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Advances in Conservation Agriculture

Volume 1: Systems and Science

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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

The need for Conservation Agriculture

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1 Introduction

The ability of agriculture to meet future demand is generally analysed by mainstream scientists and policy analysts in terms of available resources and production inputs to supply the required level of agricultural products. Similarly, production systems are commonly assessed on the efficiency and effectiveness of different combinations of inputs, technologies and/or practices to produce certain agricultural outputs. Despite the continuous attention to ensure that advances in agriculture are based on science, technology and innovation (STI), it is only relatively recently that analyses have begun to address externalities of production systems, such as environmental damage; the associated input factor inefficiencies and sub-optimal yield ceilings; losses in agroecological production potentials due to land degradation; and poor resilience against major external biotic and abiotic challenges (Brisson et al., 2010; FAO, 2011a, 2016; Li et al., 2016; Nkonya et al., 2016; Vlek et al., 2017; González-Sánchez et al., 2017, 2018). However, relatively rarely do mainstream researchers question the actual agricultural paradigm itself (characterised here as conventional tillage agriculture) in terms of its continuing ecological appropriateness for the sustainable development agenda and for the environmental and land degradation challenges faced by agriculture and societies globally. Equally, the delivery of supportive, regulatory, provisioning and cultural ecosystem services to society by conventional tillage agriculture has not been an area of serious

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mainstream research concern (MEA, 2005; Beddington, 2011; Lal and Stewart, 2013; Kassam et al., 2013; Palm et al., 2014). Of even greater longer-term concern is the fact that much of the mainstream agricultural education globally continues to promote STI and knowledge to support conventional tillage agriculture – the current dominant agricultural paradigm – which represents 'business as usual'.

Thus, in general, mainstream approaches to agricultural assessments are simplistic, conservative and limited in scope. As a result, they are unable to identify and address the root causes of the damage caused to land resources, the environment and human health by the current dominant agricultural paradigm. Such assessments are also decoupled from the human and ethical consequences of the demands and pressures placed upon agricultural production by the food and agriculture system, including consumer demand, diets, industry, government and the economy.

In general, over the past several millennia, agricultural land use globally has led to soil physical, chemical, biological and hydrological degradation. This state of affairs continues unabated in most farmlands (MEA, 2005; Montgomery, 2007; FAO, 2011a; Kassam et al., 2013). This is true on small and large farms, on farms using mechanised or manual farm power, in developing countries and in industrialised countries, in the tropics and outside the tropics. The dominant farming systems paradigm globally is based on mechanical tillage of various types to control weeds (often with herbicides), soften the seedbed for crop establishment and loosen compacted sub-soil. At the centre of this paradigm there are farming practices for crop, soil, nutrient, water and pest management that are considered by most agricultural stakeholders to be 'modern, good and normal'. However, the same farming practices have also forced farmers to accept that, supposedly, any accompanying soil degradation and loss of ecosystem services are inevitable and 'natural' consequences of farming – consequences which can be kept under control but not avoided altogether. This view is increasingly being challenged and considered to be outdated, and the inherited farming practices are considered unable to deliver the multifunctional objectives of productivity with ecosystem services now being demanded from agricultural land and producers who use it for farming. Further, an unabated and continued degradation of the production resources, namely soil, water and biological, cannot secure a sustained survival of humanity on earth considering that the degradation processes are advancing globally and that 90% of the food for humankind originates from soil-based production systems.

In the past three decades, ideas and concepts, as well as an ecosystem approach to sustainable production intensification have led to the emergence of an alternative approach to farming across all continents. Not only how and what crops are grown matters, but also the interactions of the two in space and time lead to effects and consequences which influence the system performance and the delivery of ecosystem services. Some ecosystem services involve processes such as the hydrological, carbon and nutrient cycling that operate at the level of the fields on the farm, the landscape, the watershed and beyond. In addition, agricultural soil management is undertaken within different farming systems for producing biological products for the markets, and a range of production inputs, equipment and machinery, and management skills are needed to operate successfully (Kassam et al., 2009, 2013).

This chapter illustrates and discusses the inherently destructive and inefficient nature of the conventional tillage agriculture paradigm and therefore its inability to contribute sustainably and meaningfully to present and future societal needs. It highlights the role of conventional tillage agriculture in causing soil, landscape and agroecological degradation, and its consequent inability to function optimally at maximum output and profit with maximum efficiency and resilience at any level of agricultural and economic development, and to adequately deliver ecosystem societal services. The chapter elaborates the alternate production paradigm of Conservation Agriculture (CA) which can support sustainable production intensification to meet future food and agricultural needs (Kassam et al., 2009, 2013).

It is beyond the scope of this chapter to address the ethical issues related to sustainability noted earlier. However, CA's ability to reduce production inputs and increase outputs getting 'more for less' (i.e. raise factor and total productivity) and thus provide a truly pro-poor solution for poor farmers, unlike the current paradigm, is most certainly an issue of ethics, as is the ability of CA to protect and sustain the natural resource base in agricultural ecosystems (i.e. sustainable land management) and stop and reverse land degradation, regenerate agroecosystem functions and sustainably deliver societal services for all communities.

In Volume 2, Chapter 1 describes how greater crop and land productivity potentials are being mobilised under CA which has been spreading rapidly in all continents, particularly since the 1990s (Goddard et al., 2006; Friedrich et al., 2013; Jat et al., 2014; Farooq and Siddique, 2014; Kassam et al., 2009, 2010, 2013, 2015, 2017a,b).

2 The 'hidden' reality and societal cost of conventional tillage agriculture

2.1 Conventional tillage agriculture

Conventional tillage-based production systems are often referred to as the Green Revolution agriculture paradigm. Particularly since WWII, these systems have led to a paradigm for production intensification that is based on the intensification of tillage and the notion that more output can only come from applying more purchased inputs, especially of modern seeds, agrochemicals (for crop nutrition and protection), energy for tillage, and water. Conventional tillage-based systems have generally become unsustainable due to the degradation they cause (Montgomery, 2007; Kassam et al., 2013). This degradation includes loss of agricultural land, productivity and ecosystem and societal services (Montgomery 2007; Goddard et al., 2006; Kassam et al., 2009, 2013; Lindwall and Sonntag, 2010; Basch et al., 2012; Jat et al., 2014; Farooq and Siddique, 2014). Yet, agricultural science that continues to be supported by most governments and institutions deals mainly with tillage agriculture, whether inorganic or organic. However, the situation has been changing and increased attention is being directed towards generating and applying scientific and empirical knowledge and experience for CA, particularly since the end of the 1990s and the beginning of this century (Kassam et al., 2009, 2010, 2013, 2015, 2019).

The Green Revolution approach does not seem to be going anywhere now, even in nations such as India and Pakistan where it is claimed to have made a special impact in the 1960s and the 1970s, nor in the West where it all began after the end of WWII. For example, it is often stated that countries in Asia were the first to benefit from the Green Revolution paradigm in the developing world, but the question that arises is, why did the Green Revolution not continue to spread across India and Pakistan, or across Asia to benefit more and more smallholder farmers? (FAO, 2011b, 2016). In fact, the conventional 'modern' approach to crop production intensification, based on expensive inputs of intensive tillage, modern seeds, high agrochemicals and energy is often not affordable by resource-poor smallholder farmers. Where inputs are affordable or subsidised, the situation invariably leads to increased soil erosion and land degradation and sub-optimal yield ceilings.

The input-intensive Green Revolution mindset also includes the indoctrination and creation of a certain behavioural culture in agri-*culture*. This culture promotes the notion that farmers and their service providers and governments do not need to worry about the negative externalities that arise from the production practices being applied (Pretty, 2002; Beddington, 2011). The approach does not even call for an understanding by producers, dealers and their extension advisors, of the key ecological elements, functions and processes in the agroecosystem that should be managed and sustained to serve as the ecological foundation of sustainable production intensification (Kassam et al., 2009, 2010, 2013). In addition, the science and technology related to intensification under the Green Revolution paradigm has led to the application of economic models such as commodity specialisation that have led to extended landscapes with monocropping (Pretty, 2002).

Thus, the question of how the ecological foundation of agriculture should be managed to enhance and deliver both the desired output and ecosystem services[1] to society, while performing at the highest possible levels of efficiency and resilience, including coping with the climate change, does not receive the attention it deserves. Nor is there any serious concern being expressed in the Green Revolution approach about agricultural land area continuing to be severely degraded and abandoned in the North and the South due to the negative impact of the conventional tillage-based production paradigm (Juniper, 2013; Montgomery, 2007; Nkonya et al., 2016; Vlek et al., 2017). Indeed, many areas which in human history were the cradle of culture and intensive tillage-based agriculture are deserts today (Montgomery, 2007).

2.2 Agricultural soil degradation

Soil is a non-renewable resource that mediates and ensures crucial environmental, social and economic functions, and it has a central role in any approach aimed at defining the principles and practices of sustainable agriculture (Warkentin, 1995). Agricultural soil degradation is generally understood as the loss in the quality or productivity of soil because of human activities, leading therefore to less intensive usages or even land abandonment for agricultural use. In the 'Guidelines for General Assessment of the Status of Human-induced Soil Degradation' (Oldeman, 1988) the different forms of human-induced soil degradation are distinguished comprehensively between two main categories, which are: (a) the displacement of soil material through water and wind erosion; and (b) the chemical and physical deterioration, such as the depletion of soil nutrients and organic matter, salinisation, acidification and pollution, but also compaction, sealing and crusting, truncation of the soil profile or waterlogging. Despite this distinction between the two categories, there is a strong relationship between them, once the occurrence and degree of soil displacement is appreciated as being a consequence of chemical and physical deterioration of the soil. In addition, both categories of agricultural soil degradation may lead to severe off-site effects such as the sedimentation of reservoirs, harbours or lakes; flooding, river-bed filling and riverbank erosion, eutrophication of water bodies, etc.

In such earlier definitions and descriptions of agricultural soil degradation, the soil is treated mainly as a physical entity. However, a productive agricultural soil is a living system in which biological processes

1 Ecosystem services are provided to society by nature. Such services include edible and nonedible biological products, clean drinking water, processes that decompose and transform organic matter, and cleansing processes that maintain air quality. Several categories of ecosystem services are recognised: provisioning, regulating, cultural, and supporting (Millennium Ecosystem Assessment – MEA, 2005). In agricultural landscapes, provisioning ecosystem services can be delivered effectively and efficiently when the linked regulatory and supporting services are also allowed to operate normally. Ecosystem functions that protect and enhance regulatory and supporting ecosystem services in the soil and landscape in which crops are grown appear, in general, to offer an effective way of harnessing the best productivity, as well as ecological and economic performances (Kassam et al., 2013). Chapter 13 in Volume 2 is about harnessing ecosystem services with CA.

carried out by soil microorganisms and meso-fauna are key elements in the creation, maintenance and enhancement of soil health and its productive capacity. Soil health represents the soil's physical, chemical, hydrological and biological status and its ability to respond to agricultural production inputs and to climatic variability including extreme weather events. For example, soil physical, hydrological and chemical characteristics such as soil structure and porosity, soil aeration, water infiltration and drainage, soil water and nutrient retention capacity, total exchange capacity, pH are greatly influenced by soil biological properties such as soil organic matter turnover and the dynamics of soil biodiversity which has an intimate relationship with plant roots, affecting its phenotypic expression and stress behaviour below and above the ground. The deterioration of soil biological health, and the consequent loss in soil productive capacity, is often not given much prominence in agricultural soil management and degradation research or in farming system management. Thus, the role of soil microorganisms and meso-fauna and the soil organic matter they require to function effectively and self-sustainably in the maintenance of soil health and the important role they play in crop phenotypic expression, resilience and crop performance, are overlooked. This includes the diverse kinds of symbiotic relationships that exist between soil biodiversity and plants about which we know very little (Uphoff et al., 2006), presumably because of the difficulty in establishing through scientific experimentation the causal relationships with productivity and ecosystem services.

According to The Global Assessment of Human-Induced Soil Degradation (GLASOD) up to half the world's agricultural land is degraded to some degree (Oldeman et al., 1991). Degradation of cropland is most extensive in Africa, affecting 65% of cropland areas, compared with 51% in Latin America and 38% in Asia (CA, 2007). Loss of organic matter and physical degradation of soil, that not only reduces nutrient availability and has significant negative impacts on infiltration and porosity that consequently impact local and regional water productivity, the resilience of agroecosystems, and global carbon cycles. Accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation and the degradation of water bodies and infrastructure (Vlek et al., 2010). Nutrient depletion and chemical degradation of soil are a primary cause of decreasing yields and result in low on-site water productivity and off-site water pollution. Globally, agriculture is the main contributor to non-point-source water pollution. Water quality problems can often be as severe as those of water availability. Secondary salinisation and waterlogging in irrigated areas threaten productivity gains. According to the Millennium Ecosystem Assessment (MEA, 2005) some two-thirds of our ecosystems are degraded. According to FAO (2011a), only some 10% of the global agricultural land is under improving condition, the rest has suffered some degree of degradation, with 70% being characterised as being moderately to highly degraded.

Unfortunately, the problem of agricultural soil degradation is often considered to be unique to tropical and sub-tropical regions (Greenland and Lal, 1977) or confined in the developing regions, which is now recognised to be not so. Soil mismanagement and the traditional physical view of soils have led to serious soil degradation in temperate agroecologies in the industrialised countries (Pretty, 2002; Montgomery, 2007). For example, in 2002 the European Union initiated the so-called 'Thematic Strategy for Soil Protection', as it recognised that 'Soil is a vital and non-renewable resource and had not been the subject of comprehensive EU action'. At that time, the Commissioner of Environment even said that 'for too long, we have taken soil for granted. However, soil erosion, the decline in soil quality and the sealing of soil are major problems across the EU.' The ensuing discussion in the frame of this strategy identified eight major soil threats, which are soil erosion, decline in soil organic matter, soil contamination, soil sealing, soil compaction, decline in soil biodiversity, salinisation, floods and landslides. Notwithstanding this, the approach to understanding the root causes of soil degradation in any agricultural environment has remained relatively narrow, lacking the fuller appreciation of the role of soil biology in the maintenance of soil health, the role of symbiotic relationships between soil microorganisms and crop performance, and the disruptive effect of mechanical soil disturbance on soil health and productive capacity, and on production system resilience (Kassam et al., 2009, 2010, 2013).

2.3 Causes of degradation of agricultural soils

The root cause of soil degradation in agricultural land use and of decreasing productivity – as seen in terms of loss of soil health – is the low soil-carbon and soil-life disrupting paradigm of mechanical soil tillage which, to create conditions for improved crop performance, debilitates many important soil-mediated ecosystem functions (FAO, 2008). For the most part agricultural soils are becoming de-structured; our landscape is exposed and unprotected; and soil life is starved of organic matter, reduced in biological activity and deprived of habitat. The loss of soil biodiversity, damaged structure and its self-recuperating capacity or resilience, increased topsoil and sub-soil compaction, runoff and erosion, and greater infestation by pests, pathogens and weeds indicate the current poor state of the health of many of our soils. In the developing regions, this is a major cause for inadequate food and nutrition security.

In industrialised countries, the poor condition of soils due to excessive disturbance through mechanical tillage is being exacerbated by (a) the over-reliance on the application of mineral fertilisers, as the main source of plant nutrients, on to farmland that has been losing its ability to respond to nutrient inputs due to degradation in biological soil health – related to declining stocks of soil carbon – including loss/destruction of adequate soil porosity and reduced soil moisture storage and increased runoff, leading to poor root system, nutrient loss and decreased in nutrient uptake, and (b) reducing or doing away with crop diversity and rotations including legumes and pastures (which were largely in place around the time of WWII) facilitated by high levels of agrochemical inputs, standardised fixed agronomy, and commodity-based market forces that are insensitive to on-farm and landscape ecosystem functions.

The situation in the industrialised nations is now leading to further problems of increased threats from insect pests, diseases and weeds against which farmers are forced to apply ever more pesticides and herbicides, and which further damages biodiversity and pollutes the environment.

It seems that with mechanical tillage (intensive or otherwise) and with low soil input of atmospheric carbon and nitrogen and exposed soil surfaces as a basis of the current agriculture production and intensification paradigm, we have now arrived at a 'dangerous' point in soil and agroecosystem degradation globally, including in the industrialised North. However, we also know that the solution for sustainable soil management for farming has been known for a long time, at least since the mid-thirties when the mid-west of USA suffered massive dust storms and soil degradation due to intensive ploughing of the prairies. Dust bowls and large-scale soil degradation continue to occur in vast regions and in developed and developing countries (Baveye et al., 2011), despite the recognition of soil health being critical to life on earth.

For instance, in 1943, Edward Faulkner wrote a book *Ploughman's Folly* in which he provocatively stated that there is no scientific evidence for the need to plough. More recently, David Montgomery in his well-researched book *Dirt: The Erosion of Civilizations* shows that generally with any form of tillage, including non-inversion tillage, the rate of soil degradation (loss of soil health) and soil erosion is generally by orders of magnitude greater than the rate of soil formation, rendering agroecosystems unsustainable. According to Montgomery's research, tillage has caused the destruction of the agricultural resource base and of its productive capacity nearly everywhere, and continues to do so (Montgomery, 2007).

For these natural science writers as far back as 1945, tillage, regardless of type and intensity, is not compatible with sustainable agriculture. We only have to look at the various international assessments of the large-scale degradation of our land resource base and the loss of productivity globally to reach a consensus as to whether the further promotion of any form of tillage-based agriculture is a wise development strategy. We contend that to continue with intensive tillage agriculture now verges on irresponsibility towards society and nature. Thus, we maintain that with tillage-based agriculture in all agroecologies, no matter how different and unsuitable they may seem for no-till farming, crop productivity (efficiency) and output *cannot be optimised* to the full potential. Further, agricultural land under tillage is not fully able to deliver the needed range and quality of environmental services that are mediated by ecosystem functions in the soil, terrain, climate and biodiversity system. Obviously, something must change.

3 Agricultural intensification based on the Green Revolution agricultural paradigm

3.1 Intensification since WWII

The post-WWII agricultural intensification placed increasing reliance upon breeding ‘new' high yielding seeds, more intensive tillage of various types pulled by heavy and more powerful machines, combined with even more chemical fertilisers, pesticides and herbicides, supposedly making crop rotations superfluous and promoting apparent efficiency through specialisation with monocropping. This was complemented with the notion that with more mineral nitrogen input came the need for new, more responsive cultivars because the traditional cultivars were not capable of responding to higher doses of mineral nitrogen. A slogan of that era, coined by DuPont, was ‘Better Living through Chemistry'. Agroindustry and the Land Grant Colleges joined forces in promoting an industrial model for agriculture that was based on the use of chemical inputs and large volumes of output. Even FAO launched in 1961 the Freedom From Hunger Campaign (FFHC), which was partly financed by the world fertiliser industry. The FFHC's main target was to encourage the use of fertilisers by small-scale farmers through education, effective means of distribution and credit. The overall idea was that agricultural production could not be significantly increased in the developing countries of the world without improving the nutrient status of most soils. In the late 1970s, the FFHC was replaced by FAO´s Fertiliser Programme. Concurrently, rapid urbanisation and land consolidation in the industrialised countries forced agriculture ‘labour' to be substituted by ‘capital', particularly in the form of agricultural equipment and machinery. Large tractors with large ploughs became common in the 1980s and symbolised modern farming. This technological ‘interventionist' approach became the accepted paradigm for production intensification, and was promoted globally including in the developing regions – referred to as the Green Revolution paradigm of the 1950s, ’60s and ’70s – and which, despite boosting crop yields, increased the likelihood of soil erosion and degradation, loss in ecosystem functions and in productivity and output, leading to abandoned and desertified farmland and landscapes.

Smallholder farmers in developing regions using manual labour to till the land and burning or removing all crop residues from the field also experience the above consequences and remain trapped in a degrading vicious cycle that cannot be broken just by applying mineral fertiliser and replacing traditional varieties with the latest breeding results. This also applies to farms in industrialised regions where the voices demanding more sustainable farming practices, both environmentally and economically, are getting louder. As soil degradation advances, the need for purchased inputs increases until the point where the compensatory effect is no longer possible, forcing farmers to use even higher inputs with equally higher environmental impact.

Examples of large-scale agricultural soil degradation from different parts of the world appear to share several common experiences as can be seen from the cases of South America, China and Australia reported in Kassam et al. (2013). These cases reflect contrasting agricultural environments ranging from the tropical and sub-tropical environment with summer rainfall in Brazil to sub-tropical environment with winter precipitation in Western Australia to temperate environment with winter precipitation in northern China from east to west.

Various reports state that between 7 and 12 million ha of agricultural land are lost or abandoned every year due to land degradation. We believe this area includes 0.4 to 0.5 billion ha of agricultural cropland that was once suitable but has been degraded and abandoned over the years (Dregne and Chou, 1992; Pimentel et al., 1995; Montgomery, 2007; Gibbs and Salmon, 2015), particularly since WWII. This abandonment is due to the severe degradation and erosion arising from tillage-based agriculture systems, and the science, education and development community that supports them through the public, private and civil sector institutions, in both industrialised and less-industrialised countries (Montgomery, 2007). A recent study puts the annual global cost of agricultural land degradation due to land use and cover change at 300 billion USD (Nkonya et al., 2016). Other reports indicate much higher costs, and in cases where priceless ecosystem services are lost, it is not possible to put a cost value (Juniper, 2013).

Additionally, it is assumed that yield gaps can continue to be filled based on the current practice of intensive tillage-based soil management and increased application of costly and excessive production inputs, assuming the same or even higher production increase rates than in the past. In other words, the current agricultural paradigm assumed to meet future food demand in the scenarios of the FAO and of their collaborators such as the IFPRI, World Bank and others, is the land degrading and land destroying 'business as usual' tillage agriculture (FAO, 2012a). This 'more of the same' approach to intensification and maintenance of sub-optimal yields, factor productivities and overall performance can no longer be considered to be economically, environmentally, socially or developmentally sustainable anywhere; not in industrialised nations nor in emerging economies (Montgomery, 2007; Beddington, 2011; Gibbs and Salmon, 2015; Nkonya et al., 2016). In low-income countries, tillage agriculture based on the use of hoes and animal traction to pull simple ploughs and tillage equipment also leads to land degradation and loss of top soil and soil functions, to the point where land is eventually abandoned. Often, the lack of mineral fertilisers and fertility-enhancing and soil-health-promoting cropping systems accelerates the loss in crop and land productivity (Montgomery, 2007; Gibbs and Salmon, 2015; Nkonya et al., 2016).

Further, in many important high yielding production areas, crop yields have reached sub-optimal ceilings. For example, national-level yields of wheat crops appear to have stagnated at about 7 t ha^{-1} since around 1996 across several countries in Europe (Fig. 1) with inputs and input costs going up, and diminishing returns setting in (Brisson et al., 2010). In some countries in Europe such as Switzerland and Spain, wheat yields seem to have stagnated over the last 25 years (Table 1).

3.2 Agricultural land use unsustainability at a structural level

As indicated earlier, 0.4–0.5 billion ha of agricultural lands are reported to have been abandoned since WWII due to severe soil and land degradation, and loss of biodiversity and resilience. Yields of staple cereals in industrialised and

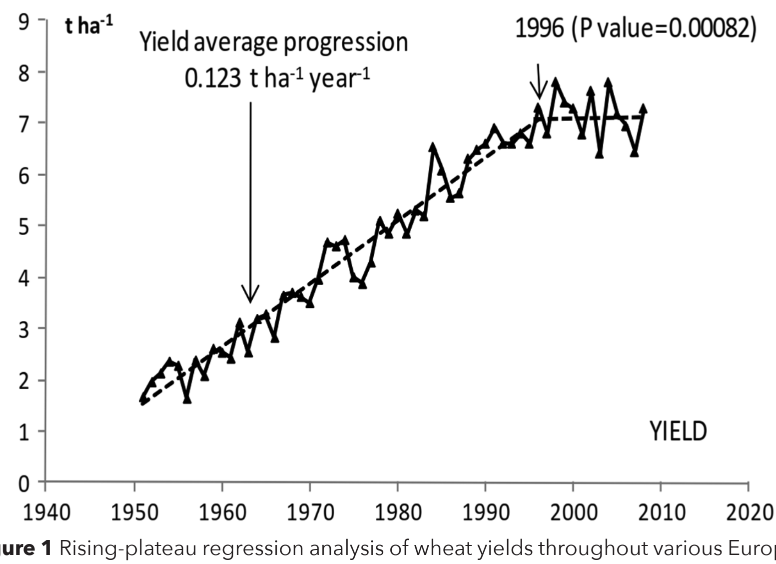

Figure 1 Rising-plateau regression analysis of wheat yields throughout various European countries. Source: adapted from Brisson et al. (2010).

Table 1 Year of stagnation in wheat yields in countries in Europe

Country	Year of stagnation
Denmark	1995*
France	1996*
Germany	1999
Italy	1994
The Netherlands	1993*
Spain	1989
Switzerland	1990*
United Kingdom	1996*

Year of stagnation: * very significant $P < 0.01$; no star $P > 0.05$.
Source: adapted from Brisson et al. (2010).

less-industrialised regions appear to have stagnated under tillage agriculture (Kassam et al., 2009, 2013, 2017b; Montgomery, 2007; Brisson et al., 2010, Jat et al., 2014; Farooq and Siddique, 2014; Gibbs and Salmon, 2015). These are signs of unsustainability and the institutionalisation of the supporting systems of agricultural research to generate new technology and knowledge. Thus, it is at the structural level, for both the supply and demand sides of food and agricultural security, that we need transformed mindsets about production, consumption and distribution, and policies and institutional capacities for science and development to support an alternative agricultural paradigm described in the next section.

What is surprising though is that agricultural land degradation continues unabated even though there are several UN treaties and programmes that are supposed to address the problem (e.g. UN Programme on Combating Land Degradation and Desertification; UN Convention on Biodiversity, Global Soil Alliance). Some of them have been ongoing since 1992, after the Rio Earth Summit. However, as has been pointed out by Montgomery (2007), conventional tillage-based agriculture globally, and the national and international knowledge and development systems that maintain it, is the main driver of agricultural land degradation. This structural nature of unsustainability in agricultural land use is not being addressed at the practical land management level for farmers and land managers by any of these UN treaties and programmes.

Thus, conventional tillage-based agricultural practices have all contributed to more soil and land degradation, decreased infiltration and waterlogging (Fig. 2), runoff and erosion (Fig. 3a and b), water pollution, and vulnerability of agriculture to extreme climatic events. At all levels of agricultural and economic development they have resulted in loss of agricultural land, decrease in attainable yields and in input factor productivity

Figure 2 Soil compaction and loss in water infiltration ability caused by regular soil tillage lead to impeded drainage and flooding after a thunderstorm in the ploughed field (right) and no flooding in the no-till field (left). Photograph taken on June 2004 in a plot from a long-term field trial 'Oberacker' at Zollikofen close to Berne, Switzerland, started in 1994 by SWISS NO-TILL. The three water-filled 'cavities' in the no-till field derive from soil samples taken for 'spade tests' prior to the thunderstorm. Source: Wolfgang Sturny.

(Montgomery, 2007). They have also contributed to excessive use of seeds, agrochemicals, water, energy and labour, all leading to increased cost of production. They have led to poor production system resilience, dysfunctional agroecosystems, degraded ecosystem services to society, including lower water quality and quantity, poor nutrient and carbon cycling, sub-optimal water, nutrient and carbon provisioning and regulatory water services, and loss of soil and landscape biodiversity. They all constitute the high, real cost of food production, of agricultural products for industry, and of environmental management being passed on to the public, and to future generations (Kassam et al., 2009, 2013).

On the other hand, if we are to (i) mobilise greater crop and land productivity potentials sustainably to meet future food, agriculture and environmental demands; (ii) maintain the highest levels of productivity, efficiency and resilience (getting 'more from less'); and (iii) rehabilitate degraded and abandoned agricultural land and ecosystem services we would need to replace the faltering production 'engine' of the conventional tillage-based production paradigm. We need to transform all the components of the food and agriculture systems, including the supporting science, education and policy that are built

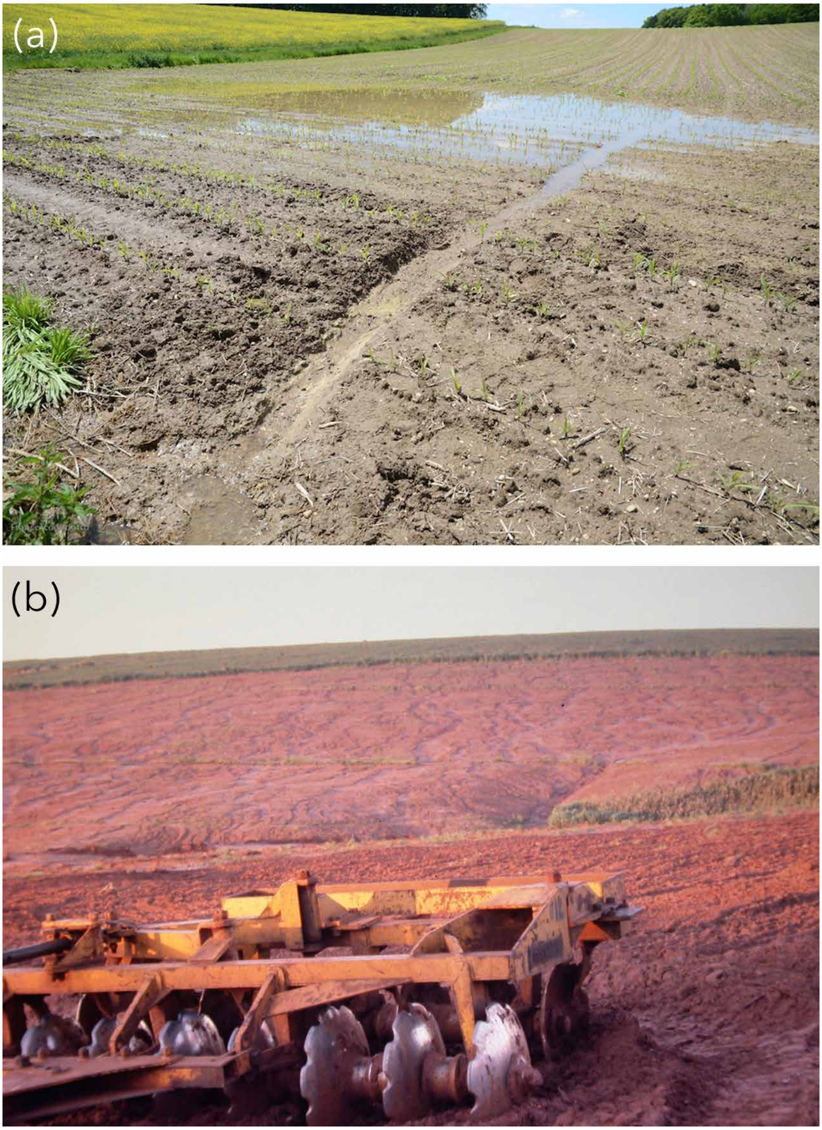

Figure 3 (a) Erosion and runoff on conventionally tilled bare soil near Cordoba, Spain (Source: Emilio Gonzalez-Sanchez). (b) Erosion and runoff on conventionally tilled bare soil in southern Brazil (Source: Rolf Derpsch).

upon it. This transformation is now ongoing as far as agriculture production is concerned and needs to be accelerated (Goddard et al., 2006; Kassam et al., 2009, 2013, 2015, 2017b, 2019; Lindwall and Sonntag, 2010; FAO, 2011b, 2016; Jat et al., 2014; Farooq and Siddique, 2014).

The following sections elaborate on an alternative agricultural paradigm that is being applied by farmers to: minimise and reverse the agricultural soil and landscape degradation trends; and mobilise greater agricultural land potentials.

4 Replacing conventional tillage agricultural with Conservation Agriculture

4.1 Nurturing soils as living biological systems

A productive soil is a living biological system and its health and productivity depend on managing it as a complex biological system, not as a geological entity. This is because soil's productive capacity is derived from its many components (including physical, biological, chemical, hydrological, climate, cropping system, management, development level) all of which interact dynamically in space and time within cropping systems and within agroecological and socioeconomic environments (Kassam et al., 2013).

Alongside the concern for soil erosion and the destruction of soil structure and soil life caused by frequent and intensive tillage has been the growing understanding of the important role soil life and soil biology play in the maintenance of soil health. According to Doran and Zeiss (2000):

> Soil health is the capacity of soil to function as a living system with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health.

According to Peter Trutmann, quoted in FAO (2008), the above emphasises, a unique property of biological systems, since inert components cannot be sick or healthy. Management of soil health thus becomes synonymous with management of the living portion of the soil to maintain essential functions of soil to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health (Kassam et al., 2013). According to David Wolfe, quoted in FAO (2008), healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots (e.g. nitrogen-fixing bacteria and mycorrhizal fungi); recycle essential plant nutrients; improve soil structure (e.g. aggregate stability) with positive repercussions or soil water and nutrient holding capacity, and ultimately improve crop production. More recently, it has become clear that mycorrhiza also play an important role in carbon sequestration by producing glomalin, and inert sugar-protein that also acts as a biological cement in the creation of stable soil micro- and macro-aggregates.

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