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Advances in Conservation Agriculture

Volume 2: Practice and Benefits

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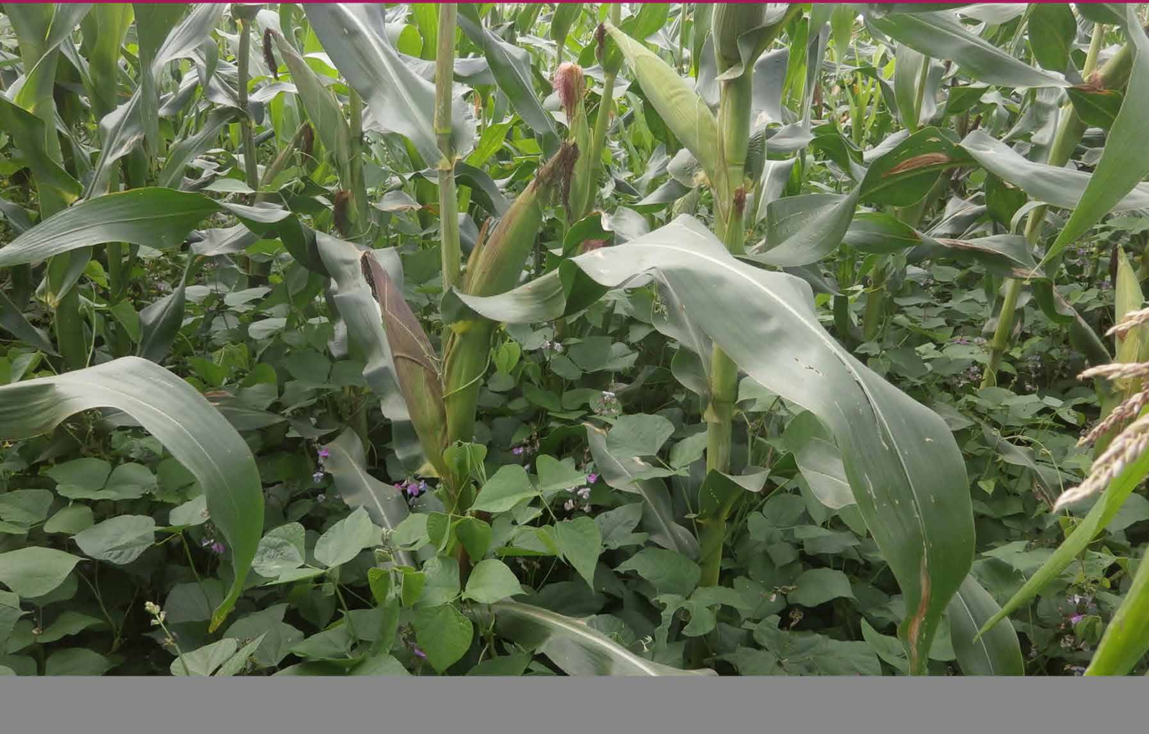

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Contents

Foreword

These volumes are a timely celebration of the most progressive change in farming practices that has been set in motion during the past 60 years and which is gathering momentum around the world at an extraordinary pace.

For thousands of years, soil inversion, whether by hoe or plough, has been almost universally applied by farmers and seen as essential for the successful growing of annual crops. Tilling the soil buries weeds, loosens the soil to let roots penetrate easily and allows rainfall to sink in and become available to the crop. By burying crop residues, it may also interrupt the life cycles of crop diseases and pests.

However, as the frequency and depth of tillage has increased, the negative effects have become more obvious. Every time soil is dug or ploughed, its structure is broken up and it becomes increasingly at risk to water and wind erosion. The speed with which soil organic matter content falls is accelerated, causing the surface to become susceptible to crusting, thereby reducing rainfall infiltration and increasing run-off while also restricting moisture retention capacity in the plant rooting zone below the surface. These processes tend to make crops and soils more vulnerable to drought and can ultimately lead to farmland becoming so degraded that it is abandoned.

As we understand more about the processes of climate change, we are becoming increasingly aware of the extent to which frequent tillage also contributes to global warming. As the organic matter content of soil falls this reduces the capacity of farmed land to serve as a carbon sink. Moreover, soil inversion, whether manual or mechanical, is very heavy in its energy requirements, with tractor use for ploughing accounting for a large share of the fossil fuel consumption in food production.

We are also belatedly learning that frequent soil inversion, especially when associated with heavy applications of pesticides, reduces soil biotic activity and undermines soil health with a corresponding fall in productivity.

The 'Dust Bowl' in the United States in the 1930's awoke farmers and scientists to the damaging effects of excessive tillage but it was not until the 1960s that American farmers began to adopt various no-till systems to reduce wind and water erosion. These set a precedent for the progressive emergence in the following decades of Conservation Agriculture (CA) which consists of a combination of continuous no tillage with year-round biomass soil cover and crop associations and/or rotations involving cover crops – often legumes.

The USA continues to be the country with the largest area under CA (43.5 million ha in 2015/16 or 35.1% of its arable farming area). Its farmers' associations are very active in pioneering new technologies, especially those related to the better use of cover crops in CA systems to increase Nitrogen availability and to cut herbicide dependence

One could claim that CA was ahead of its time in that it contains the main elements of what is now termed ‘sustainable agriculture’. Indeed, there is much to be learnt from the CA story of the past 60 years which is relevant to inducing the global shift that must urgently be made from the currently unsustainable food production and consumption systems to ones that are truly sustainable.

Five of such lessons from the CA experience are:

Firstly, CA shows that fundamental changes in farming technologies – in this case, getting rid of the plough - can spread very rapidly throughout the world, in both developed and developing countries in which it is being taken up by large and small-scale farmers alike. The area of arable land under CA has grown from about 2 million ha in the USA in the early 1970s to 180 million ha (12.5% of global cropland) in 78 countries in 2015-16.

Secondly, the growth in CA uptake and the adaptation of CA methods to different ecological and societal conditions has been driven largely by practitioners, especially innovative farmers and machinery and hand-tool manufacturers. Approaches to CA are constantly evolving and new developments are being openly shared between all those involved. The more that farmers find that CA can boost their incomes, the faster will be the pace of change.

Thirdly, formal research has been important in developing new approaches to CA but most studies have been focussed on identifying the impact of the shift to CA on crop performance; the physical and biological conditions of soils; global warming, and farm incomes. Such validation studies have help boost the case for policy support for CA.

Fourthly, in most countries, however, CA has so far spread between farmers without explicitly supportive government policies. It seems certain that the rate of diffusion can be accelerated by targeted incentives (for instance, subsidies on appropriate machinery and equipment, payments to farmers for soil carbon accumulation and enhancement of water resources) and improvements in agricultural extension.

Lastly, although international agencies such as the FAO have only invested quite small resources in CA, they have played a valuable catalytic role, mainly by promoting exchanges of experiences between practitioners, countries and regions and nurturing the emergence of regional promotional institutions. FAO has placed CA at the core of its vision for sustainable food and agriculture which calls for ‘a world in which food is nutritious, safe and accessible for everyone, where natural resources are managed sustainably, and where rural dwellers have decent livelihoods and contribute actively to economic development’. The FAO has also sponsored the foundation of a CA Community of Practice (COP) which shares new developments between its many members.

Although my own country, China, carried out trials on zero tillage from the 1980s, it was only after the turn of the century that the promotion of CA was adopted as a national priority. As a result, there has been a very rapid growth in the area under CA from just a few ha in 2002 to 9 million ha in 2015. The results have been good in terms of yield increases, especially for maize, and of reductions in erosion and river sedimentation. The government, therefore, intends to take additional measures to boost farmer uptake of CA including the recent creation of the China Institute for Conservation Tillage, technical support for the manufacture of improved machinery, subsidies for the provision of eco-systems services by farmers, and improvements in agricultural extension. It also intends to enhance the benefits of CA by linking its promotion to other aspects of its sustainable development agenda including Integrated Pest Management (IPM).

This edifying book is a compendium of much of what we have learnt across the world about CA. Its authors have all been deeply and enthusiastically involved in one way or another in the remarkable evolution and spread of Conservation Agriculture in recent decades. It will serve as an immensely valuable source of reference – and inspiration - for all those who are committed to putting the world's food systems on a truly sustainable footing.

It is with great pleasure, therefore, that I commend this book to you,

Qu Dongyu,
Director General, UN Food and Agriculture Organization (FAO),
Rome

Preface

Conservation Agriculture (CA) and its community of practice have made tremendous strides in the last two decades, particularly since the modern version of CA as we know it today was defined by the FAO at its first Regional Workshop on CA in Harare, Zimbabwe in 1998. The term CA was globalized through the 1st World Congress on Conservation Agriculture organized by the ECAF in partnership with the FAO in 2001 in Madrid, Spain. In 1999, the global spread of CA stood at about 45 M ha of cropland with some 10 countries in which CA was being practiced and promoted. In 2008/09, the global spread of CA was about 106 M ha of cropland across some 36 countries, corresponding to an annual rate of expansion of about 6.1 M ha. In 2015/16, the global spread of CA was some 180 M ha of cropland, split about equally between the Global South and the Global North, involving 78 countries. This corresponds to an annual rate of increase of some 10.5 M ha, a spectacular rate of transformation, led mainly by farmers and their associations with support from national and international champions and enthusiasts, many on a voluntary basis, and some national and international institutions. Although the spread of CA in the 1990s and 2000s was led by countries in North and South America and Australia, the spread of CA since 2008/09 across Europe (including Russia and Ukraine), Asia and Africa has been accelerating, making the transformation from conventional tillage agriculture to CA a truly global phenomenon.

The Green Revolution of the 1960s and 1970s was based on production intensification of wheat and rice, and later maize, relying on the unsustainable intensive tillage-based agriculture and expensive production inputs which brought short-term benefits to some types of farmers only in a handful of countries. The Green Revolution agriculture lost its effectiveness and appeal in the 1990s due to the unacceptably high negative economic, environmental and social impact as well as due to the loss of control by farmers of their own affairs related to production management and capital investment. The alternate CA revolution on the other hand has involved all types of smallholder and large-scale farmers, men and women, and rich and poor farming households, in all major land-based agro-ecologies in all continents. It has brought to the rural communities and society at large a wide range of productivity, economic, environmental and social benefits which cannot be harnessed with the conventional Green Revolution agriculture.

The expansion in area of CA across the world and the increase in number of smallholders adopting CA has benefitted from the growing support of the international research and development community including the FAO, the IFAD, the World Bank, the EU, CIRAD, and CGIAR as well as from many national and local level research and extension systems including NGOs, farmer associations and private sector service providers. Overall, the spread of CA since the very beginning has largely been led by farmers. Initially this was in response to the need to minimize soil erosion and land degradation, but soon this became a strategy to build and maintain soil health and productivity, reduce the high cost of production and diminishing returns, harness ecosystem services for society and nature, address climate change, and support pro-poor sustainable agricultural development strategies.

The CA Community of Practice is made up of many stakeholders and champions including farmers and their families, extension workers, development experts, researchers and academics, heads of institutions, policy analysts and decision-makers, as well as national and regional CA associations. Collectively, they have provided the pioneers and champions and support that keeps generating and sustaining the momentum to what has now become a global phenomenon, transforming conventional tillage-based agriculture into CA as the basis for sustainable agriculture and land use intensification. At the same time, they have generated enormous amounts of new knowledge, formal and experiential, as well as scientific and empirical evidence, regarding CA science and systems, CA practice and benefits and CA adoption and spread. All this knowledge and evidence constitutes the new understanding about regenerative and sustainable agriculture and represents the desire by the CA Community of Practice to move away from the degrading paradigm of tillage-based Green Revolution agriculture to the alternative paradigm of CA.

In light of the above, I was easily persuaded by the publisher Burleigh Dodds Science Publishing to take up the challenge of editing this book 'Advances in Conservation Agriculture' to bring together the latest state-of-the-art global knowledge and development-oriented information about CA science and systems, practice and benefits and adoption and spread. This book is purposely not designed to be a theoretical debate about what scientists and academics with no practical experience of real farming or of CA think about CA and how CA is performing internationally. Global scientific and empirical evidence speaks volumes about the productivity, economic, environmental and social attractiveness of CA to farmers in all continents. Globally, the rate of adoption of CA is accelerating but much remains to be explained in terms of the superior performance of CA, and also much remains to be innovated in the coming decades to maximize the wide range of benefits offered by CA to farmers, society and the natural world.

The past and current research on CA reviewed in this book is aimed at being of value to all CA stakeholders, including students, especially in the practical context of addressing global challenges related to sustainable development with effective solutions. This is particularly true in the adoption of strategies dealing with: sustainable production intensification, climate smart agriculture, regenerative agriculture, agroecology, and restoration of degraded lands including biodiversity and land-mediated ecosystem services. Thus, this book is a contribution to making sustainable agriculture development real globally. This would not have been possible without the extraordinary help of colleagues and field experts from the global CA Community of Practice who have been involved over many years in championing and bringing about the ongoing and accelerating global CA revolution. More than 120 authors based in more than 30 countries have made this book possible, building their respective chapters on the vast amount of global evidence and knowledge that is now available regarding the superior global performance of the alternate ecologically sustainable paradigm of CA.

In the long run, the expanding knowledge and education system globally must become fully engaged in generating the future human and institutional capacity and appropriate new mindset to underpin and sustain the process of mainstreaming the CA paradigm as a core component of the much-needed sustainable global food and agriculture system. Mainstreaming of any alternate paradigm in any field requires that all the relevant public, private and civil sector institutions and policies must align themselves behind it and ensure the necessary strategic and practical support to sustain its evolution. It is hoped that the information contained in this book will contribute to more rapid mainstreaming of CA globally by inspiring and generating increasing number of stakeholders and champions, particularly youngsters with practical training of CA, to become engaged in the promotion of CA as a foundation for sustainable agricultural development.

Chapter 1

Practice and benefits of Conservation Agriculture systems

Amir Kassam, University of Reading, UK; and Laila Kassam, Animal Think Tank, UK

1 Introduction

Conservation Agriculture (CA) was defined in Chapter 1 (Kassam and Kassam, 2019) and Chapter 2 (Kassam et al., 2019) of Volume 1 as an ecosystem approach to regenerative sustainable agriculture and land management based on the context-specific, locally adapted and practical application of three interlinked principles of (i) continuous, no or minimum mechanical soil disturbance (no-till seeding/planting and weeding and minimum soil disturbance with all other farm operations including harvesting); (ii) permanent maintenance of soil mulch cover (crop biomass, stubble and cover crops); and (iii) diversification of cropping system (economically, environmentally and socially adapted rotations and/or sequences and/or associations involving annuals and perennials, including legumes and cover crops), along with other complementary good agricultural production and land management practices (Hobbs et al., 2008; FAO, 2008, 2011; Friedrich et al., 2009; Kassam et al., 2009, 2013, 2018) (www.fao.org/conservation-agriculture). CA systems are present in all continents, involving rainfed and irrigated systems including annual cropland systems,

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perennial systems, orchards and plantation systems, agroforestry systems, crop-livestock systems, pasture and rangeland systems, organic production systems and rice-based systems. Conservation Tillage, Reduced Tillage and Minimum Tillage are not CA, and nor is no-till on its own.

Conservation tillage has many variants and is often oversold for its conservation benefits; in some cases, unacceptable soil degradation continues under practices called 'conservation tillage' (Derpsch et al., 2014; Reicosky, 2015). Given the significance of no-till/direct seeding in minimizing environmental impacts, this chapter treats no-till as a separate activity with minimum soil disturbance for seed placement and uses the term conservation tillage more narrowly to denote any other type of reduced tillage practice other than no-till, after Eagle et al. (2012). Continuous no-till is preferred for optimum multiple environmental benefits (Eagle et al., 2012).

Volume 1 has focussed on CA science and systems, comprising of chapters that elaborate different CA systems in different agro-ecologies and regions, how they have developed globally and how they are managed and supported. This volume focuses more on the main practices that are core and complementary constituents of CA systems and the benefits that are harnessed by farmers and for society as a result. Given that all CA systems are integrated land-use management operations comprised of multiple components working synergistically, they do not lend themselves easily to reductive experimentation over 1 or 2 years in small plots on research stations. Often, reported research work has failed to understand that CA systems cannot be established or transformed from conventional tillage systems overnight or instantly like switching on an electric light bulb. CA is a whole new paradigm of agriculture and whatever topics and fields of interest and stakeholder involvement apply to conventional agricultural systems also apply to CA systems. Further, CA systems and their practices pay special attention *inter alia* to (i) maintaining a healthy ecological foundation to underpin sustainability, (ii) promoting biodiversity to enhance system resilience, (iii) establishing large root systems actively engaged with soil microorganisms and mesofauna, (iv) creating a healthy and regenerative soil environment for efficient soil, nutrient, water productivity, (v) harnessing ecosystem services and (vi) building adaptability to climate change. Consequently, a large range of productivity, economic, environmental and social benefits are offered to the farmer, society and nature. Given the large variations in biophysical and socio-economic conditions in farming systems, and the historical and prevailing space-time variations amongst CA systems, researchers have had a difficult challenge in establishing reliable CA research programmes and explaining the nature of their results, despite the many advantages and benefits that have been claimed by CA farmers globally.

This chapter first describes, in Section 2, CA as a basis for sustainable soil, land and natural resource management and production intensification.

Section 3 elaborates the generic process of transformation from conventional systems into CA systems. Section 4 provides an overview of some of the main practices and benefits that are possible in CA systems and their potential contribution to the Sustainable Development Goals (SDGs) (UN, 2015). Of the 17 SDGs, the following are more directly relevant to this chapter: SDG 1 (no poverty), 2 (zero hunger), 6 (water), 7 (energy), 8 (economic growth and employment), 12 (sustainable consumption and production), 13 (climate action), 14 (marine resources) and 15 (terrestrial ecosystems), although it is realized that all SDGs are interconnected. Section 5 describes some of the global evidence of benefits from CA, and Section 6 deals with constraints and enabling conditions. The final section draws some conclusions and policy implications.

2 Conservation Agriculture as a basis for sustainable soil, land and natural resource management practice and production intensification

The farming practices required to implement the above-mentioned transformation will differ according to local conditions and needs. They will however have the following required characteristics, based on optimizing conditions in the root zone in the soil and at the ground and above the ground surface as being essential to (a) biotic activity; (b) provision of water and crops; (c) assurance of self-sustainability of soil structure and porosity; (d) protection against weeds, insect pests and pathogens; and resilience to cope with extreme events especially excess water, and drought and heat stress.

These include capacities for achieving maximum rain infiltration/minimum run-off and optimum water storage; minimum compaction; reduced diurnal temperature ranges in upper soil layers; regular supply of C-rich organic matter to surface; minimal loss of soil organic matter (SOM) by oxidation; maintained N levels in the soil; optimized P availability; conditions that favour integrated management of weeds, insects and pathogens; and system resilience that can cope with extreme biotic and abiotic stresses. As described in Volume 1, Chapter 1 (Kassam and Kassam, 2019) and Chapter 2 (Kassam et al., 2019), and in Hobbs et al. (2008), FAO (2008, 2011), Friedrich et al. (2009) and Kassam et al. (2009, 2013, 2018), such capacities are best achieved by applying the following three interlinked principles of CA as a base or a foundation for sustainable soil and system management, along with other complementary good agricultural practices, namely (www.fao.org/conservation-agriculture):

1 *Continuous, no or minimum mechanical soil disturbance:* implemented by the practice of no-till seeding or broadcasting of crop seeds, and direct placing of planting material into untilled soil; no-till weeding; causing

minimum soil disturbance from any cultural operation, harvest operation or farm traffic. Sowing seed or planting crops directly into untilled soil and no-till weeding: reduces run-off and soil erosion; minimizes the loss of SOM through oxidation; reduces disruptive mechanical cutting and smearing of pressure faces; promotes soil microbiological processes; protects and builds soil structure and connected pores; avoids impairing movement of gasses and water through the soil; and promotes overall soil health.

2 *Maintaining a permanent mulch cover on the soil surface*: implemented by retaining crop biomass, root stocks and stubbles and biomass from cover crops and other sources of biomass from ex-situ sources. Use of crop residues (including stubbles) and cover crops reduces run-off and soil erosion; protects the soil surface; reduces evaporation; moderates surface soil temperatures; conserves water and nutrients; supplies organic matter and carbon to the soil system; promotes soil microbiological activity to enhance and maintain soil health, including structure and aggregate stability (resulting from glomalin production by mycorrhiza); and contributes to integrated weed, insect pest and pathogen management and to integrated nutrient and water management.

3 *Diversification of species in the cropping system:* implemented by adopting a cropping system with crops in rotations, and/or sequences and/or associations involving annuals and/or perennial crops, including a balanced mix of legume and non-legume crops and cover crops. This crop diversification contributes to diversity in rooting morphology and root compositions; enhances the number and biodiversity of the soil organisms important in organic matter decomposition and nutrient cycling; increases biological diversity and carbon storage in the soil; enhances microbiological activity; enhances crop nutrition and crop protection through the suppression of pathogens, diseases, insect pests and weeds; and builds up SOM. Crops can include annuals, short-term perennials, trees, shrubs, nitrogen-fixing legumes and pastures, as appropriate.

CA practices related to the above principles add to sustainability of production and agro-ecological systems, including soil systems, and generate a range of field-level ecosystem services important for crop productivity and for the society and nature (Friedrich et al., 2009; Kassam et al., 2013). Table 1 outlines the kinds of contribution that are made by individual and collective core practices of CA towards achieving a range of soil-mediated objectives (Friedrich et al., 2009). These core principles also improve the soil hydrological, biological, physical and chemical conditions related to soil

Table 1 Effects of CA production system components fully applied together on sustainability and soil-mediated productivity-related ecosystem services

System component ► To achieve ▼ Initially: seek, identify and alleviate any subsurface soil-compaction or pans before planting	Mulch cover (crop biomass, cover crops, stubbles)	No tillage (no or minimal soil disturbance)	Legumes (as crops for fixing nitrogen and supplying plant nutrients)	Crop rotation/association (for several beneficial purposes)
Simulate optimum 'forest-floor' conditions	√	√		
Reduce evaporative loss of moisture from soil surface	√			
Reduce evaporative loss from soil upper soil layers	√	√		
Minimize oxidation of soil organic matter, CO_2 loss		√		
Minimize compactive impacts by intense rainfall, passage of feet, machinery	√	√		
Minimize temperature fluctuations at soil surface	√			
Provide regular supply of organic matter as substrate for soil organisms' activity	√			
Increase, maintain nitrogen levels in root zone	√	√	√	√
Increase CEC of root zone	√	√	√	√
Maximize rain infiltration, minimize run-off	√	√		

(Continued)

Table 1 *(Continued)*

System component ► To achieve ▼ Initially: seek, identify and alleviate any subsurface soil-compaction or pans before planting	Mulch cover (crop biomass, cover crops, stubbles)	No tillage (no or minimal soil disturbance)	Legumes (as crops for fixing nitrogen and supplying plant nutrients)	Crop rotation/association (for several beneficial purposes)
Minimize soil loss in run-off and wind	√	√		
Permit and maintain natural layering of soil horizons by actions of soil biota	√	√		
Minimize weeds	√	√		√
Increase rate of biomass production	√	√	√	√
Speed soil-porosity's recuperation by soil biota	√	√	√	√
Reduce labour input		√		
Reduce fuel-energy input		√	√	√
Recycle nutrients	√	√	√	√
Reduce pest pressure of pathogens				√
Re-build damaged soil conditions and dynamics	√	√	√	√
Pollination services	√	√	√	√

Source: based on Friedrich and Kassam (2009) and Kassam et al. (2013).

Table 2 How CA improves soil conditions

	Key features of Conservation Agriculture ⇒			
Components of soils' productive capacity	No-till ⇓	Mulch ⇓	Rotations/associations ⇓	Legumes ⇓
Hydrological	1	4		
Physical	2	5	7	10
Biological	3	6	8	11
Chemical			9	12

Key: 1 = Water percolation; 2 = Varied soil porosity; 3 = Favours biological soil-layering; 4 = Buffers impacts of rainfall, wide diurnal ranges of surface temperature; 5 = Prevents soil-crusting; 6 = Source of energy and nutrients; 7 = Augments root channels – distribution and depth; 8 = Favours biodiversity in soil; 9 = Beneficial root exudates; 10 = Favours development of optimum soil architecture (solids × spaces); 11 = Nitrogen + C-rich organic matter; 12 = Nitrogen.
Source: adapted from Kassam et al. (2013).

productive capacity (Table 2) and result in beneficial outcomes for production, ecosystem services and socio-economic conditions (Table 3) (Kassam et al., 2013). However, to achieve sustainable *intensification,* these CA practices need to be complemented by additional best production and management practices (FAO, 2011; Lal, 2018), including:

- use of well-adapted, high-yielding cultivars and good-quality seeds;
- enhanced crop nutrition based on healthy soils;
- integrated management of insect pests, diseases and weeds;
- efficient water management;
- careful management of machines and field traffic to avoid soil compaction.

Sustainable crop production intensification is the combination of all these improved practices applied in a timely and efficient manner, underpinned by the interlinked core practices of CA. For this, the ensuring of soil stability, and the favouring of self-recuperation of appropriate soil structural conditions, are essential (see Tables 1–3). Thus, sustainable soil management depends on how and what crops are grown. However, for sustainable production *intensification* to occur, the core or foundation CA practices must integrate with other complementary practices that allow the intensification of output and the optimization of the production inputs. Such sustainable production systems, and the associated sustainable crop, soil, nutrient, water, pest and energy management practices, are knowledge and management intensive and relatively complex to learn and implement. They are dynamic systems, offering farmers many possible combinations of practices to choose from and adapt, according to their local production conditions and constraints (Kassam et al., 2009, 2017b; Godfray et al., 2010; FAO, 2011; Pretty et al., 2011).

Table 3 Some resulting beneficial outcomes with CA

For agricultural production e.g. ⇓	For ecosystem services e.g. ⇓	For socio-economic conditions e.g. ⇓
Greater security of output under varying weather conditions	Diminished water pollution by agrochemicals, eroded soil; reduced costs of water treatment	Greater efficiencies of use of labour, financial resources
Greater efficiency of rainwater use, leading to more-stable yields	Less frequency, depth, duration of flooding after unit storms of equal severity	Better health and nutrition
No/minimal soil erosion; smaller losses of applied energy, fertilizers, seeds and so forth	Longer duration of streamflow; recharge of groundwaters	Reduced frequency of flooding and severity of damages to roads, bridges and so forth
Improved soil health provides better biological controls of weeds, pests	Reduced loss of soil organic matter by tillage-induced oxidation to CO_2	More time for diverse activities on-farm (technical)
Re-circulation of carbon, micro- and macro-nutrients	Maintenance/improvement of soil-carbon content	More time for diverse activities off-farm (social)
Lesser effects of climatic drought events	Lesser damage to normal multiple functioning of soil in wider ecosystem	
Etc.	Etc.	Etc.

Source: adapted from Kassam et al. (2013).

The development of sustainable crop production intensification requires building on the core principles and practices outlined above as the production base and finding ways to support and self-empower producers to implement them all, through participatory approaches and stakeholder engagement. In addition, sustainable crop production intensification must be supported by coherent policies, institutional support and innovative approaches to overcome any barriers to adoption. Monitoring and evaluating the progress of change in production system practices and their outcomes at the farm and landscape levels is critical.

One of the main criteria for ecologically sustainable production systems such as CA is the maintenance of an environment in the root zone to optimize conditions for soil biota including healthy root function to the maximum possible depth (Mokany et al., 2006; Kell, 2011). Roots are thus able to function effectively and without restrictions to capture plant nutrients and water as well as interact with a range of soil microorganisms beneficial for soil health and crop performance (Pretty, 2002; Uphoff et al., 2006). In such systems, with the above attributes there are many similarities to resilient 'forest floor' conditions (Kassam et al., 2009). Maintenance or improvement of SOM content and soil structure and associated porosity are critical indicators for sustainable production and other ecosystem services.

A key factor for maintaining soil structure and organic matter is to limit mechanical soil disturbance in the process of crop management. For this reason, no-tillage production methods – as practiced, for example, in CA – have in many parts of the world been shown to improve soil conditions, reduce degradation and enhance productivity (Gebregziabher et al., 2006; Lal et al., 2007a). However, as a stand-alone practice, the elimination of tillage would not necessarily lead to a functioning sustainable production system. This requires a set of complementary practices to enable a functioning soil system as well as the whole agro-ecosystem to deliver a range of ecosystem services.

The contribution of practices that implement the technical principles of CA – including mulch cover, no-tillage, legume crops and crop rotations – to important ecosystem services is shown in Tables 1–3. However, for any agricultural system to be sustainable in the long term, the rate of soil erosion and degradation (loss of organic matter) must never exceed the rate of soil formation (though the steeper the slope, the greater the danger that this could happen). In most of the agro-ecosystems, this is not possible if the soil is mechanically disturbed (Montgomery, 2007). For this reason, the avoidance of mechanical soil disturbance is a starting point for moving towards sustainable production. Once it has been brought into good physical condition, no further tilling of the soil is therefore a necessary condition for sustainability, but not a sufficient condition. For sustainable crop production intensification, including ecosystem services, other complementary techniques are required as mentioned already, of which the practices related to the above three CA principles constitute the bare minimum for ecological sustainability (FAO, 2011; Kassam et al., 2013).

Considering the above, it is clear that sustainable soil management depends on both what and how crops are grown, as well as on additional aspects of soil and landscape management, which includes the horizontal integration of other production sectors such as forestry. The special role of deep-rooted legumes such as pigeon pea (*Cajanus cajan*), lablab (*Dolichos lablab*) and mucuna (*Stizolobium cinereum*) in building soil structure and biopores for drainage and aeration, in contributing biologically fixed nitrogen to improved nitrogen stocks in soils, and in generating both biomass and edible products is a case in point (Hargrove, 1991; Kell, 2011). Similarly, species diversification as the third principle of CA is related to integrated management of insect pests, pathogens and weeds, and the effectiveness of control of pests, pathogens and weeds depends on both what and how crops are grown (Liebig et al., 2014; Tsiafouli et al., 2015; Lange et al., 2015). Species diversification involving crops of different durations and complementarity is also related to the use and management of resources of different crops in space and time to maximize and optimize the production during the growing season every year to its fullest potential in an increasingly variable and unpredictable climate. Furthermore, to establish diversity of soil biological activity, it is necessary to include in the cropping system a diversity of crops instead of mono-cropping or reduced crop diversity.

CA is now (in 2015/16) adopted on about 180 million ha of arable land worldwide, which corresponds to some 12.5% of the total cropland (Kassam et al., 2019). Around 50% of this area is in the Global South. During the past decade, land under CA has been expanding at an average rate of more than 10 million ha per year. Thus, it is likely that the current area of CA globally is more than 200 million ha. The highest adoption levels, exceeding 50% of the cropland, are found in the southern part of South America, in the Canadian prairies and western Australia. Fast adoption rates are now being seen in Central Asia and China, alongside increasing policy support and early large-scale adoption taking place across Africa, particularly in Zambia, Zimbabwe, South Africa, Tanzania, Kenya, Morocco and Tunisia. Europe now has some few pockets of adoption, particularly in Finland, Spain, France, Italy, UK and Switzerland (Kassam et al., 2009; Derpsch and Friedrich, 2009; Friedrich et al., 2013).

3 Transforming conventional systems into Conservation Agriculture systems

In general, many researchers and farmers find that the best performance from CA is derived when the system quality is good and that all the core CA practices and complementary production system practices are well integrated to maximize synergies (Goddard et al., 2006; Jat et al., 2014; Kassam et al., 2013, 2017b; Farooq and Siddique, 2014).

The transformational change from the often-degraded conventional tillage agriculture conditions to good-quality responsive CA conditions is a time- and biology-related multi-year evolutionary process of ecological regeneration. The transformation from conventional system to CA cannot be done overnight in a single event. The application of the interlinked CA principles into concrete production practices depend on local situation and require the formulation of locally adapted practices based on the local biophysical, economic, social and management situation. Thus, the CA adoption process involves a system approach to managing change at the cropping system level. At the farm level, the adoption process can be implemented not on the whole farm at once but portion by portion to allow learning by doing and experiential knowledge to be generated. Such an approach also allows room for innovation, adjustments and acceptable

Index