

BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Advances in Conservation Agriculture

Volume 2: Practice and Benefits

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Contents

Series list	xii
Dedication	xviii
Acknowledgements	xix
Foreword	xxi
Preface	xxiv
1 Practice and benefits of Conservation Agriculture systems <i>Amir Kassam, University of Reading, UK; and Laila Kassam, Animal Think Tank, UK</i>	1
1 Introduction	1
2 Conservation Agriculture as a basis for sustainable soil, land and natural resource management practice and production intensification	3
3 Transforming conventional systems into Conservation Agriculture systems	10
4 Benefits of Conservation Agriculture systems and their potential contribution to the Sustainable Development Goals (SDGs)	12
5 Global evidence of benefits from Conservation Agriculture	21
6 Constraints and enabling conditions	24
7 Conclusion and future trends	26
8 Where to look for further information	27
9 References	28
2 Crop and cropping systems management practices and benefits in Conservation Agriculture systems <i>Muhammad Farooq, Sultan Qaboos University, Oman, University of Agriculture, Pakistan, and The University of Western Australia, Australia; Ahmad Nawaz, Bahauddin Zakariya University, Pakistan; Yashpal Singh Saharawat, International Center for Agricultural Research in the Dry Areas (ICARDA), Lebanon; Timothy Reeves, The University of Melbourne, Australia; and Kadambot Siddique, The University of Western Australia, Australia</i>	37
1 Introduction	37
2 Crops for CA: management practices and benefits	41

3	Cropping systems for CA: management practices and benefits	47
4	Case studies	50
5	Conclusions and future trends	59
6	Where to look for further information	60
7	References	60
3	Soil management practices and benefits in Conservation Agriculture systems	75
	<i>Michele Pisante, University of Teramo, Italy; Angelica Galieni, Council for Agricultural Research and Economics and Research Centre for Vegetable and Ornamental Crops, Italy; Gottlieb Basch, University of Évora, Portugal; Theodor Friedrich, Food and Agriculture Organization of the United Nations (FAO), Italy; and Fabio Stagnari, University of Teramo, Italy</i>	
1	Introduction	75
2	The principles of CA	76
3	Environmental benefits and ecosystem services	83
4	Economic benefits	89
5	Future trends	91
6	Conclusion	91
7	Where to look for further information	92
8	References	92
4	Weed management practices and benefits in Conservation Agriculture systems	105
	<i>Gottlieb Basch and Fernando Teixeira, University of Évora, Portugal; and Sjoerd W. Duiker, Penn State University, USA</i>	
1	Introduction	105
2	Weed control under CA	106
3	Smallholder farmers' strategies for weed control in developing countries: sub-Saharan Africa	120
4	Future trends	127
5	Conclusion	129
6	Where to look for further information	132
7	References	133
5	Insect pest and disease management practices and benefits in Conservation Agriculture systems: a case of push-pull practice	143
	<i>Z. R. Khan, International Centre of Insect Physiology and Ecology (icipe), Kenya; A. W. Murage, Kenya Agricultural and Livestock Research Organization (KALRO), Kenya; and J. O. Pittchar and C. A. O. Midega, International Centre of Insect Physiology and Ecology (icipe), Kenya</i>	

1	Introduction	143
2	Push-pull technology: a sustainable innovation in Conservation Agriculture	145
3	Dissemination and adoption of push-pull practice	147
4	Benefits of push-pull practice in Conservation Agriculture systems	149
5	Future trends and conclusion	161
6	References	162
6	Nutrient management practices and benefits in Conservation Agriculture systems <i>Stephane Boulakia, Florent Tivet and Olivier Husson, Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France; and Lucien Séguy, AgroécoRiz, France</i>	169
1	Introduction	169
2	Integrated nutrient management and the conceptual 'forest model' of CA	170
3	Bio-availability of elements and mineral use efficiency in CA systems	178
4	Conclusions and future trends	184
5	Case study 1: A Brazilian Fazenda initiating a transition from 'generic' CA to CA based on multifunctional mix species cover	187
6	Case study 2: A dairy farm evolution in SW France restoring soil potential and animal feed autonomy as a result of diversification and intensification of the biomass inputs	189
7	References	190
7	Carbon management practices and benefits in Conservation Agriculture systems: carbon sequestration rates <i>João Carlos de Moraes Sá, State University of Ponta Grossa, Brazil; Florent Tivet, Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), France; Rattan Lal, The Ohio State University, USA; Ademir de Oliveira Ferreira, Federal Rural University of Pernambuco, Brazil; Clever Briedis, Brazilian Agricultural Research Corporation, Agricultural Instrumentation Center, Brazil; Thiago Massao Inagaki, Technical University of Munich, Germany; and Daniel Potma Gonçalves and Jucimare Romaniw, State University of Ponta Grossa, Brazil</i>	199
1	Introduction	199
2	The potential for carbon (C) sequestration by Conservation Agriculture (CA) in subtropical and tropical agroecosystems: a case study	201
3	Key results	206
4	Soil organic carbon (SOC) restoration and sequestration rates in response to cropping systems under Conservation Agriculture (CA)	213

5	Conclusion	221
6	Acronyms	221
7	References	222
8	Carbon management practices and benefits in Conservation Agriculture systems: soil organic carbon fraction losses and restoration	229
	<i>João Carlos de Moraes Sá, State University of Ponta Grossa, Brazil; Florent Tivet, CIRAD, France; Rattan Lal, The Ohio State University, USA; Ademir de Oliveira Ferreira, Federal Rural University of Pernambuco, Brazil; Clever Briedis, Brazilian Agricultural Research Corporation, Agricultural Instrumentation Center, Brazil; Thiago Massao Inagaki, Technical University of Munich, Germany; and Daniel Potma Gonçalves and Jucimare Romaniw, State University of Ponta Grossa, Brazil</i>	
1	Introduction	229
2	Soil organic carbon fraction losses and restoration: a case study	231
3	Key results	237
4	Conclusion	258
5	Acronyms	259
6	References	261
9	Biodiversity management practices and benefits in Conservation Agriculture systems	267
	<i>Scott Day, Treelane Farms Ltd, Canada; Ademir Calegari, Agricultural Research Institute of Paraná State (IAPAR), Brazil; Alessandra Santos, Marcus Cremonesi, Lilianne Maia and Wilian Demetrio, Federal University of Paraná, Brazil; and Marie L. C. Bartz, Coimbra University, Portugal</i>	
1	Introduction	267
2	Soil microorganisms and their importance	268
3	Effects of cropping practices on soil biodiversity and ecosystem functioning	269
4	Effectiveness of diversified CA cropping systems	276
5	Case study: biodiversity management practices and benefits in CA systems in South-West Manitoba (Canada)	281
6	Where to look for further information	294
7	References	294
10	Conservation Agriculture: climate change mitigation and adaptation benefits	303
	<i>Emilio J. Gonzalez Sanchez, Universidad de Córdoba, Spain, European Conservation Agriculture Federation (ECAAF), Belgium</i>	

and Asociación Española Agricultura de Conservación. Suelos Vivos (AEAC.SV), Spain; Oscar Veroz-Gonzalez, Asociación Española Agricultura de Conservación. Suelos Vivos (AEAC.SV), Spain; Manuel Morena-Garcia and Rafaela Ordoñez-Fernandez, IFAPA Centro Alameda del Obispo, Spain; Jesus A. Gil-Ribes and Julio Roman-Vazquez, Universidad de Córdoba, Spain; Antonio Holgado-Cabrera, IFAPA Centro Alameda del Obispo, Spain; Amir Kassam, University of Reading, UK; Gordon Conway, Imperial College London, UK; Saidi Mkomwa, African Conservation Tillage Network, Kenya; Paula Triviño-Tarradas, Antonio Miranda-Fuentes and Francisco Marquez-Garcia, Universidad de Córdoba, Spain; and Rosa M. Carbonell-Bojollo, IFAPA Centro Alameda del Obispo, Spain

1	Introduction	303
2	Fundamentals of climate change mitigation	305
3	Fundamentals of adapting to climate change	312
4	Case study: the LIFE+ Agricarbon Project	321
5	Conclusion	323
6	Future trends	325
7	Where to look for further information	326
8	References	327
11	Benefits of Conservation Agriculture to farmers and society <i>Patrick Wall, Independent Consultant - Sustainable Agricultural Systems, Mexico; Christian Thierfelder, International Maize and Wheat Improvement Center (CIMMYT), Zimbabwe; Peter Hobbs, Cornell University, USA; Jon Hellin, International Rice Research Institute (IRRI), The Philippines; and Bram Govaerts, International Maize and Wheat Improvement Center (CIMMYT), Mexico</i>	335
1	Introduction	335
2	Farm benefits of Conservation Agriculture	336
3	Difficulties with Conservation Agriculture	348
4	Conservation Agriculture adoption	353
5	Benefits of Conservation Agriculture to society	359
6	The way ahead: support for Conservation Agriculture	362
7	Where to look for further information	363
8	References	364
12	Social benefits of Conservation Agriculture systems <i>Rafael Fuentes Llanillo, Tiago Santos Telles and Dimas Soares Junior, Agricultural Research Institute of Paraná State (IAPAR), Brazil; Sara Kaweesa, University of Natural Resources and Life</i>	375

	<i>Sciences (BOKU), Austria; and Anne-Marie B. Mayer, Independent Nutrition and Agriculture Consultant, UK</i>	
	1 Introduction	375
	2 Farmers' organization	376
	3 Social governance and water conservation	379
	4 Varied socioeconomic benefits	380
	5 Social capital and community development	384
	6 Food security and nutritional aspects	385
	7 Conclusion	386
	8 Where to look for further information	387
	9 References	387
13	Harnessing ecosystem services with Conservation Agriculture <i>Amir Kassam, University of Reading, UK; Emilio J. Gonzalez Sanchez, Universidad de Córdoba, Spain, European Conservation Agriculture Federation (ECAAF), Belgium and Asociación Española Agricultura de Conservación. Suelos Vivos (AEAC.SV), Spain; Tom Goddard, Alberta Agriculture and Forestry, Canada; Li Hongwen, Conservation Tillage Research Centre, China Agriculture University, China; Ivo Mello, Instituto Rio Grandense do Arroz, Brazil; Saidi Mkomwa, African Conservation Tillage Network, Kenya; Francis Shaxson, Land Husbandry Group, Tropical Agricultural Association, UK; and Theodor Friedrich, Food and Agriculture Organization of the United Nations (FAO), Italy</i>	391
	1 Introduction	391
	2 Ecosystem services in production fields	394
	3 Large-scale ecosystem services from agricultural landscapes and watersheds	399
	4 Conclusion and future trends	411
	5 Where to look for further information	412
	6 References	413
14	Rehabilitating degraded and abandoned agricultural lands with Conservation Agriculture systems <i>Telmo Jorge Carneiro Amado, Federal University of Santa Maria, Brazil; Carlos Alexandre Costa Crusciol, São Paulo State University (UNESP), Brazil; Claudio Hideo Martins da Costa, Universidade Federal de Goiás, Brazil; Otávio dos Anjos Leal, Catarinense Federal Institute, Brazil; and Luan Pierre Pott, Federal University of Santa Maria, Brazil</i>	419
	1 Introduction	419
	2 Conservation Agriculture adoption in Brazil, mainly in Brazilian Southern region, as a tool to prevent and reverse soil degradation	424

3 Case study 1: Integrated strategies for restoration of compacted and low productive soils under no-tillage system in Southern Brazil	428
4 Case study 2: Strategies for soil quality improvement in crop-livestock integration under Conservation Agriculture in acidic tropical soils	436
5 Conclusion	452
6 Acknowledgements	453
7 References	453
Index	465

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
- 2 Conservation Agriculture as a basis for sustainable soil, land and natural resource management practice and production intensification
- 3 Transforming conventional systems into Conservation Agriculture systems
- 4 Benefits of Conservation Agriculture systems and their potential contribution to the Sustainable Development Goals (SDGs)
- 5 Global evidence of benefits from Conservation Agriculture
- 6 Constraints and enabling conditions
- 7 Conclusion and future trends
- 8 Where to look for further information
- 9 References

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,

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 ▼	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)
Initially: seek, identify and alleviate any subsurface soil-compaction or pans before planting				
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

Components of soils' productive capacity	Key features of Conservation Agriculture ⇒			
	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

- AAPRESID. *see* Argentinian No-Till Farmers' Association (AAPRESID)
- Accessible nutrients pools, timing and development of 177–179
- Achilles heel 359
- Acid-extracted total polysaccharides 236, 239–240
- Acidic tropical soils
overview 436–437
pasture quality and productivity 441–443, 445, 446
subsoil acidity alleviation 438–444
tropical pasture role 446–452
- ACT. *see* African Conservation Tillage Network (ACT)
- Active pool 230
- Africa 385
- African Conservation Tillage Network (ACT) 310, 378
- Agrarian ecosystems 305
- Agricultural decision-making process 383
- Agrobiodiversity 398
- Air pollution, reduction of 360
- Allelopathy 114
- AMF. *see* Arbuscular mycorrhizal fungi (AMF)
- AMLC. *see* Mexican Association of Conservation Tillage (AMLC)
- ANAPO. *see* Oil Seeds and Wheat Farmers Association (ANAPO)
- Ants 269
- APDC. *see* Associação de Plantio Direto no Cerrado (APDC)
- Arbuscular mycorrhizal fungi (AMF) 175–176
- Argentina 38, 53, 54, 274, 275, 354
- Argentinian No-Till Farmers' Association (AAPRESID) 378
- Associação de Plantio Direto no Cerrado (APDC) 377
- Australia 13, 20, 38, 43, 45, 57–58, 355
- Auto fertility margins 185, 186
- Bangladesh 41
- Base saturation rate 181
- Beetles 269
- Biodegradable film 109
- Biodiversity 318–320, 324, 360
- Biodiversity management practices and benefits 267–268
case study 281–294
cropping practices effects and ecosystem functioning 269–270
CA system positive effects 270–272
crop and livestock integration 274–276
plant diversity importance 273–274
diversified CA cropping systems effectiveness 276–281
soil microorganisms and importance 268–269
- Biological chiselling 430
- Biological N₂ fixation (BNF) 281
- Biological soil conditioners 427
- Bio-mediation 182
- Biotrophic diseases 351
- Bipolaris sorokiniana* 352
- Black oat 278
- Black plastic sheets, as soil cover 108
- Blue lupin 278
- BNF. *see* Biological N₂ fixation (BNF)
- Brazil 13, 20–22, 38, 49, 53, 54, 126, 128, 181, 187, 200, 272, 274, 275, 377, 419–422, 424–428
- Brazilian No-Till Farmers Federation 377
- Brazilian no-till federation 403
- Bulk density 433–435
- Burkina Faso 147
- Burundi 147

- CA. *see* Conservation Agriculture (CA)
- CAAANZ. *see* Conservation Agriculture Alliance of Australia and New Zealand (CAAANZ)
- CAADEP. *see* Comprehensive agriculture development program (CAADEP)
- CAAPAS. *see* Confederation of Farmers Organizations Toward a Sustainable Agriculture (CAAPAS)
- CA-CoP. *see* Global Conservation Agriculture Community of Practice (CA-CoP)
- Cambodia 181
- Cameroon 45
- Canada 13, 14, 20, 38, 47, 59, 355, 382, 400-402
- Canadian Standards Association 401
- CAP. *see* Common Agricultural Policy (CAP)
- Carbon capture 399
- Carbon dioxide (CO₂)
 cumulative loss 312
 emissions of 304, 311-312, 321, 323, 344, 360
 sequestration of 307
- Carbon management practices and
 benefits 199-201, 213-221, 229-237
 case study 201-206
 key results 206-213
see also Soil organic carbon (SOC)
- Carbon offset scheme in Alberta 400-402
- Carbon sequestration 19, 87-88, 213-221
 potential, in subtropical and tropical agroecosystems
 context 201-202
 experimental procedures 202-206
- Carbon sink 306-311
- CASPA. *see* Conservation Agriculture Service Providers Association (CASPA)
- Catchment Management Committees 380
- Cation exchange capacity (CEC) 180, 181, 438
- CCs. *see* Cover crops (CCs)
- CEC. *see* Cation exchange capacity (CEC)
- Center for Development of Zero Tillage CEDECELA of Chile 378
- Cereal-based systems in Europe 52-53
- Cereal crops 41-42
- Cereal-oilseed-legume-based systems in Australia 57-58
- Chemically stabilized organic C (CSO-C) 236, 237
- Chile 274, 275
- China 13, 20, 41, 45, 50, 109, 310, 353, 404-408
- Cleaner civic water supplies 397, 399
- Climate change, adapting to
 definition 312-313
 improved soil quality and structure 316-318
 improved water balance 313-316
 pest and disease control 318-320
- Climate change mitigation
 definition 306
 fundamentals of 305-312
 future trends of 325-326
 mechanisms 306, 307
- 'Climate-smart' agriculture 27
- Colombia 38
- Common Agricultural Policy (CAP) 52
- Community development 384
- Compaction, of soil 428-430
- Companion cropping 145, 146
- Complementary agricultural practices 427-428
- Comprehensive agriculture development program (CAADEP) 57
- Confederation of Farmers Organizations Toward a Sustainable Agriculture (CAAPAS) 378
- Conservation Agriculture (CA) 305, 310, 312, 321-324, 379-380, 382-386, 405, 408, 436-452
 adoption 321, 335, 353-355, 376, 381, 382, 385, 424-428
 concentration of 354
 on small farms 355-359
 contribution in agricultural systems 313, 314
 difficulties with 348-352
 ecological advantages of 420
 farm benefits of 336-348
 principles 305-306, 353, 375, 397
 processes in 313, 314, 316, 317, 319
 reduced run-off 315
 societal benefits 359-361
 socioeconomic benefits 376, 380-384
 on soil fertility 404-405
 support for 362-363
 sustainable input intensification 394
 sustainable output intensification 394
- Conservation Agriculture Alliance of Australia and New Zealand (CAAANZ) 378
- Conservation Agriculture Quality Assessment 403

- Conservation Agriculture Service Providers Association (CASPA) 378
- Conservation Cropping Protocol (CPP) 400
- Conservation Technological Information Center (CTIC) 378
- Contextualisation 428-430
- Conventional plow tillage (CT) 202
- Conventional tillage (CT) 397, 420
- Conversion index 237
- Corn grain yields 447-452
- Corn/maize-based systems in North America 58-59
- Cover crops (CCs) 79-81, 118, 423-424, 427-431
- Coyote 292
- CPP. see Conservation Cropping Protocol (CPP)
- Crop and cropping systems management 37-60
- Crop associations 398
- Crop diseases 351-352
- Crop diversification 320
- Crop-livestock systems 358, 427
- Crop residue 353
- Crop rotations 48, 88, 118-119, 130-131, 320, 349-350, 398, 441
- Crop succession 430
- Crop yield 346-348
- CSO-C. see Chemically stabilized organic C (CSO-C)
- CT. see Conventional plow tillage (CT); Conventional tillage (CT)
- CTIC. see Conservation Technological Information Center (CTIC)
- Cultivando Água Boa* programme 403
- Cultivating Good Water 380
- Deforestation, mitigation of 360
- Denitrification 176-177
- Denmark 77, 113
- Desmodium* spp. 115, 146, 150, 151, 154-155
- Direct flaming, for weed control 110
- DU. see Ducks Unlimited (DU)
- Ducks Unlimited (DU) 288, 291
- Earthworm Club 377
- Earthworms 84, 268-269, 272, 286-287, 319, 345
- ECAF. see European Conservation Agriculture Federation (ECAF)
- Ecoagricultural systems 362
- Ecosystem engineers 345
- Ecosystem functions 393
- Ecosystem services
 agricultural landscapes and watersheds 399-411
 cultural services 391, 392
 future trends of 411-412
 harnessing 393, 399
 from nature 391, 392
 in production fields 394-399
 provisioning service 391-393
 regulatory service 391-393
 supporting services 391-393
- Energy consumption 304, 312, 321, 323, 324
- Energy crops 45-46
- Energy savings 337-339
- ERM. see Extra-radical mycelium (ERM)
- Erosion control services, in China 408
- Erosion losses 341
- Ethiopia 57, 115, 120, 147
- Europe 383
- European Conservation Agriculture Federation (ECAF) 52, 308, 310, 327, 378
- Eurosoil 327
- Extra-radical mycelium (ERM) 175
- Farmer field schools (FFSs) 147
- Farmers' organization 376-377
- Farmer-to-farmer extension model 148
- Federação Brasileira de Plantio Direto na Palha (FEBRAPDP) 377
- FEPASIDIAS. see Paraguayan No-Till Farmers' Federation (FEPASIDIAS)
- Fertilisation management 427
- FFSs. see Farmer field schools (FFSs)
- Field days 148
- Finland 10
- Flea beetle damage, to Canola seedlings 285-286
- FOM. see Fresh organic matter (FOM)
- Food security 385-386
- Forage dry matter yield and crude protein 442, 445, 446
- Fourier Transform infra-red spectroscopy (FTIR) 231
- Fourier-transform infra-red (FTIR) spectroscopy 257-258
- France 10, 183, 184
- Fresh organic matter (FOM) 171-174, 178
- Friends of the Land Clubs 377

- FTIR. *see* Fourier Transform infra-red spectroscopy (FTIR)
- Fuel savings 337, 360
- Fusarium graminearum* complex 352
- GCAN. *see* Global Conservation Agriculture Network (GCAN)
- Germany 52
- Ghana 124, 125, 147
- GHG emissions. *see* Greenhouse gas (GHG) emissions
- Global Conservation Agriculture Community of Practice (CA-CoP) 378
- Global Conservation Agriculture Network (GCAN) 379
- Glyphosate (*N*-(phosphonomethyl) glycine) 111-112
- Grain yield, tropical pasture role in 446-452
- Green Cane Trash Blanketing 361
- Greenhouse gas (GHG) emissions 304, 305, 400
reduction 51, 76, 87, 311-312, 360
- Groundcovers 308, 309, 317, 349, 408-411
- Hand-weeding 108, 121-122
- Herbicides
glyphosate 348
resistance 349
- Hot water extractable organic carbon (HWEO-C) 236, 239-240
- Household Economy Approach 386
- Humification index 237
assessed through fluorescence spectroscopy 256-257
- Hungary 53
- HWEO-C. *see* Hot water extractable organic carbon (HWEO-C)
- Imidazolinone 115
- India 41, 43, 45, 51-52, 87, 126, 127
- Indo-Gangetic plains 310, 312, 382
- Infiltration rate 315
- Insecticides 284-285
- Insect pests and disease management
practices and benefits 143-145
see also Push-pull technology
- Intercropping 48-49, 119-120, 124, 145-146
- Intergovernmental Panel on Climate Change (IPCC) 305, 312, 316
- Intermediate pool 230
- International Centre of Insect Physiology and Ecology 145
- IPCC. *see* Intergovernmental Panel on Climate Change (IPCC)
- Itaipú Dam Authority 403
- Itaipú Dam *Programa Cultivando Água Boa* 402
- Itaipu Hydroelectric Plant 376
- Italy 10
- Kenya 10, 115, 120, 125, 126, 153, 160
- Labour savings 337-339
- Land degradation 419
of croplands 420-421
definition 419
of pasturelands 421-422
- Laser-induced fluorescence spectroscopy (LIFS) 230-231
- Latin America 376
- Legume crops 42-43, 276, 281
- LIFE+ Agricarbon Project 321-324
- LIFS. *see* Laser-induced fluorescence spectroscopy (LIFS)
- Litter transformers 345
- Lixiviation 177
- Lucas do Rio Verde site 205, 209, 212, 234-235, 252
- Machinery cost savings 337
- Machinery productivity 342-343
- Macroporosity 433-435
- Madagascar 174
- Maize, under conventional push-pull technology 146
- Maize-based systems in Africa 54-57
- Maize-based systems in South America 53-54
- Malawi 41, 42, 49, 55-57, 115, 123, 125, 147, 386
- Managerial capacity 350-352
- MAOC. *see* Mineral-associated organic carbon (MAOC)
- Marsh hawk nest 289, 290
- MEA. *see* Millennium Ecosystem Assessment (MEA)
- Mean weight diameter (MWD) 252
- Mechanical chiselling 431-433, 435, 436
- Mechanical weed control 107
- Mexican Association of Conservation Tillage (AMLC) 378
- Mexico 126
- Microbiological oxidation 306
- Microbiome genetic with plant varieties 183-184

- Mid-Northern Uganda 384
 Millennium Ecosystem Assessment (MEA) 391, 392
 Milpa system 348
 Mineral-associated organic carbon (MAOC) 236, 240, 242-243
 Minimum tillage (MT) 202-203
 Mixed farming 119
 Monocropping 47, 350, 397, 420
 Monoculture systems 38, 118, 160
 Moose 292, 293
 Morocco 10
 Mouldboard ploughing 404
 Mozambique 55-57, 122
 MT. *see* Minimum tillage (MT)
 Mulches 80, 114, 117-118, 122-123, 130
 direct effects, on acidity and soil chemical parameters 179-180
 MWD. *see* Mean weight diameter (MWD)
 Mycotoxins 160
- Napier grass 146, 152, 154
 Native vegetation (NV) 199, 200, 202, 204-206, 209, 212, 214, 221, 230, 232, 234, 237, 239, 243-245, 247, 250-252, 256, 259
 Natural vegetation systems 335
 Necrotrophic diseases 351-352
 Nematode populations 345-346
 Nepal 41, 49
 Net primary productivity (NPP) 419-420
 Nitrogen fixing 174-176
 Nitrogen flush 343
 Nitrogen use efficiency (NUE) 183
 Nitrous dioxide (N₂O) emissions 88-89, 360
 North America 353, 382
 Northern Kazakhstan 355
 Northern Plains of North America 287
 Norway 52
 No-tillage (NT) 308, 309, 346-347, 375-377, 382, 425-426
 compacted and low productive soil restoration 428-436
 scoring index model 403
 NPP. *see* Net primary productivity (NPP)
 NT. *see* No-tillage (NT)
 NtUE. *see* Nutrient use efficiency (NtUE)
 NUE. *see* Nitrogen use efficiency (NUE)
 Nutrient cycling 15
 Nutrient management practices and benefits 169-170
 bio-availability of elements and mineral use efficiency 178-179
 CA and soil chemical parameter evolution 179-182
 CA-induced biological modifications influencing nutrient use efficiency 182-184
 case study
 Brazilian Fazenda 187-189
 dairy farm evolution 189-190
 CA system design current trends 170-171
 forest model and nutrients dynamic framework 171-178
 future trends 184-187
 Nutrient use efficiency (NtUE) 184
 knowledge gaps and improvements of 185, 187
 Nutrition education 386
- OC. *see* Organic carbon (OC)
 Oceania 353
 Off-farm effects 336
 Oilseed crops 43, 45
 Oil Seeds and Wheat Farmers Association (ANAPO) 378
 Olive groves, soil conservation services in 408-411
 OM. *see* Organic matter (OM)
 Organic carbon (OC) 304
 as humic acids 439, 441
 physico-chemical protection of 439
 Organic matter (OM) 305
 decomposition and distribution 345
 increase in 317-318
 mineralization 304, 306, 307
 Overseeding 427
 Oxisol 438
- Pakistan 41, 50, 52
 Paraguay 53, 54, 274
 Paraguayan No-Till Farmers' Federation (FEPASIDIAS) 378
 Participative Quality Index (IQP) 380
 Particulate organic carbon (POC) 236, 240, 242-243
 Passive pool 230
 Pasture degradation 421-422
 Penetration resistance (PR) 428, 431-433, 452
 Phosphogypsum 431-441, 443-445
 Physical fractionation 232

- Planting green approach 128
- POC. *see* Particulate organic carbon (POC)
- Point of zero charge (PZC) 438
- Polyculture, of cover crops 427, 430-436
- Ponta Grossa site 202-209, 233-234
- Portugal 23, 112
- PR. *see* Penetration resistance (PR)
- Practice and benefits 1-3
 - conservation agriculture, as basis for sustainable soil, land, natural resource management and production intensification 3-10
 - constraints and enabling conditions 24-26
 - conventional systems transformation, into conservation agriculture systems 10-12
 - future trends 26-27
 - global evidence 21-22
 - scientific and empirical evidence 22-24
 - global evidence spread of conservation agriculture as evidence 24
 - large-scale landscape-level benefits 13-14
 - sustainable development goals (SDGs) 12-13, 14
 - adaptability to climate change 18-19
 - climate change mitigation 19-20
 - decreased soil erosion and land degradation 16-17
 - degraded lands and ecosystem services rehabilitation 20
 - enhanced ecosystem services to society 20-21
 - improved soil health and reduced fertilizer use 15
 - increased biomass for livestock 17-18
 - increased productivity and profit 14
 - reduced machinery, energy, and labour use and costs 15-16
 - reduced use of pesticides and herbicides 15
 - see also* individual entries
- Prairie birds and mammals 287-291
- Productive agricultural systems 335
- Pronghorn 293
- Push-pull technology 145-147
 - benefits 149
 - disease management and benefits 159-160
 - environmental health 156
 - gender equality 156-157
 - general economic welfare 157-158
 - improved market participation 152-153
 - improving human health 155
 - improving soil health 154-155
 - increased household economic returns 153-154
 - increasing dairy milk production 151-152
 - increasing grain yields 150-151
 - pests and weeds and control 149-150
 - Sustainable Development Goals (SDGs) 158-159
 - dissemination and adoption of 147-149
 - future trends 161-162
- PZC. *see* Point of zero charge (PZC)
- Redox potential regulations and CA 180
- REDS. *see* Rural Enterprise Development Services (REDS)
- Rehabilitation, of degraded agricultural lands 423-424
- Relay cropping 50, 120, 124
- Re-seeding 341
- Resilience index 237
- Resilient agricultural ecosystems 324
- Rice-wheat and rice-maize-based systems in South Asia 51-52
- Roundup Ready* (RR) crops 111
- Rural Enterprise Development Services (REDS) 384
- Rwanda 123, 126, 147
- Rye mulches 114
- SCCC. *see* Soil Conservation Council of Canada (SCCC)
- Smallholder farmers 357-359
- Smartcane Best Management Practice (Smartcane BMP) 361
- SMBC. *see* Soil microbial biomass carbon (SMBC)
- SOC. *see* Soil organic carbon (SOC)
- Social capital 384
- Social governance 379-380
- SOCOSCHI. *see* Soil Conservation Society of Chile (SOCOSCHI)
- Soil amelioration 441-443, 445, 446
- Soil biological activity 345
- Soil breeding, developing 182-183
- Soil classification 430
- Soil conservation 404-411, 424

- Soil Conservation Council of Canada (SCCC) 378
- Soil Conservation Society of Chile (SOCOSCHI) 378
- Soil-crop-nutrient-water-landscape integrated systems 426
- Soil degradation 336, 424
see also Land degradation
- Soil disturbance 304, 305, 324
- Soil erosion 86-87, 336, 359, 421
 costs of 361
 reduction 316-317, 340-341
- Soil fertility 405-407
 improvement in 317-318
 stratification of 420
- Soil health 346, 419, 422
- Soil macro- and mesofauna 345
- Soil management practices and
 benefits 75-76
 cropping system diversification 82-83
 economic benefits 89-91
 environmental benefits and ecosystem services 83-89
 future trends 91
 no/minimum mechanical soil disturbance 76-79
 permanent soil cover maintenance 79-82
- Soil management systems 304
- Soil microbial biomass carbon (SMBC) 43
- Soil moisture content 315
- Soil organic carbon (SOC) 84, 85, 170, 181, 184, 201-202, 212-221, 229, 233-235
 annual fixation 310
 fraction losses and restoration
 aggregate carbon depletion and restoration 259
 aggregate hierarchy and stabilization 252, 256
 aggregate size classes, SOC concentrations, and stocks distribution 243-250
 context 231-232
 CSO-C, HWEO-C, and TPS 237-240
 humification and organic carbon compounds assessment 259
 indexes as soil quality indicators 237
 particulate and mineral-associated organic carbon concentrations 250
 pools extraction and analysis 236
 pools of different fractions 243
 site description and land uses management 232-233
 soil aggregation indices 252, 253-255
 soil sampling 235-236
 subtropical and tropical sites comparison 250-252
 sequestration 308
- Soil organic matter (SOM) 22, 23-24, 84, 181
 increases in 343-344
 oxidation of 344
 stabilisation 439
- Soil profile acidity alleviation 441
- Soil sampling 206
- Soil Science Society of America Glossary of Terms 79
- Soil seedbank dynamics and tillage 116-117
- Soil solarization 110
- Soil's storage capacity of C 304
- Soil structure 344-345
- Soil total nitrogen (STN) 85
- Soil water balance 339-340
- SOM. *see* Soil organic matter (SOM)
- South Africa 10, 41
- South America 353, 376
- South Asia 353, 355
- Southern Brazil 354
- South-West Manitoba (Canada), biodiversity management practices and benefits 281-294
- Soybean yields 435, 436, 447, 450
- Spain 10, 13, 20, 53, 408-411
- SSA. *see* Sub-Saharan Africa (SSA)
- Stemborer infestation 160, 161
- STN. *see* Soil total nitrogen (STN)
- Striga* spp. 114-115, 150
- Strip cropping 49-50
- Sub-Saharan Africa (SSA) 56, 57, 108, 115, 120-124, 162
- Sudan 115
- Surface-reapplied lime/gypsum 445, 446
- Surface residue retention 88
- Sustainable production management 13-14
- Sweden 174
- Switzerland 10
- Tanzania 10, 115, 120, 125, 147
- Thermal weed control 109-110
- Tillage-based agriculture 393

- Time saving 341-342
- Total biomass and carbon input 205
- Total porosity 43
- Tunisia 10

- Uganda 120, 147, 153, 157
- Ukraine 53
- United Kingdom 10
- United States 38, 87, 128, 354-355, 382
- Urbanization 156
- Uruguay 274

- Vegetable crops 46-47

- WANTFA. *see* Western Australian No-Tillage Farmers Association (WANTFA)
- Water conservation 379-380
- Water erosion 340-341, 355, 405, 408
- Water evaporation, reduction of 316
- Water infiltration 86, 351, 360
- Watershed services in Paraná Basin, Brazil 402-404
- Water-stable aggregate distribution 440-443
- WCCA. *see* World Congress on Conservation Agriculture (WCCA)
- Weed management practices and benefits 105-106
 - agricultural practices 118-120
 - biological weed control methods 113-115
 - chemical weed control 110-112
 - future trends 127-128
 - herbicides under CA 112-113
 - physical weed control methods 106-110
 - smallholder farmers' strategies in developing countries 120-127
- Weeds 348-349
- Western Australian No-Tillage Farmers Association (WANTFA) 378
- Wind erosion 317, 318, 341, 355, 405, 408
- Winter crops 278-280, 289
- World Congress of Soil Sciences 327
- World Congress on Conservation Agriculture (WCCA) 327, 379

- Zambia 10, 41, 55-57, 125, 147, 385, 386
- Zero-tillage (ZT) 77, 89, 345, 347, 348, 375, 378
 - adoption 353
 - of annual crops 381
 - in Brazil 377
- Zimbabwe 10, 38, 41, 43, 49, 55-57, 115, 121, 122, 147, 386
- ZT. *see* Zero tillage (ZT)