fungi, myxomycetes, and actinomycetes: these microorganisms decompose organic matter and release mineral nutrients which plants absorb. Diversity in soil biota is one of the key indicators of soil health (Leskovar et al. 2016). Earlier research has demonstrated that soil microbial activity is positively influenced by reductions in tillage combined with the retention of crop residues (Habig and Swanepoel 2015; Leskovar and Othman 2018; Leskovar et al. 2016). A CA experiment, conducted in Jilin Province, China, reported more microbial organisms in the top 5 cm of a black soil with no tillage and with residues incorporated than in soils under traditional cultivation. Increased soil microbial metabolic activity under CA was observed up to a depth of 20 cm (Sun et al. 2016).

The population of actinomycetes and bacteria increases under reduced tillage compared to tilled soils (Li et al. 2020). In a global meta-analysis, Li et al. (2020) reported that zero tillage combined with residue retention increased the population of actinomycetes and bacteria by 28% and 3%, respectively. Guo et al. (2016) reported that zero-tillage-enhanced soil microbial activities in a rice (*Oryza sativa* L.)—wheat (*Triticum aestivum* L.) cropping system in Central China; soil structure was also improved. Further, the improved soil health increased soil organic carbon levels by promoting dissolved organic carbon within the soil. In another study, Sun et al. (2018) observed that reduced-tillage and no-tillage enriched bacterial communities over those recorded under conventional tillage in Hebei province, China, and that total soil carbon was more highly correlated with bacterial population than with fungal biomass.

The CA principle of crop rotation also influences microbial activity (Umaerus et al. 1989). Triple crop rotations such as sweet potato-winter wheat-summer maize and spring peanut-winter wheat-summer maize have resulted in higher cropping system yields and improved soil quality than achieved in the common winter wheat-summer maize cropping system (Wang et al. 2020). Wang et al. reported that including either sweet potato or spring peanut in the crop rotation increased soil microbial activity which in turn improved soil organic carbon, total nitrogen, available phosphorus, alkaline phosphatase, and urease activity. Balota et al. (2003) and Spedding et al. (2004) reported that reduced tillage in combination with residue retention increased SMB and soil carbon and nitrogen levels in the 0–10 cm soil layer in maize-based cropping systems compared to reduced tillage along. Other research reported higher concentrations of SMB and soil carbon and nitrogen under zero tillage in the 0–20 cm layer than compared to conventional tillage practice on Ultisols in southern Chile (Alvear et al. 2005). Soil microbial populations are positively influenced by reduced tillage alone; however, the effects of reduced or zero tillage on soil microbial presence are enhanced where crop residues are retained and/or incorporated.

The most important soil meso- and macro-fauna are springtails, mites, epigeic worms, and earthworms, millipedes, isopods, myriapods, and insect larvae. These connect soil biological activities with soil biological properties (Sofo et al. 2020) and influence soil aggregation and structure by breaking down soil litter. Soils under reduced tillage have minimal disturbance and also greater available soil organic carbon as a result of the incorporation of crop residues; both these factors improve the soil habitat for meso- and macro-fauna (Bedano and Domínguez 2016; Hiel et al. 2018; Page et al. 2019).

Some soil arthropods (e.g. coleoptera and Araneae) incorporate organic matter into the soil and improve its structure (Pretorius et al. 2018; Alyokhin et al. 2019). The populations of insects such as spiders, carabids, and staphylinidis beetles increase in soils following the uptake of reduced tillage and other CA practices.

28.4 Conservation Agriculture Improves Crop Productivity

Conservation agriculture management practices include maintaining as far as practicable a stable soil cover, minimizing soil disturbance, and maximizing crop diversification in order to maintain or increase cropping system yields while sustaining natural resources and protecting the environment (Kassam et al. 2019). CA practices which show promise in the key South Asia rice-wheat cropping system include dry seeding of rice, (DSR) and zero tillage (ZT) in wheat, with the retention of previous crop residues in rice and wheat. The potential of CA to improve crop productivity is widely accepted (Farooq and Siddique 2015; Alam et al. 2017; Kassam et al. 2019), but it is known that the optimal CA practices are highly location-specific and vary across South Asia. The advantages of CA are generally not fully realized by small and marginal farmers within the region because of a lack both of understanding of the nuances of CA management and of technical skill to implement the practices. For example, farmers are often not aware of the amount of residue required to be retained after harvest, of irrigation scheduling requirements, or of the selection of a suitable rice cultivar and corresponding establishment method.

CA management practices facilitate improved crop establishment and timely sowing, increase yield, reduce irrigation water requirements, lower production costs, and boost income in farmers' fields across South Asia (Gathala et al. 2020). In Bangladesh, the adoption of CA has been primarily limited to the major food grain crops rice, wheat, and maize (Farooq and Siddique 2015; Kassam et al. 2019). Recently, CA has been tested in other crops including pulses, oilseeds, and jute with promising results (Barma et al. 2014). Across South Asia, CA not only increases cropping system yields over traditional tillage-intensive tillage systems, it also significantly reduced the cost of cultivation (Fig. 28.2), by up to 41.3% of the

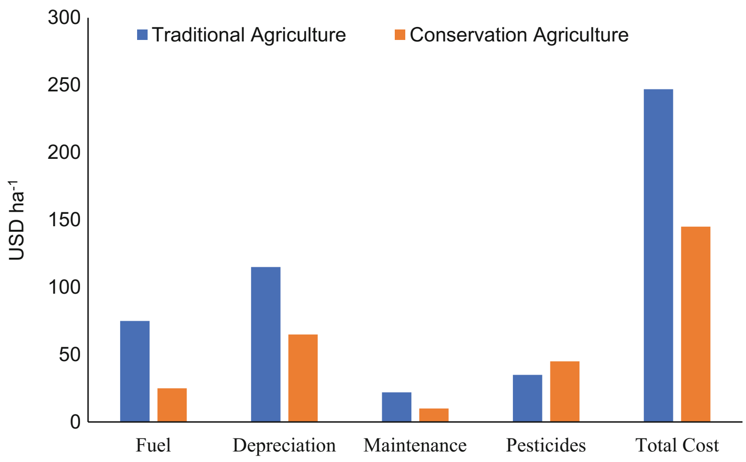

Fig. 28.2 Cost comparison of traditional and conservation agriculture (source: Farooq and Siddique 2015)

cost of cultivation under traditional practice (Meena et al. 2010; Farooq and Siddique 2015).

The performance of CA under rice-wheat cropping systems varies from the time of introduction of the CA management across South Asia (Rehman et al. 2015). After initial conversion from traditional practice to CA, the average yield of crops under CA is sometimes lower than that of crops grown under conventional tillage, which may be due to increased root penetration resistance, sometimes combined with an initial drop in plant-available soil nitrogen (Farooq and Siddique 2015). However, after three to five crop cycles, crop productivity under CA increases above that observed in crops under conventional management, due increases in soil health, plant-available nutrients (including water), and plant biomass (Nawaz 2012).

The benefits of CA, in terms of increased productivity and reduced cultivation costs, are most apparent in the non-rice aerobic crops wheat, maize, and pulses (Bell et al. 2018). The increase in cropping system productivity following the adoption of CA is positively correlated with years since its adoption; thus, more widespread uptake of CA occurs after farmers have had time to see the benefits over a few seasons than can be observed in a shorter period (Bell et al. 2017, 2018). In of the experiments conducted across a number of countries in South Asia, wheat yields under zero tillage with rice residues retained were comparable to the yields achieved under conventional management, but overall total net return and cropping system productivity were significantly higher under the CA system than under the control (Singh et al. 2016; Alam et al. 2017; Kassam et al. 2019).

Conservation agriculture management practices are more viable in areas at risk of drought stress, where mechanized seeding operations and crop establishment utilizing residual soil moisture still present immediately after the harvest of wet-season rice (Hossain et al. 2009). Upland (rainfed) crops also benefit from CA management in terms of higher yields, reduced tillage costs, and turnaround time between crops (Hossain et al. 2015). Hoque and Miah (2015) observed significantly higher cropping system yields under CA practices than under conventional crop establishment in upland wheat-maize cropping systems. Rehman et al. (2015) and Gupta and Seth (2007) reported the benefits of increased wheat yields under CA from several experiments across South Asia ranged between 1% and 39% with an average yield advantage of 11% over traditional wheat management. The benefit of CA practices can be further explored by using cropping system models such as APSIM (Holzworth et al. 2014) or DSSAT (Corbeels et al. 2016) to examine complex research questions including the timing of mulch applications, the amount of residues to retain, optimal tillage methods for a location, and the impact of climate change on cropping system management options (Naveen-Gupta et al. 2016). CA provides an opportunity for the resource-challenged, risk-averse farmers in South Asia to sustainably increase their crop productivity and profitability to meet their food security needs and to grow more lucrative cash crops than the traditional rice-wheat cropping systems.

28.5 Conservation Agriculture Is Cost-Effective and Environmentally Friendly

Across South Asia, country populations continue to expand, and the region will need to produce up to 33% more of key food grains such as rice and wheat by 2015 to meet additional food demand. Current cropping intensities are high across the region, and there is little scope to expand the footprint of arable land due to competing demands from other economic sectors. Options to increase food productivity are the adoption of new crop varieties adapted to increased productivity under climate change and the scaling out of conservation agriculture management practices (FAO 2009a, b). Here we present a case study of the potential to adopt CA practices in Bangladesh.

Research has demonstrated the productivity and soil health benefits of conservation agriculture for agriculture in Bangladesh (Akteruzzaman 2018). Agriculture contributes more than 10% to Bangladesh's gross domestic product (Government of Bangladesh 2019) and employs more than 39% of the country's total labour force (World Bank 2020). Retaining or increasing soil fertility, reducing crop production costs, and increasing yield and cropping system profitability by promoting the uptake of CA practices will substantially increase Bangladesh's economic growth.

To date, uptake of CA practices in Bangladesh is very limited, despite enormous potential for the practices. Eighty percent of the arable land in Bangladesh is cultivated using two-wheeled tractor-driven power tillers (Mottaleb et al. 2017): in 2014, there were more than 550,000 power tillers in Bangladesh. The widespread prevalence of these power tillers indicates the enormous potential for Bangladeshi farmers to adopt two-wheeled tractor-based CA machinery. To achieve widespread uptake of CA machinery, socioeconomic challenges will need to be overcome, with the support of CA-enabling government agricultural policies.

Globally, the potential maximum area over which CA is estimated to be suitable is around 38–81% of the total global arable land; by 2018, 9–15% of the total global arable land was under CA-based management systems (Prestele et al. 2018). In Bangladesh also, the adoption of CA has been limited. Currently, there are well-established systems of service provision for irrigation and tillage services, where well-resourced farmers or entrepreneurs lease irrigation or tillage machinery to other nearby farmers (Mottaleb et al. 2017, 2019). As yet, the service provision model has not yet extended in Bangladesh to include crop establishment under minimum or zero tillage. A study of the market potential for zero-till service providers in Bangladesh found that farmers' social networks, awareness of new practices, and the opinion of their spouse and/or other family members all affect the uptake of conservation agriculture (Keil et al. 2015; D'Souza and Mishra 2018). It is thus imperative to ensure that farmers' clubs, farmers' field days, and general education and training opportunities for farmers are avenues through which their awareness of CA can be raised and they can explore avenues to test and adopt the practices. Additionally, the implementation of strong government policy in Bangladesh which supports the scale-out of conservation agriculture technology will be crucial to underpin long-term benefits of CA within the country.

28.6 Conclusions

In the current chapter, we have reviewed earlier studies to illustrate that conservation agriculture is a next-generation, climate-resilient agricultural technology which contributes to increased food security and environmental health. Under the green revolution, then-modern technologies improved cropping system productivity, while inadvertently leading to conditions where high-input farming degraded agricultural landscapes and polluted the environment. The widespread introduction of CA management practices across South Asia will be critical to facilitate sustainable, intensified cropping systems which will maintain or increase the productivity and profitability of the region's rice-based cropping systems while concurrently managing the natural resources (i.e. soil, water, energy) in an ecologically and environmentally friendly manner.

Conflict of Interest All authors declare no conflict of interest.

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29

Socioeconomic Challenges and Prospects in the Adoption of Conservation Agriculture Practices in India

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Abstract

Conservation agriculture (CA) though a good technology capable of protecting the soil resources its rate of adoption by Indian farmers is not so promising. This chapter discusses major reasons behind the low adoption of CA with the help of 'social learning model' of diffusion as farmers mostly adopt innovative technologies because of its outcome in prior adopters field rather than the scientific advantage of the technology; and the 'progressive farmer strategy' in technology transfer as extension worker-progressive farmer attraction is observed to be another factor that slow down the rate of technology adoption. In fact, demonstrations of CA technologies in different cropping systems of India convey that farmers benefitted economically and ecologically with those technologies. However, knowledge-intensive nature of CA demands strong awareness generation about the technology among the rural farmers of India to fuel up its adoption rate. Moreover, the heterogeneity of farmlands throughout the country demands more farmer field demonstrations of the CA practices to make it need based rather than a 'one-size-fits-all' technology.

Keywords

Conservation agriculture · Diffusion models · Adoption of CA

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29.1 Introduction

Agriculture is the main source of livelihood for a lion share (>60%) of rural population in India. Conventional farming practices include deep intensive tillage of farmland and residue burning before crop season is an unavoidable management practice for crop production. The concept of conservation agriculture (CA) emerged as an alternative to tillage-based soil management in the United States of America (USA) during late 1930s. It started getting importance and acceptance in Indian agriculture in the last 10–15 years at a slow pace. The CA system emphasises on 'sustainable production intensification' with its three complementary principles viz., minimum mechanical soil disturbance, permanent soil organic cover, and crop diversification. It ensures a sustainable livelihood to the farm family along with conserving environment and its resources, reduces degradation of agricultural land and ecosystem services, and promotes rehabilitation of already degraded agricultural lands (Food and Agriculture Organization 2001; Kassam et al. 2013). For a country like India where area of degraded lands increased from 94.5 million hectares (2003–2005) to 96.40 million hectares (2011–2013) in a span of 5 years (SAC-GoI 2016), the potential of CA seems to be ideal for the management of degraded agricultural lands as well as to prevent further land degradation. However, data on expansion of land under CA in India is not promising as it is hardly 1.5 million hectare (0.96% of the arable land) since 2013–2014 (Kassam et al. 2019). The adoption level of CA is very low in India compared to developed nation such as the USA, South America, and Australia. Low adoption of CA practices in India is mainly because of lack of knowledge of farmers about farming with minimum tillage and permanent soil cover (Ramasubramaniyan et al. 2016).

Recently, the Indian Council of Agricultural Research (ICAR), the apex body for agricultural research, technology development, and dissemination in the country, has also started some efforts to popularise CA among the farming community through organising farmers' trainings, field days, and frontline demonstrations using its institutional networks. Moreover, ICAR formulated *Consortia Research Platform on Conservation Agriculture* in 2015 to carry out basic and strategic research on various aspects of CA so as to identify ideal farming practices that are ecologically, economically, and socially sustainable for the rainfed and irrigated agriculture systems of the country. However, it may take a long-time period to get CA practices adopted by the farmers of India as CA practices do not provide an immediate visible result like that of hybrid seeds, fertilizers, and plant protection chemicals. In fact, even in developed countries, achieving widespread adoption of new farming practice is not easy if that is complex or different from the current farming practice (Pannell 1999).

29.2 Factors Affecting Diffusion and Adoption of Conservation Agriculture

Diffusion and adoption are the two interrelated concepts that play a major role in the effective technology transfer of agriculture innovations. Diffusion is a social process, and it is defined as the process by which an innovation is communicated through certain channels over a period of time among the members of a social system (Rogers 1983), and it takes place autonomously without much effort (Roling 1988) once the innovation entered into the social system.

29.2.1 Rationalisation Based on Diffusion Models

There are several diffusion models that explain diffusion process in different ways. Young (2009) explained about three categories of diffusion models viz., *contagion model*, *social influence model*, and *social learning model*.

1. *Contagion Model* explains that a non-adopter will adopt an innovation as soon as he/she encounters an adopter. In this model innovation spread in the social system similar to that of an epidemic.
2. *Social Influence Model* suggests that people adopt an innovation when a reasonable proportion of the population have adopted it. Here, the individuals are assumed to have different 'threshold value' of social pressure that determine their adoption. In fact, individual adoption is considered as a function of number of other adopters in the population, i.e. innovation spread because of conformity motives.
3. *Social Learning Model* proposes that people adopt an innovation after seeing enough evidences about the benefits of the innovation from the prior adopters that convince them the innovation is better than what they are doing now. According to this model, individuals adopt an innovation at different time based on the variations in their belief, amount of information gathered, and the cost involved in adoption.

Social learning model of diffusion is a widely conferred diffusion model among the researchers as other two models failed to explain the reason behind the adoption of innovation. Sadoulet (2006) observed that social learning model of diffusion works well when farmer characteristics and/or farm field conditions are ideal across farmers, in other words in a homogenous population. He explained the model with some modifications as *Susceptible Infected Model*. Rationale of this model is that being informed about an innovation does not lead to adoption instead that make the person susceptible to adopt and informed non-adopters adopt the innovation with a certain probability that depends upon their characteristics. Here, the differences in farmer characteristics make the population heterogeneous.

Social learning emphasises on learning from the performance of the innovation from the outcome and experiences of prior adopters. Therefore, if the individual fails to observe the prior adopters' background, decisions, and experiences perfectly that impact the performance of the new technology with the new adopter, he/she may not adopt the new technology that would make the information flow weaker in the social system (Munshi 2004). Most of the people do not evaluate an innovation on the basis of scientific studies of its consequences, but they rely on the subjective evaluation of the technology that is conveyed to them by others like neighbours, friends, or who adopted the innovation (Rogers 1995). This observation makes the social learning model more important to the agricultural technology transfer process especially in the diffusion and adoption of *preventive innovations* like CA where the benefits (improvement in soil health, higher crop yield and net income, conservation of land resources, etc.) to the adopters are often delayed. In fact, getting an innovation adopted even when its advantages are evident is often difficult (Rogers 1995), and preventive innovations not only provide delayed results but also demand an action at specific time period to avoid some unwanted consequences at a future time period (Rogers 2002). Moreover, several studies showed that adoption of CA has direct relation with the farmer characteristics (Gould et al. 1989; Laxmi and Mishra 2007).

Being a country with diverse agroclimatic situations, crops, and cropping patterns, social learning is evidently weak in the diffusion of CA in India. For example, adoption of CA began in India during the 1990s in the form of 'zero-tillage' practices for the winter-wheat crop in the rice-wheat system of North Western Indo-Gangetic Plains mainly to lower the cost of cultivation through reduced use of fuel and labour (Malik et al. 2004; Friedrich et al. 2012). However, CA practices are not so prominent in other parts of India like rainfed semiarid tropics and arid regions of the mountains (Bhan and Behera 2014). The study of Foster and Rozenzweig (1995) provided confirmation for social learning process in the diffusion of agricultural innovations during the Green Revolution period in India. They also confirmed that imperfect knowledge about the management of new technologies was the major barrier of adoption, but this barrier weakened with increase in farmers' experience. Technologies contributed more profit to those adopters with experienced neighbours than those with non-experienced neighbours. There are no such reports available for CA as there are not many studies carried out in India that assess diffusion and adoption of CA technologies in the country.

29.2.2 Rationalisation Based on the Progressive Farmer Strategy in Technology Transfer

According to Roling (1988), extension worker-progressive farmer magnetic effect is one of the barriers that prevent an innovative agricultural technology to reach those who need it more. In general, the progressive farmer strategy otherwise known as farmer-to-framer extension model assumes that extension system is faced with homogenous population of farmers who produce same product; only a few among them are venturesome than others who adopt innovative ideas first and make profit, and others will copy them after seeing their benefits. This is the reason why mostly agricultural innovations are being demonstrated in progressive farmers' fields.

Roling explained why extension service in the world operates at progressive farmer strategy in his book *Extension Science: Information System in Agricultural Development* as:

1. Progressive farmers mostly own large operational holdings, and the production targets of extension worker could be easily met with that without much effort.
2. Progressive farmers are mostly successful in controlling their production environment, and convincing them is relatively easy.
3. Demand for assistance from progressive farmers insists extension workers to make more visits to their farmlands.
4. Progressive farmers are mostly economically strong enough to try new ideas or technologies.
5. Progressive farmers homophilous with extension workers that make their communication easy.
6. Progressive farmers are often a professional challenge to the extension worker as these farmers always aspire for good farming standards.

The idea behind the progressive farmer-oriented technology transfer is for motivating others by seeing the benefit of early adopters' experience; however, the difference in socioeconomic background and on-farm resources among farming population makes it difficult to copy the technology to another farm field. Muneer (2014) identified that progressive farmer strategy often creates inequality in getting benefits of extension services between the farmers with relatively limited resources and the resource-rich farmers of the same locality and that in turn widen the income gap between the two groups. Also, a small percentage of farmers who are recognised as the leaders of agricultural modernisation (Blanckenburg 1972) otherwise called as 'rural elites' (Chambers 1983) who need least amount of information get most of the extension services and that keep the rest of the farmer group away from information. Under these situations, the agricultural extension workers are being mostly conveyed by the interests and needs of these 'rural elites' as farmers' priorities for development.

All India report on agriculture census 2010–2011 conveyed that in India, nearly 95% of the farming population is of marginal (less than 1 ha landholding), small (1–2 ha landholding), and semi-medium (2–4 ha landholding) and 68.8% of the landholding are owned by these three categories who practice mostly conventional tillage in their farmlands. Hence, progressive farmer strategy may become a serious hurdle in motivating these farmers to adopt CA because convincing small and medium farmers that farming is profitable with minimum or zero tillage is tedious (Bhan and Behara 2014) if the demonstrations on CA will be carried out only under the resource-rich condition of progressive farmers.

29.3 Prospects of Conservation Agriculture in India and Possible Challenges in the Diffusion of CA: Experience from other Developing Countries

Farmers adopt new agricultural technologies for a variety of reasons. However, factors which motivate smallholder farmers to adopt a particular technology used to be more or less similar throughout the world. Major reasons behind farmers' shift to CA practices used to be associated with deteriorating soil health due to land degradation, soil erosion, or declining soil fertility. According to the Food and Agriculture Organization, smallholder farmers are often aware of soil degradation in many cases, but they hardly address these problems because mostly they make decisions about the use of their soil resources under the constraints imposed by their on-farm resources and socioeconomic status. So, other factors of production mask the soil health management needs. The conceptual framework given by FAO for studying the adoption of conservation agriculture (Fig. 29.1) explains various factors that affect farm family's technology choice and decision in using the farm resources (FAO 2001).

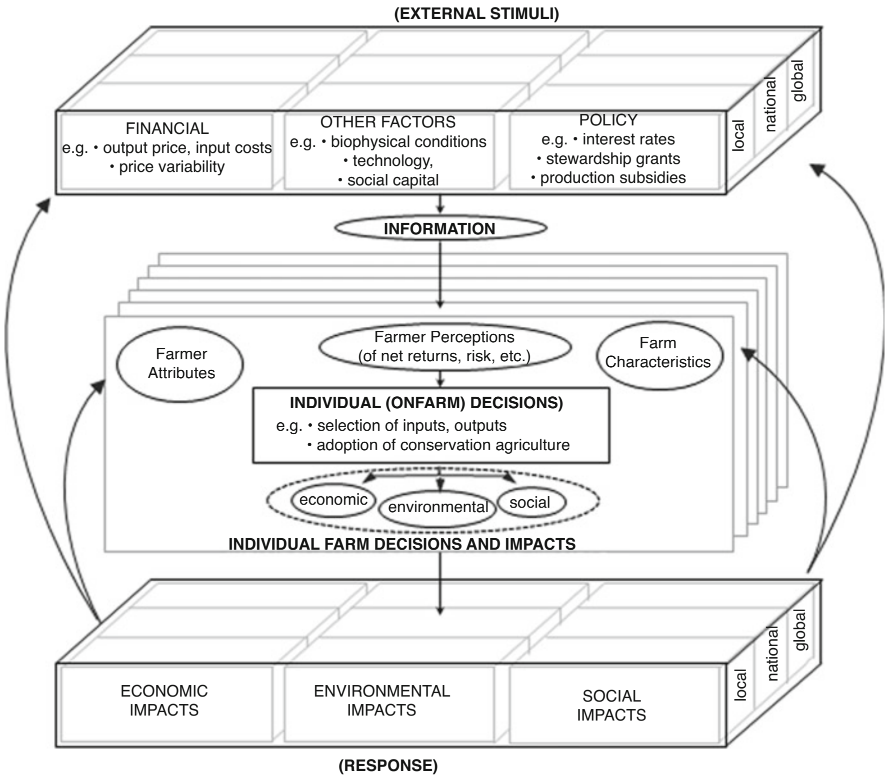

Fig. 29.1 Conceptual framework for studying the adoption of conservation agriculture

In India, along with soil degradation problems, the increasing cost of cultivation also puts smallholder farmers under risk of debt. The average real cost of cultivation is increasing steadily at the rate of 2.14% per annum over the past 25 years. However, the change in gross return is disproportionate, and the net farm income received by the farmers during 2005–2006 was better than that of 2014–2015 (Srivastava et al. 2017). Moreover, agricultural work force in the country is also moving away from the primary sector, and it has declined by 30.57 million between 2004 and 2005 and 2011 and 2012 (FICCI 2015). This labour shortage in the agricultural sector might be also a factor behind the hike in daily wages of agricultural labours in the country. Under these situations, adoption of CA practices definitely provides an additional monetary benefit to the all groups of farmers in India by reducing the cost of cultivation without compromising crop yield.

Evaluation of CA in the rainfed uplands of Odisha district in India gave economic benefit with minimum tillage for maize intercropped with mustard though the economic advantages with reduced labour were largely offset with the increased labour requirement for weeding (Pradhan et al. 2016). In another evaluative study of Happy Seeder, the machine developed for the in situ management of paddy straw showed around 14.8% reduction in cost of cultivation in the rice-wheat systems of Punjab (@Rs.2310 per ha) by adopting conservative tillage practices and sowing of wheat crop using Happy Seeder after the rice crop (Dhillon 2016). Estimates show that adoption of CA in Punjab benefited the state indirectly by saving 0.30 million ha meter of water, 176.69 million kwh of power, and Rs. 50.53 crore in power subsidies annually (Sidhu et al. 2010). These reports suggest that expansion of CA to different parts of the nation not only benefit the farmer and farmlands but also can make positive impact on a range of scarce resources of the nation. However, in order to improve the adoption status of CA in India, it is necessary to formulate ideal strategies that motivate farmers to adopt the CA technology package. For this, analysis of the performance of technology under farm field conditions of various CA-adopted countries with more or less similar agricultural situations, their technology transfer approaches, benefits of adoption, and constraints is required.

29.3.1 Success of CA in the Intensive Rice Systems of Bangladesh

In the intensive rice-based cropping systems of Bangladesh, CA has been promoted by Murdoch University, Australia, in collaboration with Bangladesh Agricultural University, Bangladesh Agricultural Research Institute, and Bangladesh Rice Research Institute through public-private partnership approach. The promotional activities were mainly carried out under the CA project supported by the Australian Centre for International Agricultural Research. Various stakeholders involved in the approach were farmers, researchers, extension officers, agricultural input suppliers, machinery manufacturers, and local service providers (who offer custom hiring of ploughing, pumping, and threshing services to smallholder farmers). The promoters of the technology established a Conservation Agriculture Service Providers Association (CASPA) together with 9800 farm families of

224 farmers' groups and linked the association with local service provider network, and the Department of Agricultural Extension, Bangladesh. CA technologies ideal for the rice systems like non-puddled transplanting using versatile multi-crop planter powered by a two-wheel tractor were developed. Farmers were trained on CA practices through on-farm demonstrations, field days, focus group discussions, and promotional meetings. Demonstrations on CA were carried out in a participatory mode where only critical inputs were provided through the project. Farmers who adopted CA with non-puddled transplanting gained more grain yield for lentil, mung bean, and wheat at 38%, 8%, and 6%, respectively, over conventional rice farmers. Moreover, farmers who practiced three-crop rotation with monsoon rice, wheat, and mung bean crops in a year as a part of CA could achieve greater net profit (29%, 54%, and 14%, respectively) (additional income of 372 USD ha^{-1} in a year) compared to farmers practicing conventional tillage + conventional puddled transplanting (Bell et al. 2019).

29.3.2 Challenges in the Diffusion of Conservation Agriculture in Smallholder Farms

CA is such a complex technology that its adoption involves not only change in the cultural practices of the farm but also change in mindset of farmers too. However, in a scenario where tillage activities considered as symbol of agriculture making the leap to do away with tillage is difficult. The knowledge-intensive nature of CA in controlling weeds, sowing dates and time, management of crop residue and soil cover, crop rotations, and harvesting techniques, etc. is one of the prime reasons behind its slow adoption in the smallholder agriculture systems (Wall 2007). The success of CA in farmer fields depends more on what the farmer does (management) than on the level of inputs he applies (Ekboir 2002).

Further possible challenges that prevent adoption of CA in smallholder systems is the higher transition cost and constraints on key resources. In most cases, the positive net benefits of CA are not large enough to outweigh the transition costs. Shifting from an established farming system to a new one is likely to involve new machinery, infrastructure, and time required to learn about the performance of the new system and how to implement it. Also, constraints on key resources related to farm level economics of CA such as labour and capital, risk and uncertainty, interactions between enterprises, and time-related factors, such as interest rates and the urgency of providing credit for the farm family, have significant influences on farmers' decisions about whether to adopt the technology or not (Pannell et al. 2014).

Retention of crop residue as soil mulch is one of the important activities of CA systems feeding of livestock with crop residue in smallholder farming systems act as another constraint before CA. Like most of the smallholder systems in the world, livestock are an integral part of smallholder agricultural system in India. Since they benefit the farm family many ways like source of extra income, reduce human labour requirement in land preparation, source of manure for farming, and source of cooking fuel (cow dung cakes are used for cooking in many parts of India), alternative use of crop residues as soil mulch force them to make a compromise between residue retention on the field and cattle feed (Mueller et al. 2001).

29.4 Way Forward

Many researchers discourage promoting CA as a 'one-size-fits-all' solution to farmer fields because of the heterogeneity of farming circumstances. Also the approach is bound to waste the time and energy of the promoting agency and resources of farmers under those conditions where CA is not economically attractive to farmers. Also, the traditional linear model of technology transfer where researchers directly communicate their successful technology to the farmer will not work with complex technologies such as CA. Demonstration or on-farm evaluation of technology in a participatory and multidisciplinary mode is suggested as the best way to change the mindset of farmer to adopt CA practices (Pannell et al. 2014; Ekboir 2002). Under the heterogeneous farming conditions of Indian smallholder farmers, participatory field demonstrations are the best way to convince them about the benefits of CA over conventional agriculture. However, it is necessary to ensure that the demonstration leads to adoption while conducting demonstrations in farmer fields. Because, many times farmers agree for field demonstrations only for the incentives from the promoters, and these kinds of farmers hardly adopt new technologies. A study from Zambia (Habanyati et al. 2020) also recommends that the promoters of CA should focus on demonstrating the benefits of CA to smallholders rather than provision of material incentives to motivate them to adopt CA. Training them to become self-reliant in terms of on-farm resources through livelihood diversification helps to bring a change in their mindset to reduce their dependence on free inputs. Because, in most cases, free inputs make them incapable to compare the economic benefits of the new farming practice compared to their practice.

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Conclusions: Perspectives on Conservation Agriculture 30

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Abstract

Feeding the increasing global population, which is projected to increase between 8.9 and 10.6 billion by 2050, there has been increasing demands for more improved/sustainable agricultural management practices that can be followed by farmers to improve productivity and maintain environmental sustainability without jeopardizing the ecosystem. About 95% of our food directly or indirectly comes from soil. It is a precious resource, and sustainable soil management is a critical socio-economic and environmental issue. South Asia (SA) has been experiencing high economic growth but still suffering from extreme rate of poverty, hunger, and deterioration of natural resources including soil. In this region, the presence of a large rainfed area with its associated challenges urgently calls for cost-effective resource conservation technologies such as conservation agriculture (CA). The Indo-Gangetic Plains (IGP) of SA region is one of the hotspots for the adoption of no-till farming/CA. Although conventional tillage

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(CT)-based farming offers some important short-term benefits, long-term adoption of these practices may lead to the loss of soil organic carbon/fertility, poor soil health, and soil degradation. Conservation agriculture (CA) is being practiced globally approximately in 180 M ha of land, whereas in south Asia it remains less than 5 Mha. Thus, CA is one of the major sustainable soil/agricultural management systems that can meet the needs of farmers as well as offer numerous benefits to farmers as well as ecosystem services. CA is a multi dimensional approach that is studied not only for its positive environmental and ecological impacts but also as an alternative to reduce crop residue burning. In this chapter, issues, challenges, benefits, and future perspectives of CA have been discussed.

Keywords

Conservation agriculture · No-till farming · Soil organic carbon · Greenhouse gas emission · Ecosystem services · Future perspectives of CA

Feeding the increasing global population, which is projected to increase between 8.9 and 10.6 billion by 2050, there has been increasing demands for more improved/sustainable agricultural management practices that can be followed by farmers to improve productivity without jeopardizing the ecosystem (Amundson et al. 2015). About 95% of our food directly or indirectly comes from soil. It is a precious resource, and sustainable soil management is a critical socioeconomic and environmental issue. Maintaining the environmental sustainability while the world is facing resource degradation, increasing climate change and population explosion is the current challenge of every food production sectors. South Asia has been experiencing high economic growth but still suffering from extreme rate of poverty, hunger, and deterioration of natural resources including soil (Mozumder 2008). In India, the presence of a large rainfed area (86 M ha) with its associated challenges (Sharma et al. 2010) urgently calls for a cost-effective resource conservation technologies such as conservation agriculture (CA). The Indo-Gangetic Plains of India is one of the hotspots for the adoption of NT farming (Lessiter 2002; Somasundaram et al. 2020). Starting from the direct seeding of wheat in Punjab states of India and Pakistan during the 1980s, and establishment of the rice (*Oryza sativa*)-wheat (*Triticum* spp) consortium (RWC) established by CGIAR in 1994 to deal with the rice-wheat (RW) farming systems practiced extensively in the Indo-Gangetic Plains (IGP) and the Himalayan mid-hills of SA (CIMMYT 2002), CA has come a long way in Southeast Asia. Although conventional tillage (CT) offers some important short-term benefits such as better soil aeration (Da Silva et al. 2004), loosening of surface soil (Kay and Vanden Bygaart 2002), enhanced mineralization of nutrients, improved soil water infiltration rate (Pagliai et al. 2004), and proper root growth (Triplett and Dick 2008), the long-term intensive application of CT may disturb the soil structure at such a high intensity that leads to the loss of soil fertility and increasing soil degradation (Hand et al. 2016). CA is one of the sustainable technologies being recommended to achieve resilient intensification. CA is a set of

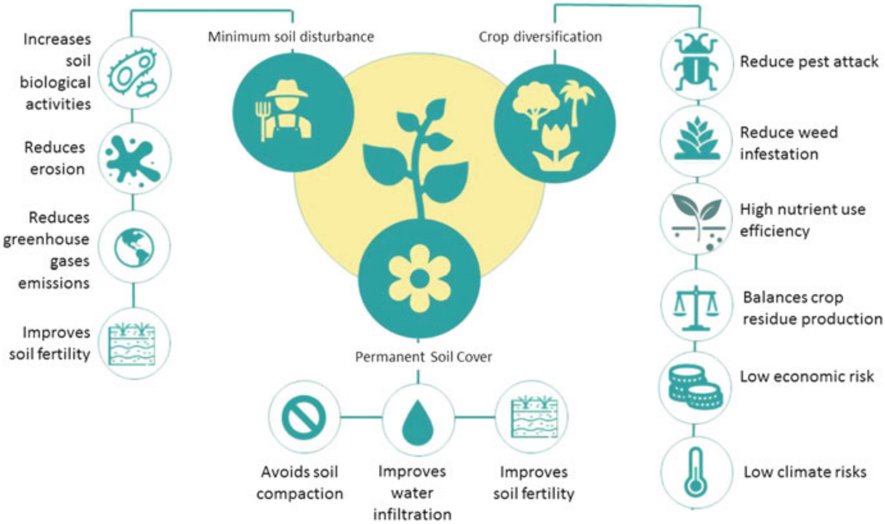

Fig. 30.1 The positive impacts of three management principles of CA

management principles that encompasses minimal soil disturbance, crop residue retention, and crop rotations or intercropping, with another fourth principle of integrated nutrient management (Lal 2015a). Conservation agriculture (CA) is being practiced globally approximately in 180 M ha of land (Kassam et al. 2014a, b, 2019), whereas in south Asia, it remains less than 5 Mha. Thus, CA is one of the major sustainable agricultural management systems that can meet the needs of the farmers as well as offer numerous benefits to farmers (Sayre and Hobbs 2004).

CA is a multidimensional approach that is studied not only for its positive environmental and ecological impacts but also as an alternative to reduce crop residue burning (Hobbs 2007; Sayre and Govaerts 2009) (Fig. 30.1). Soil as a medium for plant growth and support system for millions of fauna and flora is greatly affected by repeated burning of crop residues (Sarkar et al. 2018; Bhuvaneshwari et al. 2019). Changes in soil microbial activity upon crop residue burning depends on soil temperature, length of burning, rain incidence after burning, dominant group of microorganisms, and time of sampling (Mandal et al. 2004). The increased soil temperature at the time of residue burning not only inhibits and reduces the activity and diversity of soil microbes but also depletes soil organic carbon level (Gadde et al. 2009). Under CA, if 0.3 m high standing crop residue is left on the field, an additional amount of 1.6–2.0 t/ha of crop residue is being added to the field compared to the farmers' practice where almost all aboveground crop residue is removed. Retaining of this crop residue improves soil aggregation, infiltration, and organic C status and enhance biological properties (Ahmed et al. 2015; Somasundaram et al. 2017, 2018). Cropping systems that generates a huge amount of crop residues (rice, sugarcane, wheat, etc.) need to follow CA practices for proper utilization of these crop residues while reducing the negative impacts of crop residue burning. Retention of crop residues is also beneficial in improving nutrient-use efficiency, and it also reduces the agrochemical-related environmental pollution (Singh et al. 2005).

No-till (NT) farming, where soil is disturbed minimally, has an edge over the conventional intensive tillage practices in soil conservation, reducing costs and energy losses, and enhancing soil health (Fig. 30.1). The significant improvements in the physical (soil structure and aggregation, bulk density and penetration resistance, porosity, hydraulic conductivity, infiltration, runoff, and least-limiting water range) aggregation (Blanco-Canqui and Lal 2004), chemical (soil pH, CEC, TOC, TON, C:N) (Kern and Johnson 1993; Franzluebbers 2010; Dalal et al. 2011; Lal 2015b), and biological (potentially mineralizable N, soil microbial biomass C and N, soil enzyme activities, labile organic C and N pools) (Oorts et al. 2007; Abdalla et al. 2016) properties of irrigated CA-adopted soils have been highlighted. However, limited research is available on the efficiency of CA in rainfed soils (Somasundaram et al. 2019, 2020). Moreover, the long-term adoption of CA might suffer from challenges such as weed and pest management, stratification of soil nutrients and soil compaction (Chauhan et al. 2012; Chauhan and Mahajan 2012). In addition to it, the use of herbicides in CA has been increasing due to shortages of farm labour and concerns about the affordability of labour costs. The continuous use of herbicides in CA for a prolonged period will create problems such as herbicides resistance and dominance of particular weed species or changes in weed flora to a greater extent (Owen 2008, 2016). However, the strategic non-inversion tillage could minimize the turnover of deep-layer weeds seeds to the surface or exposing the surface weed seeds to predators and/or inhibition of weed seed germination through allele chemicals (Reicosky 2015). Therefore, through manipulation of timing, type of tillage, soil type, and cropping systems, occasional strategic tillage has been opted by farmers to deal with the negative impacts of long-term NT (Dang et al. 2015).

Inclusion of cover crops in CA can enhance the benefits of CA through soil quality improvement and reduce erosion. Therefore, to explore its maximum potential, right choice of cover crops is an important determinant in increasing the productivity of CA (Singh et al. 2015; Jat et al. 2019). The adoption of CA in pulse-based cropping system proved to be a feasible way of ensuring sustainable production of food and helps in maintaining ecological integrity. Crop residue recycling in CA has enabled to achieve sustainable crop production in pulse crop-based cropping systems in Central India (Kumar et al. 2019b).

In rice-fallow cropping systems of Eastern India, CA allows the utilization of carry-over residual soil moisture in post rainy season crop (Kumar et al. 2018). An approximate area of 22.3 Mha under rice-fallow system exists in South Asia (Gumma et al. 2016). CA finds it large scope in conversion of these rice-fallow lands into productive ecosystems (Dey et al. 2016; Kumar et al. 2018). With CA, pulse or oilseed crops are also potential candidate crops that can be used for efficient utilization of these fallow lands (Kumar et al. 2019a, b). The benefits of CA can also be explored in the areas with extreme weather conditions, increasing soil erosion, and undulating topography such as Bundelkhand region of India. The low moisture retention capacity of these soils demands for an alternative management practice such as CA that aims to improve in situ moisture conservation practices (Srinivasrao et al. 2013). CA also proved to be efficient in improving soil health and offering ecosystem services in hilly ecosystems of Northeastern India, predominantly occupied by acidic soils (Gosai et al. 2009). Although the prospects of CA varies according to the agroclimatic conditions, the expansion of CA from semiarid regions to arid areas raised uncertainties due to its extreme climates, unfavourable soil conditions, high-potential evapotranspiration, low and non-uniform distribution of rainfall and greater wind erosion. However, CA offers specific roles that are crucial for arid ecosystem such as moderation/reducing of evaporation, regulating water and nutrient in soil and reducing wind erosion, higher C sequestration, low emission of CO_2 flux from soil, and moderation of soil salinity (Abdalla et al. 2016). For CA to work successfully in arid zones, the three main principles, namely, minimum disturbances of soil through no and reduced tillage, permanent soil cover, and crop rotation, must be critically followed together or simultaneously for improving soil health, crop productivity through high nutrient and water efficiency, carbon sequestration, mitigation of climate change, and resource sustainability. These indicate high opportunities in promoting CA in diverse agroecologies, even though the efficiencies across various climatic conditions vary.

CA is also a promising practice that mitigates increasing greenhouse gases (GHG) through its better crop residue and nutrient management (Oorts et al. 2007; Abdalla et al. 2016). The crop rotations or crop diversification positively affects the carbon sequestration process through retention and generation of crop residue and root biomass in soil. The C sequestration in CA is accomplished through addition of carbon through residues, protection of soil organic carbon in soil aggregates under minimum soil disturbance (Somasundaram et al. 2017, 2018), and addition of soil organic carbon to deeper soil layers due to inclusion of legumes in the cropping system (Kumar et al. 2018; Sapkota et al. 2018; Jat et al. 2020). Therefore, optimum N management in CA is one of the prime factors in maintaining/increasing SOC stocks, reducing net GHG emissions, and sustaining food production. CA can sequester organic carbon at rates of 300–600 kg C ha^{-1} yr^{-1} depending on the type of soil and climatic conditions. However, the counterpart school of thought is given by some authors that conservation tillage may stabilize carbon but may lead to higher GHG emissions as compared to the conventional tillage. The nitrous oxide (N_2O) emissions from agricultural fields are mainly affected by quantity, quality, and timing of crop residues retained/N management, availability of nitrate (NO_3^-), and decomposability of carbon substrate in the field. In addition, Wang and Dalal (2015) highlighted the importance for life cycle analysis (LCA) (i.e. including pre-farm, on-farm, and off-site emissions) while accounting for GHG emission/the global warming impacts compared to considering SOC changes or N_2O emissions alone, yet it is crucial to accurately measure SOC changes and N_2O emissions in CA practices. Among cropping systems/crop diversification in CA, legume residues resulted in higher N_2O-N losses compared to non-legume. Therefore, to understand the complex process of GHGs emission in CA practices, it is mandatory to understand the relative importance of each CA components in carbon sequestration and climate change. CA can also help in restoration of degraded lands by improving their soil health.

Despite all the positive corpus of evidences supporting CA, scaling up CA practices for small-scale holders, especially in developing countries, has always been a challenge because of various agronomical, technological, and socioeconomic constraints. Low adoption of CA practices due to limited exposure, unsecure land tenure, lack of resources, shortage and unavailability of specialized implements, underdeveloped extension services, and lack of micro-finance mechanisms. However, these bottlenecks are location-specific and occur at certain hotspots of the world. For example, in Africa, because of the pastoral activities, old crop residues are used in mixed crop-livestock systems and are grazed during winter season, with less soil cover and protection from erosion (Mupangwa et al. 2012). The highly degraded African soils often require high amount of fertilizers or manure or better seeds, which are the current challenges to obtain through the dysfunctional markets (Morris et al. 2007). In South Asia, constraints such as communal grazing after a main crop, limited skills in weed management in CA systems, lack of credit systems suited for CA, etc. warrant the large-scale CA adoption (Lienhard et al. 2013). Low adoption rate of CA in developing countries such as India, Bangladesh, Nepal, Pakistan, and Sri Lanka could be attributed to the lack of awareness on CA, inconsistent results in field demonstrations, lack of suitable implements, and natural tendency to hesitate in switching from age-old conventional practice to a new system unless they are economically supported in case of loss of yield in early phases of CA adoption (Lal 2007).

Specialized machinery is needed in CA as standard periodic tillage operation is completely eliminated in CA and remains only for very specific tasks, such as creating the conditions by minimum soil disturbances of soil for seeding purpose and maintaining sufficient crop residue cover on the soil surface. Some of the issues such as farmers' perception, lack of awareness, weed management, crop residue management, and poor availability of specialized machines that can sow seeds in the presence of crop residues are greater challenges in CA adoption. With a view to enhance soil health, carbon sequestration and crop productivity in the untapped areas of rainfed regions, location-specific CA practices should be advocated appropriately.

Future perspectives for large-scale adoption of CA practices in South Asian region especially in India and other countries are given below.

- Dissemination of best-bet CA technologies for dominant soil types/cropping systems through participatory mode, strong linkages, and institutional mechanism/support.
- Need for optimum tillage intensity and crop residue retention based on the soil types and cropping systems under different agroecological zones.
- Need for policies and incentives/rewards for farmers vis-à-vis crop residue retention for stopping residue burning and carbon storage/ecosystem services.
- Availability of location-specific machineries/equipment for larger adoption of CA technologies.

- Need for suitable crop residue, nutrient and weed management options under NT/CA for small and marginal farmers.
- In-depth study on carbon storage, nutrient stratification-based fertilizer recommendation, GHG emissions, herbicide-resistant weed/weed-ecology/weed shift, residue-borne pest and disease under CA technologies (short-term to long-term basis) are required.
- Identifying socioeconomic constraints/issues/farmers' perception related to adoption of CA technologies are urgently required.
- Capacity building of farmers/stakeholders for better dissemination as these practices are highly machine dependent/intensive and efficient weed management.
- Information exchange and interactions between all associated stakeholders must be improved for adapting CA systems locally.
- As CA is not a farm management practice that serves as a one-size-fits-all solution/single prescription-solves for all the challenges faced by developing countries, it requires significant adaptation and fine-tuning of existing technologies to meet the specific needs of the farmers in target areas.

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