Conservation agriculture systems

J. P. Mitchell[1]*, D. C. Reicosky[2], E. A. Kueneman[3], J. Fisher[3] and D. Beck[4]

Address: [1]Department of Plant Sciences, University of California, Davis, 95615, USA. [2]Emeritus Soil Scientist, USDA ARS, Morris, MN 56267, USA. [3]Retired, Food and Agriculture Organization, West Sacramento, CA 95691, USA. [4]Dakota Lakes Research Farm, South Dakota State University, Pierre, SD 57432, USA.

*Correspondence: J. P. Mitchell. Email: jpmitchell@ucdavis.edu

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Abstract

Despite positive trajectories in global production during the last century, projected food demand and limits on our ability to further expand cropland now dictate an increase in food production by roughly 70% during the first half of the twenty-first century. Conventional systems of agriculture with their general emphasis on intensive soil disturbance, limited biodiversity, monoculture cropping and practices that mine the resource base are extractive and have resulted in slow yet demonstrably severe environmental degradation that ultimately jeopardizes food security for future generations. Because future gains in production are unlikely to be achieved by further increases in genetic yield potential, as have been achieved in the past, applications of new production system paradigms are going to be indispensable. Our existing ones are no longer able to compensate for, nor reverse, the environmental problems they have caused. We summarize the history of how agricultural systems have come to be what they are today and identify ways in which these systems will need to be improved to meet future food security challenges. We describe the development of food production system options that have been proposed in recent decades and show that the core principles and concepts of what are widely regarded as conservation agriculture (CA) systems provide an important unifying framework. Our chapter provides evidence for why these systems, when flexibly applied and in ways that mimic natural ecosystems, provide a best-bet approach for moving forward. We highlight a series of examples of CA systems being applied around the world and conclude by issuing a call to action aimed at developing and more widely adopting food production systems that look long-term, mimic natural systems and transcend jargon.

Keywords: Conservation agriculture, No-tillage, Regenerative agriculture, Agricultural systems, Soil health

Review Methodology: The literature reviewed is based on multiple sources.

Introduction: The Historical Context

Humans appeared in the earth's ecosystem relatively recently. Their total existence is but a blink in time relative to the aeons that biological organisms have existed on the planet. Within this short time, there is an even shorter period prior to the present – only about 12 000 years – when humans have intentionally grown plants in order to harvest food and fibre. The conventional crop production practices employed, in all cases were and are extractive, in that the ecosystem has always been left in a state with fewer nutrients, less soil organic matter (SOM), reduced biological activity and lower diversity. When crop production was carried out on the same parcel for several consecutive years, output declined. As a consequence, it became common to move agriculture to another location by physically moving to a new parcel [1–3]. When physically moving was not a viable option as, for instance, when settlements became more permanent and available land was difficult to find, attempts were made to maintain productivity through a myriad of diverse management changes with the goal of maintaining yields as long as possible. This included the application of nutrients (mostly in the form of manure or minerals) into the system [4].

These early approaches have been used by almost all agriculture until the present time. Maximizing yield of a limited suite of crops and animals has been an over-arching goal. Centuries of trial and error, organized research, innovation, policy-making and tradition have been primarily focused on productivity and short-term economics. The actions taken in most cases were reactive, meaning that they were only taken when yields declined or when a disease, weed, insect or other management constraints threatened yield. These maladies were seen as the problem rather than as symptoms, indicating the underlying system was flawed. As a consequence, research focused on specific components of the system with the short-term goal of 'solving' the problem quickly and restoring yield. Developing crops with resistance to a disease or insect, or more recently to herbicides that could kill specific weeds, occupied a large proportion of research efforts. Diversity was seen as a constraint to yield because it meant resources were being diverted from the main goal of producing yield of the primary crop(s). Soil biology was ignored as well. It also meant that production practices became more complex and crop specific. More crops needed to be sown, managed, harvested and sold, – with each one having its particular set of agronomic practices.

The consequence of the short-term, yield-centric approach that has predominated agriculture from its inception, is widespread degradation of soils in particular, and the ecosystem in general [4]. Soil degradation has long been recognized as a concern by selected farmers, ecologists, economists and even by policy-makers, but the poor state of the world's soils and consequent implications are now gaining broader societal recognition, and correctly, a sense of urgency [2, 5–7]. The United Nations for instance, declared 2016 as the 'International Year of Soils' to advocate for urgent changes in soil management.

In the United States, founding fathers George Washington and Thomas Jefferson both postulated that the negative consequences of farming practices on soil productivity would necessitate western expansion into virgin territory in order to maintain sufficient agricultural activity to support the population [8]. The comprehensive work of Lowdermilk [9] and more recently of Perfecto *et al.* [4] offer a sobering look at soil degradation through 7000 years of agriculture in Europe and the Middle East. The same management practices that caused these impacts are still used today. Most were exported from Europe to North America, South America, Australia and the steppes of eastern Europe and Asia when land degradation in Europe led to widespread migration to find locations and ecosystems that had productive soils. The result was the same as evidenced by the creation of the 'Dust Bowl' in the United States during the 1930s with ongoing degradation of soils and water bodies throughout all of the continents where agriculture is practiced [10, 11]. Widespread mechanization of agriculture was a contributing factor, in that the extent and degree of tillage possible with powered traction far exceeded the capability of animal traction. Thus, when draft animals were not required on farms as they had been before the widespread use of powered tractors, pasture and annual crop rotations were less of a requirement. Pasture cycles had helped mitigate tillage-induced soil degradation.

Agricultural scientists and national and international agencies have become very cognizant of the negative impacts of soil and ecosystem degradation [12, 13]. Attempts to address these issues initially were similar to approaches used to address weeds, disease and insects [14]. Specifically, engineering solutions such as terraces [15] were favoured for erosion control over more complex approaches focused on improving soil stability and function. Minimum tillage systems, ridge-tillage, no-tillage and other systems were designed to address the issues of wind-driven soil erosion and degradation, and carbon efflux [16, 17]. These systems, depending on how they are employed and the conditions under which they are used, can produce vastly different results [18]. Some of the systems are widely used over large areas of land in certain locations [3, 11, 19] enabling reduced soil erosion and associated loss in water and air quality. In almost all instances these interventions have slowed but not stopped or reversed soil and ecosystem degradation. In some cases, it has addressed reduced soil erosion at the expense of increased water degradation [20–23].

The issue with these agricultural systems does not lie in the effort or quality of the research and development process. They were addressing only part of the problem. Soil and ecosystem degradation result when ecosystem processes are not functioning optimally. These processes can be described as the nutrient cycle, the water cycle, maximum sunlight capture and community dynamics/ synergies (Table 1). In any given location, well-managed native vegetation provides good examples of how these processes work in that environment with those soils [24]. Tillage-based systems cause excessive runoff and erosion as compared to undisturbed native conditions. Diverse native vegetation will capture more sunlight and cycle more nutrients than is possible with annual crops where a portion of the moisture is lost to runoff, or to evaporation instead of transpiration. If no-till is used but no other changes are made, runoff and erosion are minimized but excessively wet soils will sometimes occur and subsequent nutrient loss is probable. When tillage is eliminated and more intensive and diversified cropping systems, including perennial crops and livestock, are employed, water and nutrient cycles along with sunlight capture are much closer to natural regenerative systems.

Most research and development effort into agricultural systems has also used unrealistically short time frames. This might be acceptable if the research is testing a component in an established system, but time is not sufficient for responses to minimum soil disturbance, lack of diversity, poor sunlight harvesting and incomplete nutrient or water cycling to express themselves. In particular, the

Table 1 Ecological attributes of natural systems (Mother Nature)[1]

Harvest the maximum amount of sunlight
Leak very few nutrients including CO_2
Have biodiversity
Do not export nutrients via erosion or deep drainage
Make maximum use of water and nutrients by having highly developed porosity and vesicular arbuscular mycorrhizal fungal webs and
Do not do tillage

[1]Dwayne Beck, Dakota Lakes Research Farm, South Dakota State University, 2014 Winter Conference of No-till on the Plains, Salina, KS.

sequestering of carbon compounds in the soil is a slow process. Research time-frames and data analysis schemes need to be capable of projecting results far into the future. No one (no group of immigrants) entered a new land with the goal that they were going to degrade the ecosystem and then move to another ecosystem. We cannot continue to manage our farmland in that manner either.

Consider for instance, the 7000-year retrospective expose of Lowdermilk [9], or the chronicles of Lewis and Clark [25] (1804 originally and in abridged version 2004) who explored the Central Plains of the USA. They recorded their observations of the native vegetation on the property where the Dakota Lakes Research Farm of South Dakota State University is now located. The climate has changed in the area compared to 1804, but the degradation of the ecosystem due to human activity (farming, grazing, engineering) that has occurred in the last 200 years has very probably caused more loss of productivity than during the previous 20 000 years [2, 6, 9].

With these formidable challenges providing historical and contemporary context, how will global food security be best achieved in the future? What will be the goals, principles and systems that will provide the greatest benefit while minimizing risk, including ecological collapse and reduced access to safe food? This paper explores these challenges and the attributes of production systems that may best provide global food security in coming centuries and argues that what have been developed as the core concepts and framework of conservation agriculture (CA) systems, flexibly and creatively applied across very long-term time scales, offer in large measure our best hope. We do not argue that CA systems are the only good practices in every situation meeting every farmer's needs. In designing of today's production systems for the challenges of tomorrow, we recognize that in order to bridge the gap between global food demand and supply, we need to develop means for increasing average farm yields, while simultaneously protecting the long-term productive potential of the underlying agricultural resource base [26]. In this respect, as indicated above, these natural ecosystems have evolved over millions of years of evolution. These systems efficiently capture sunlight, CO_2, water and nutrients. They enable water cycling and biological productivity. Thus, we argue for the urgent need to manage, when appropriate, agroecosystem processes, with considerations of natural systems as the model. We encourage embracing the science of regenerative systems and an understanding of the interactions of their components. This choice or path forward is not linked to dogma or any form of scriptures of faith. Acknowledging that plant and animal communities have found ecological balances over aeons, is not in itself any kind of dictate on what will work best. Rather, understanding and then being able to strategically implement lessons learned from evolution's holy grail, provides guidance and direction for the types of production systems that might be pursued in the future. This paper focuses on the need to amplify and accelerate adoption of good agriculture practices that enable productivity increases on a sustainable basis. Choices made today regarding how agriculture is conducted will determine global food security and planetary health in the future. We assert that for many production environments, the core principle elements of CA, when applied flexibly to mimic regenerative natural ecosystems, provide the best approach to reach the interrelated tangible goals of improving farm incomes while ensuring that soil health, water and air quality, and biodiversity are protected, and that climate change is mitigated, including by reductions in energy expenditures. We do not advocate dogmatic, prescriptive, 'one size fits all' farming approaches. We emphasize that in general, current conventional soil tillage practices are not sustainable and need to be reduced to recover critical soil functions, including sequestration of atmospheric carbon. We discuss the history of CA adoption and how CA will be one of the major tools for sustainable intensification (SI) of global crop production in the future. We address current debates concerning the wide array of frameworks or pathways for future food production systems that are being proposed. These include concerns by some CA system critics that agricultural development choices need to be exhaustively nuanced to fit local contexts, and in particular, the harsh farm-family constraints often encountered in developing nations. Our paper further discusses the special extension education needs that are required to scale-up adoption of knowledge-intensive innovations such as CA. Finally, we highlight the need for longer-term thinking with respect to evaluating future food production systems options.

Challenges Going Forward

In the coming three decades alone, global demand is expected to require increasing overall food production by about 70% [27] because of increasing and more demanding population and per capita income, while agricultural resources, such as irrigation and arable land, are projected to become even more constrained and scarce [28–30]. This expanding global population will put tremendous pressure on the earth's finite land area and resources for agricultural production. With these challenges rapidly approaching, wide-ranging considerations for how global food needs will be met stress the need for new paradigms and multi-disciplinary science-based solutions [31]. We also acknowledge recent modelling studies [32] that forecast positive changes in 'crop calorie supply' in Europe due to impacts and uncertainties of a projected +2 °C of climate change, but that also indicate potential 'calorie vulnerability' associated with soil degradation in terms of soil loss, depletion of plant nutrients and SOM decrease. Concern about the continuing ability of soils to provide ecosystem services essential for food security [33] in the face of increasing demand for food and increasing pressure on agricultural resources, is thus seen as one of the major challenges for our survival on the planet [29, 34]. The world's agricultural soils have already lost 66 to 90 billion tonnes of carbon (C) due mostly to tillage [35] with a substantial amount lost to erosion, which is also mostly tillage-mediated [36]. Many of these soils have lost between 30 to 60% of their original amounts of soil C and nitrogen (N) over the past several decades [37]. Soil tillage is particularly harmful in the tropics where temperatures are always high, driving rapid and exhaustive oxidation of SOM. Low SOM means poor nutrient- and water-use efficiency.

For some 10 000 years farmers worldwide have been engaged in this slow soil degradation using intensive, high disturbance tillage [3, 38]. Montgomery [2] chronicled the effects of poor soil management and erosion on several past civilizations. Once thriving, these civilizations eventually collapsed due to erosion, salinization, nutrient depletions and other types of soil degradation. Tillage, the mechanical manipulation or disturbance of the soil [39, 40], prior to planting, loosens and moves soil down slope, easing its transport by wind or water, and inducing and increasing loss. Erosion rates from conventionally plowed agricultural fields are orders of magnitude greater than rates of soil production. It is estimated to require between 700 and 1500 years to form just 25 mm of soil [2]. Using current conventional practices, we are losing soil much faster than nature can make it.

Not only have past and current agricultural tillage practices accelerated these blatant forms of degradation and carbon (C) loss, but they have also caused more subtle changes in soil properties, or more specifically, the overall health or the ability of the soil to function optimally [41], and this has also had large impacts on productivity [26]. Tillage practices have tended to compromise the role that biological diversity in the soil has on a range of important functions, including nutrient cycling and use efficiency and emissions mitigation. The external input-intensive practices of most current conventional systems, – tillage, the use of soil biocides, and the lack of diverse crop rotations, – all work against, rather than with, soil biological diversity in a given production system. In the next section, we clarify some of the more visible terms and alternatives that have been proposed to address these challenges and conclude that the original conceptual formulation of CA, serves not only to unify, but to also clarify the goals and principles of future food production systems.

A Brief Review of Production System Options and Their Characteristics

In 1992, in Rio de Janeiro, Brazil, the United Nations organized a global meeting on the environment, known as the Earth Summit. The summit's declaration issued a global call for action to address the food production and security challenges posed by a rapidly-increasing global population. The report, Earth Summit Agenda 21 [42], produced a blueprint for increasing food production in a sustainable way and enhancing food security. The Summit's report identified 21 central environmental issues for planet health. Chapter 14 on Sustainable Agriculture and Rural Development flagged problems emerging from the input-intensive approaches to increasing food production associated with the Green Revolution which relied on fertilizer-responsive (lodging-resistant) crop varieties, irrigation and pesticide inputs. This input mix for rice (*Oryza sativa*) and wheat (*Triticum aestivum*) had been introduced in the 1960s and 1970s to smallholder farmers in Asia and South America along with intensive tillage. While food production, initially increased using these techniques and tools, a variety of associated environmental health issues soon followed [4]. North American and European agriculture had already adopted the high-input, highly mechanized approaches. Some lessons were learned from the Green Revolution, including the need for broader adoption of integrated pest management that had been widely introduced by the Food and Agriculture Organization (FAO), then later by the Consultative Group for International Agricultural Research (CGIAR), and private sector partners. Global food safety legislations mandated reductions in injudicious uses of pesticides, whose residues are strictly monitored for international trade specifications. Since 1992, the FAO, the World Health Organization (WHO) and the World Trade Organization have been conveners and facilitators of a wide variety of global safe food legal instruments.

Fertilizer overuse was also mitigated in many places due to the high cost of unsubsidized plant nutrients and by introduction of integrated plant nutrient management approaches to optimize returns to farmers. The continued destruction of soil health caused by tillage in these systems, however, was never effectively addressed globally [7].

A number of alternatives have been proposed to address problems that have surfaced as a result of the very alluring approach or heavy inputs with extensive tillage in the chase for high yields [4] for food production systems. Evidence for the view that existing conventional practices are no longer able to compensate for or reverse the significant problems that they have spawned is 'hardly contestable and has become common knowledge' as reviewed by Perfecto *et al.* [4]. A proliferation of terminology and jargon has

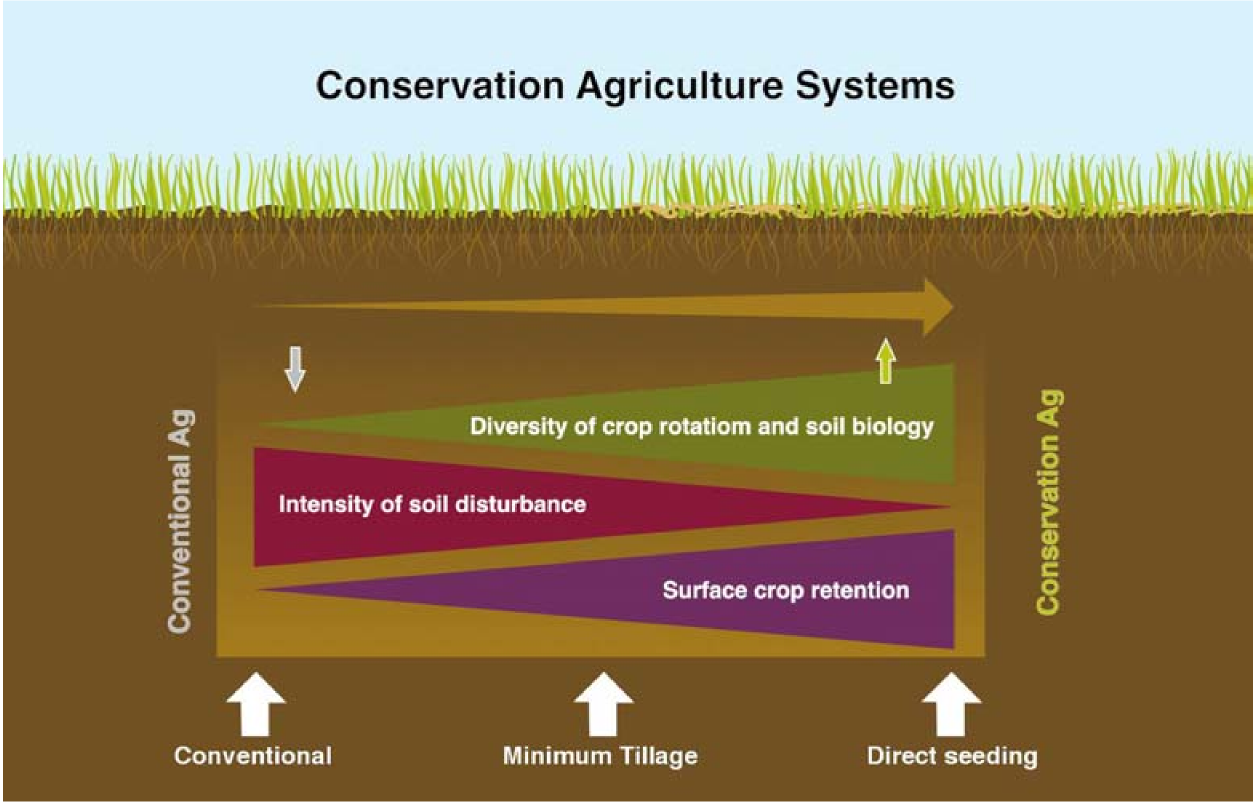

Figure 1 The three linked principles of CA. Adapted with permission from K. Sayre.

accompanied the development of these alternative models (Figure 1).

Organic and GlobalGAP farming

During the last century, high input organic farming systems have become arguably the most visible alternatives to the conventional and dominant Green Revolution agriculture paradigms. Based on the early work of Sir Alfred Howard, Rudolf Steiner, F.H. King, Lord Northbourne, Lady Eve Balfour and Masanobu Fukuoba [43], and later contributions of J.I. Rodale, Oregon Tilth and others, organic farming is now a highly developed and generally widely agreed-to set of principles and practices that restrict synthetic fertilizers and pesticides, including herbicides and use of genetically-modified organisms (GMOs) (Organic Food Production Act of 1990 [44]). A key discovery by Hutchinson and Richards [45] at Rothamsted Experiment Station in England that farmyard manure needed for organic production could be largely replaced by relatively small amounts of manure mixed with plant or crop residues, made scaling-up adoption of organic production perhaps easier than otherwise expected. Urban waste, sewage and yard debris may become increasingly valuable as sources of compost, especially for peri-urban farming, where transportation costs are favourable. The United States Department of Agriculture reports that organic food is one of the fastest growing segments of American agriculture with over 21 000 certified organic farms in the USA [46–48] and according to the International Federation of Organic Agricultural Movements [49], an estimated 2 million of the world's 1.5 billion farms are now producing organically. However, of these 2 million, many are low-input organic subsistence agriculture farmers in developing counties, barely providing for their families. Low-input organic farming has not fared well in addressing rural poverty or meeting urban food and fibre needs in these regions.

While the rise in awareness and attention to high-input organic farming did not happen suddenly and has only been possible through the sustained and deliberate dedication of many supporters over many years, organic agriculture has achieved a unique level of prominence in the USA and Europe through its labelling and certification programmes. Organic agriculture is highlighted in the recent US Farm Bill [48]. Because of production costs per unit harvested, organic costs are frequently higher, which is exacerbated further because the audit and certification for organic assurance are also expensive. Not all consumers can financially adopt these value chains. Depending on market options and production and certification costs, farmers in different situations make management decisions that make sense for their individual survival and environmental stewardship goals. CA and organic systems are considered to be in conflict by many agronomists and farmers, because CA generally includes judicious use of herbicides, which is not acceptable in organic protocols.

Criticisms of organic farming as a comprehensive platform on which to develop future production systems rest on its ideological and lesser scientific basis, its rigid rejection of parts of modern farm technology, and its 'incremental embrace' by the scientific community [50]. Nevertheless, such segregated markets will continue to grow as wealthier consumers often can, and do choose to, believe the products are safer, healthier, and with lower environmental footprints. Labels showing, for example, USDA or IFOAM certified 'organic', inspire confidence. That the veracity of the benefit-claims is not necessarily scientifically robust, seems to be of little consequence. In the context of our appraisal of regenerative systems, organic has considerable merits, however, it is generally achieved using practices with substantial tillage, which on the larger scale is not good for soil health.

Another major segregated market emerging from Europe, GlobalGAP (Good Agricultural Practices) provides farmers with opportunities to receive value-added payments based on meeting GAP certification protocols (see https://www.globalgap.org/). The accepted GAP standards are more flexible than those of organic systems, allowing judicious use of agrichemicals, but are still firmly rigid in terms of meeting maximum allowed agrichemical residue levels on produce with its label. It follows and ensures limits set by the Codex Alimentarius convened by the FAO and WHO, UN agencies. GlobalGAP is today one of the world's leading farm assurance programme, promoting good farming practices in over 125 countries. It is a demand- and market-driven set of protocols, coupled to audit and certification processes. Initially the GlobalGAP labelling was primarily horticulture focused, but now also applies to field crops and some industrial crops. GlobalGAP and CA can be easily blended, while CA and organic are often incompatible, due primarily to the frequent inclusion of herbicides in CA systems, but excluded in organic.

Sustainable agriculture

The term 'sustainable agriculture' is defined as food production systems that are economically viable, environmentally benign and socially responsible. Sustainability denotes any system capable of persisting [51–53]. FAO articulated the basis for sustainable agriculture in its drafting of Chapter Fourteen 'Sustainable Agriculture and Rural Development (SARD)' for 'Agenda 21' that was endorsed by member governments of the United Nations during the first global conference on Environment in 1992. The SARD concept was not to be overly prescriptive of precisely what actions should be taken on every farm, but promoted 12 elements, such as: integrated pest management, sustainable plant nutrition, land conservation, farming systems through diversification and rural energy. While sustainable agriculture is generally understood as an ecosystem approach to farming, criticism of the concept, by some, is its inferred or perceived incrementalism [54, 55]. This concern has been coupled to the realization that future production systems will face heavy demands of urban populations [56, 57] and increasing constraints, such as reduced energy and water availability, climate change-related impacts and the need to have a significantly smaller environmental footprint. In reality, SARD, as articulated in Agenda 21, is in no way incremental-oriented, and does address the need to feed the growing global population. The SI concept, below, primarily grew out of SARD.

Ecological and sustainable intensification

Definitions and common use of the terms 'ecological intensification' (EI) and 'sustainable intensification' (SI), first coined in the late 1990s by Cassman *et al.* [26] and Pretty [58], respectively, have recently been reviewed by Cassman [59]. EI was originally proposed as an essential means to achieve the dual goals of supplying food to a climax human population of 9.5 to 11 billion people without degrading the environment or exhausting the natural resource base upon which agriculture depends [59]. SI on the other hand, was initially conceived mostly with 'regenerative', low-input agricultural options for reducing negative impacts on ecosystem services [59]. Since being originally conceived, however, general understanding of the terms has converged with the primary distinction between the two now being that SI includes social and economic aspects of the production system options, while EI emphasizes biophysical dimensions. An understanding of these terms involves simultaneously improving both yields and the agricultural performance of crop production which is ultimately achieved by precise management of all production functions and maintenance or improvement of soil quality [59]. A final element of EI and SI concepts is recognition of the sheer complexity of the high yield production systems that will be needed to achieve future food security goals and the inevitable role that farmer-owned and controlled big data platforms that are capable of sifting through all the noise that often comes with precision agriculture tools and technologies to identify the driving variables and best combination of practices for a given situation or a particular field [59]. The term 'sustainable intensification' also arose out of what might be termed 'donor fatigue' with the FAOs promotion of sustainable agriculture in the early 1990s. Funders look for new 'buzz phrases' on which to justify expenditures while research and development experts manoeuvre to accommodate this demand by creating new programmes and terminology. The underlying concepts of these efforts, however, remain largely quite similar and consistent.

The EI and SI conceptual frameworks have been criticized as having a dominant focus on yield and a lesser emphasis on ecological dimensions of production systems. Cassman [59] has argued, however, that EI is essentially 'agnostic' with regards to farming methods and approaches to achieve these dual goals. At the end of the day, he asserts, systems must be shown to result in higher yields while decreasing negative environmental impact or they would not meet the definition of EI. Using yield and input use efficiencies as metrics for monitoring performance towards EI, is thus not likely to diminish ecosystem services or result in unintended degradation of soil function.

Soil health

Concern during the past two decades about the continuing ability of soils to provide ecosystem services essential for food security [33] has also given considerable importance to the concept of soil health as a focus of future food production systems [41, 60, 61] advanced by the United Nations Food and Agriculture Organization, the United States Department of Agriculture's Natural Resource Conservation Service and the California Department of Food and Agriculture, among many other regional and local organizations worldwide. It has been argued that the terms 'soil quality' and 'soil health' should not be used interchangeably [62–66]. They hold soil quality is related to soil functions, e.g. enabling good plant growth, sequestering carbon and cycling of nutrients, whereas soil health treats soil as a living biological entity that affects plant health. Through plant growth, soil health is also connected with the health of animals, humans and ecosystems within its domain. Through the supply of macro- and micronutrients, soil health, which is mediated by soil organic carbon dynamics in and outside of living systems, is a strong determinant of global food and nutritional security [62, 63].

History of the soil health concept has been reviewed by Karlen [41]. Maintaining soil health in the face of increasing demand for food and pressure on agricultural resources is seen as a major challenge of the twenty-first century [29, 34]. Since the publication of 'Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial)' by Karlen *et al.* [64], and the pointed rebuttal, 'Reservations Regarding the Soil Quality Concept', by Sojka and Upchurch [67] (reviewed by [68]), an energetic and at times acrimonious debate has been waged between proponents and critics of the concept of soil quality, or more recently, the related concept of soil health. Supporters point to the urgent global need to protect soils to ensure food security and ultimately human security [12, 33]. Skeptics argue, however, that relationships between soil attributes and how a given soil functions are poorly understood, it is difficult to apply soil health practices broadly across diverse environments, and that the entire notion of soil health is abstract, particularly in regions like California where farmers achieve some of the highest crop yields, and yet soil quality assessments generally indicate low inherent soil quality [67, 69]. The fact is, in places like California's Central Valley or the drylands in Israel, where irrigation water is abundant and inputs are economical, soil health loses can be substantial before economic productivity is exhausted. The environmental and economic costs are real, nevertheless. Even in these remarkable agricultural paradises, many farmers are moving from annually-sown row crops towards perennial crops, where soils are more protected and nourished without tillage. This trend is also expanding rapidly through Oregon and Washington, although the perennial crops differ in response to temperature and markets niches (M. Nagely and A. Heinrich, personal communication, 2018).

Furthermore, farmers themselves tend to not pursue soil health as a goal in itself, but rather, they seek to develop overall improved performance systems that may be less expensive, more efficient and with fewer regulatory issues, or that address their own overall long-term farm goals. Despite these concerns about the soil health concept, in general, the USDA NRCS in the USA embarked upon an ambitious national public relations campaign for soil health to, 'Unlock the secrets of the soil', that was launched on 11 October 2012 at the farm of long-term no-till and cover crop farmer, Dave Brandt, in Carroll, OH. Principles that underlie the NRCS soil health initiative were developed from a literature search [70] of the agency's practice standards that are used in allocating payments to farmers via Farm Bill programmes and are essentially identical to principles of CA (see section 'Conservation Agriculture Systems as a Unifying Concept').

Regenerative agriculture

The term 'regenerative agriculture' is at present perhaps a less formally-articulated concept or approach to farming systems, yet one that is also gaining attention as a design platform for future production systems. Its origins date to the 1980s with Robert Rodale and the Rodale Institute's use of the term [71]. A later (2014) Rodale publication defined regenerative agriculture by 'its tendencies toward closed nutrient loops, greater diversity in the biological community, fewer annuals and more perennials, and greater reliance on internal rather than external resources.' An adjunct proposed benefit of organic regenerative agriculture is increased soil carbon stocks and decreased greenhouse gas emissions. Promoters of the new Regenerative Agriculture Organic Certification policy that is currently being proposed for the 2018 US Farm Bill point to comparable yields for numerous crops including corn, wheat, rice, soybean and sunflower with organic regenerative systems compared to conventional systems [72]. Proponents assert that future risks of hunger and food access are not food supply issues that will not be addressed by ever-greater yields, but are rather, social issues of inappropriate agriculture and development policies and inequality [73–75]. The authors of the Rodale paper hold that all parameters must be addressed to meet even near-term global needs.

Systems agronomy

The theoretical and broadly field-tested foundations of 'systems agronomy' have been developed over the past two decades largely by European and African crop production and pest management ecologists using co-learning methodologies between farmers and agronomists [76]. This work has been designed to explore and develop 'place-based' science and grounded knowledge to help farmers best identify and apply appropriate management options that are suited to their conditions. Systems agronomy approaches have been developed as a shift from 'adapting principles or technologies to local circumstances, toward localized agronomic knowledge production' [76]. They represent a move beyond dogmatic, prescriptive and often value-laden approaches, and aim to provide more adaptive, locally-based tool boxes of options for the SI of agriculture. These 'locally-adapted practices' have also been referred to as 'complementary practices' [77], and include efficient weed management [78], integrated soil fertility management [76, 77] and controlled traffic farming (CTF) [79]. The fundamental orientation of systems agronomy is thus to place the ultimate beneficiaries of knowledge, – farmers, – at the centre of the discovery and application of knowledge process, where they belong [76]. It promulgates that overly prescriptive and inflexible approaches that have tried to apply 'universal' principles and practices, such as reduced disturbance no-tillage production, to specific and diverse local conditions have largely failed for a variety of reasons, including lack of farmer access to capital, tools and implements for success. Both the theoretical underpinnings and the applied local application testing of systems agronomy in Africa are quite extensive and developed [80]. The added complexity of scaling-up adoption brings major additional challenges, especially in the context of developing countries with many thousands of smallholder family farmers, who each must engage and learn, supposedly with only minimal outlines on what to explore on each farm. In South Asia, good examples exist of training and empowering 'Service Providers' – farmers who can contract plant no-till and manage weeds during crop establishment. Such an approach could relieve mechanization constraints for smallholder farmers in Africa. Methodology such as Farmer Field Schools, developed by the IPM programme of FAO, may provide innovations in extension – learning processes for systems agronomy discovery learning. Scaling-up the individual or farmer group capacity for this type of nuanced systems agronomy will require huge numbers of skilled facilitators who understand the size of the expansion domain and what is needed to reach farmers even at 10 km distance from their innovation hubs. Investment is necessary.

On the other hand, approaches in systems agronomy, which are not entirely based on farmer discovery and open-ended approaches, can be more readily scaled. For example in Brazil, EMBRAPA [81] introducing integrated crop/pasture/livestock systems through farmer organizations, *Friends of the Soil* clubs. These clubs were largely formed by farmers who needed to share information to adopt CA practices beginning in the mid-1980s. Many clubs receive support from agro-business industries and public-sector facilitation.

Conservation agriculture systems

The FAO of the United Nations defines CA systems as an 'approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (http://www.fao.org/ag/ca/1a.html)'. CA has three linked principles (Figure 1), that underpin additional complementary technologies, namely

- Minimum mechanical soil disturbance
- Preservation of residues that provide permanent soil cover
- Diversification of crop rotations and soil biology

The FAO further describes CA as widely applicable to most agricultural landscapes and land uses with locally-adapted practices [78, 82–85]. CA is more than avoidance of tillage, – it is an ecosystem approach that involves progressive system-wide change in the farmer's cultural practices along with a change in mindset, to bypass the use of the plow. In addition, as presented later, CA is C-based and C-focused and an ever-evolving, integrative approach that manages C flows to sustain manifold ecosystem functions, including the efficient production of food, feed and fibre over the long term. The use of cover crops between main crops is a means for generating residues and for adding diversity in CA systems.

The early history of cover crops begins with their introduction in the Chou dynasty in China, circa 1134–247 B.C. [86]. Their use has been a component mainstay of most animal-traction based agriculture over the last two millennia. The role of cover crops in CA systems cannot be overstated. In tropical systems, Brazilian CA scientists and farmers have been leaders, providing in-depth study and practice in cover crop use and production system resilience through increased biodiversity [87]. Because adequate SOM is fundamental for CA success, cover crops are often an important key component. Plant growth must be vigorous to build biomass for soil regeneration and for crop productivity. The strategic use of nutritional inputs and water control become pivotal. While many inputs and energy-use are lower compared to high input mechanized production, CA is not promoted as a low-input solution. CA is however, part of the FAO mantra

Save and Grow [61], by promoting optimization of inputs along with assimilation of IPM.

CA is thus a broad term to describe continuous no-tillage, residue cover, and diverse agronomic cropping systems, including cover crops when possible [27, 84, 88–91]. While each of these principles may be considered a separate entity, it is their continuous integration that is key to sustained CA success. The natural interactions and the integration of diversity within CA cropping systems contribute to numerous economic and environmental benefits [92–95]. Soil cover can be either live cover crops or mulches composed of crop residues remaining after previous harvests that accumulate on the soil surface. Retaining mulch between crops provides better protection against erosion and can also maintain higher soil moisture in dry regions, enrich the soil with organic matter, and, if the mulch is sufficiently dense, prevent the regrowth of weeds [10]. While these three main CA principles are general in their application, specific differences in each principle need to be defined clearly so that there is no confusion in communication resulting from the use of jargon terms. CA thus contributes to environmental conservation and to sustainable production by maintaining a permanent or semi-permanent residue cover to optimize carbon management.

Biodiversity is an element of community and landscape sustainability associated with CA that is necessary for stability in natural systems [94, 95]. Liebig *et al.* [92] summarized benefits of plant diversity which enables solar energy capture as long as biologically possible, evens out spatial and temporal variation of soil coverage, provides diverse carbon and nutrient sources for soil biology, reduces and spreads risks, increases the potential for synergy and co-benefits, controls pests and diseases, better handles climate extremes, is aesthetically pleasing and increases total productivity of the ecosystem in ways that mimic natural systems. In sum, CA systems provide a synergistic simplicity of reduced soil disturbance to minimize C and soil loss and the use of diverse rotations and cover crop mixes to maximize soil coverage and C input for soil diversity protection and regeneration benefits that as described below, contribute to enhanced water use efficiency [96, 97] and food security.

The food security challenges facing agriculture today are unlike anything we have experienced before, and they require revolutionary and science-based approaches to solving food production and sustainability problems [31]. The preceding discussion includes different terms to describe agriculture that are commonly associated with 'sustainable' agricultural systems. Each of the modifiers relates to the concept in a slightly different way, however, most come under the broad umbrella of 'sustainable' agriculture. Unfortunately, everyone has their own definition and perception of sustainability. Different types of agriculture listed in Figure 2 illustrate the challenges in interpreting and understanding of the descriptive modifiers for implementing sustainability standards. There is a need to develop a common understanding of sustainable agriculture utilizing a common language easily understood by all that avoids the use of 'ag buzz words' and 'jargon terminology'. Because of the critical importance of food security, we must communicate clearly and concisely to address food quality, economic, environmental, social and policy issues. There is a need to develop a 'common language of sustainability' with scientific principles and concepts or the 'agriculture terminology conundrum' will likely continue. Utilizing transdisciplinary system approaches in CA systems, a number of social, economic and environmental goals can be simultaneously achieved as progress is made towards short- and long-term global sustainability and food security [58, 83, 88, 93, 98].

Conservation Agriculture: Implications for Water Use Efficiency

Soils perform a broad range of functions, many of which are vital to society and the environment. Biophysical soil functions include nutrient cycling, water cycling, chemical filtering and buffering, physical stability, support of plant systems and human structures, and promotion of biodiversity and habitat [94, 95]. Soils and their management also play a large role in influencing hydrologic cycles that are important to humankind [99, 100]. In this regard, soil management, especially with respect to intensive tillage, is at the centre of water management in agriculture and has direct bearing on food production and security. Building resilient food production systems in the face of increasing population and climate change requires improved water and soil management [96, 97] to underpin productivity improvements across the entire range of production environments from exclusively rainfed, to supplementally and fully-irrigated. Recent reviews of agricultural management practices in response to climate extremes of droughts and floods have been provided by [93, 100–106]. Our understanding of the linkages between soil properties and soil functions and the resultant ecosystem services they provide is incomplete [107–109]. The following discussion focuses on soil carbon management as a critical aspect of CA systems and specific impacts of carbon management on water use efficiency. We note that most benefits of CA, either directly or indirectly relate to enhanced carbon management (Figure 2).

Plant-Derived Carbon – The Key to Water Use Efficiency

Understanding the interdependency of the carbon and water cycles is essential for evaluating water management practices related to soil functions and crop water use efficiency. Indeed, carbon and water cycles are so intricately coupled, they cannot be evaluated in isolation [110]. A key link between soil and food is the use of water by plants.

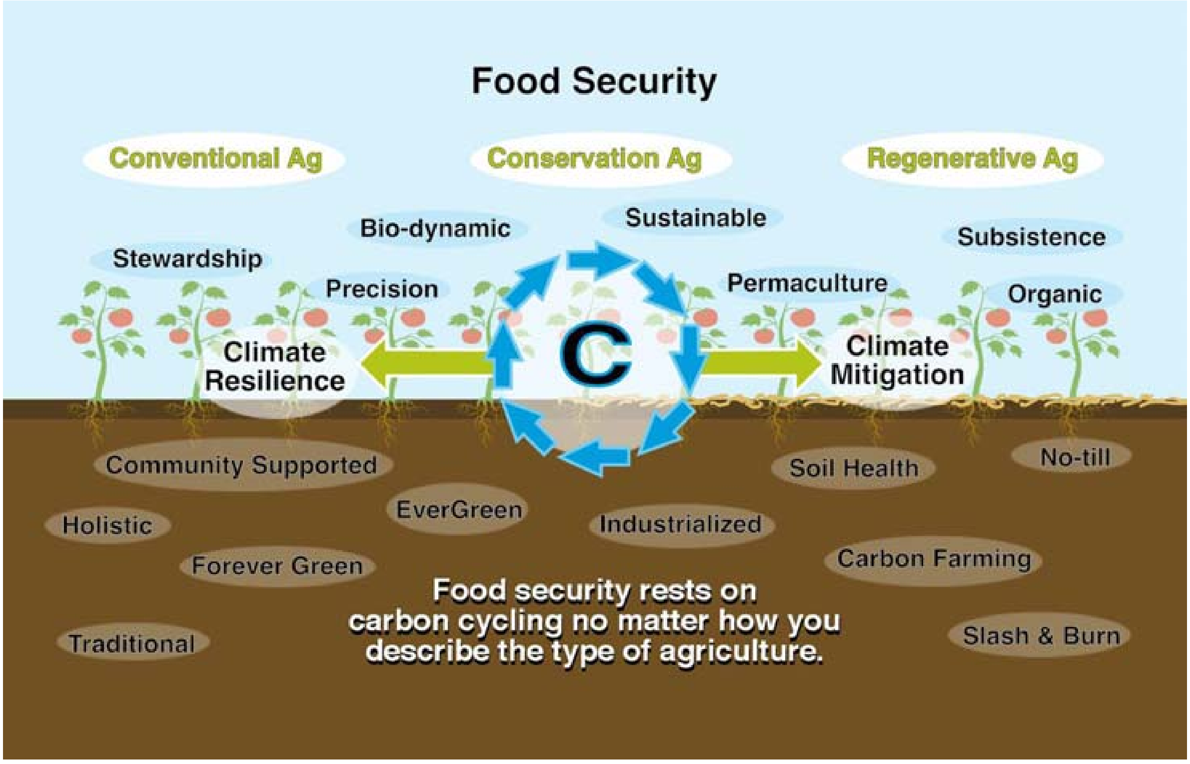

Figure 2 The importance of carbon management in food production systems

Water provides many functions in plant physiology, but some of the most important are the transmission of nutrients and photosynthates and providing evaporative cooling for the plant. The relationship between plant water use and plant growth is a fundamental facet of agriculture and food production and has thus received considerable attention [96, 97, 111–113]. Without water in the photosynthetic equation, there would be no carbon fixation and no biochemical energy provided for all living creatures. In turn, without good carbon management, plant productivity and water use efficiency cannot be optimized.

As a society, we are slowly learning about the importance of soil carbon in agricultural ecosystems. In 1938, Albrecht [114] asserted that 'organic matter in the soil may be considered our most important national resource'. He described how it furnishes fuel for 'bacterial wrecking crews' and how it holds and cycles plant nutrients. He showed that many of our farm practices have enormously reduced the supply originally present in the soil and warned that we must expect a permanently lower level of agricultural efficiency if we do not take steps to counteract this trend. Carbon in agricultural fields is always in transition from initially being fixed in photosynthesis to create plant biomass, and then returned to the soil and converted to SOM, and ultimately converted to humus and humic acids eventually yielding CO_2 that is emitted back to the atmosphere [115]. Stevenson and Cole [116] noted that the carbon cycle is the driving force of other cycles, – especially the water cycle, – and therefore needs enhanced management to protect its function from a range of climate extremes such as droughts, extreme rainfall events, and flooding that have increased during the last century and that are expected to continue, causing erosion, declining water quality and negative impacts on transportation, agriculture, human health and infrastructure. In the last few years alone, there have been several 'one in 1000 years' rainfall events [117]. Current and future loss and degradation of agricultural soil and water assets due to increasing extremes in precipitation will continue to challenge both rain-fed and irrigated agriculture unless innovative conservation methods are implemented. Evidence suggests that climate change will bring hotter temperatures, changing rainfall patterns, climate extremes and more frequent climate-related natural disasters, such as wildfires [118]. Agricultural production systems will have to adapt to these extreme changes and practices that increase water use efficiency to even greater levels will be required.

Tillage disrupts and destroys soil structure by breaking aggregates and releasing carbon to the atmosphere through oxidation and associated increased microbial activity [99, 119]. Populations of larger soil fauna such as earthworms and other burrowing and surface-layer organisms are reduced with intensive tillage that destroys macro pores and impacts infiltration and root penetration [120, 121].

Tillage disturbance fragments fungal hyphae networks and upsets the balance between fungi and bacteria impacting soil carbon loss [122]. Ecosystems that are tilled have lower fungal activities and lower stored C than those maintained under native or no-tillage systems. Six *et al.* [123] indicate that most agricultural soils are now dominated by bacterial activity. Basche and DeLonge [103] used meta-analysis to compare conventional tillage-intensive systems with perennial and annual systems in which no-tillage techniques are used with living cover practices and found that the reduced disturbance surface cover systems had increased porosity and water storage capacity. Their findings further suggest that continuous living cover practices may be an adaptation strategy to combat rainfall variability and intensity, presumably by allowing water to infiltrate to greater depth [121, 124].

Diversity that is achieved by extended CA crop rotations, the inclusion of cover crops, legumes and grasses, shallow- and deep-rooted crops and fibrous and tap-rooted crops [121, 124–126] provide synergistic benefits to cropping systems with respect to water management. In the semi-arid Great Plains region of the USA, for example, multi-year experiments found that wheat cover crop systems (including vetch, pea [*Vicia sativa*], clover (*Trifolium pretense*) and triticale (*Triticosecale*) cover crop species) significantly improved water-stable aggregates compared with wheat fallow or continuous wheat systems [127] in a silt loam soil. At another location, they found that wheat-sorghum (*Sorghum bicolor*) rotations including cover crops increased the mean weight diameters of soil aggregates by 80% in the surface soil and improved water infiltration rates up to three times more than in fields that did not include cover crops [128]. There is also evidence of cover crops improving water dynamics in California vineyard environments. Folorunso *et al.* [129] found improved soil strength and water intake (by up to 100%) after 5 years of mixed cover crop use in orchard and tomato (*Solanum lycopersicum*) system environments. Gulick *et al.* [130] similarly found that just one to two years of cover crop use in sandy loam environments of California increased infiltration rates by more than 140%. Mitchell *et al.* [68] found similar improvements in soil aggregation and infiltration with cover cropping and no-tillage in annual crop systems in California's San Joaquin Valley while soil water depletion by cover crops tended to be generally less than 7.4 cm in the 0 to 90 cm soil profile [131–133]. Steele *et al.* [134] incorporated cover crops into continuous maize systems and improved several soil physical properties including water infiltration and aggregate stability. Sharma *et al.* [135] found that green manure crops increased both soil moisture and water infiltration, and ultimately led to greater crop productivity compared to the no cover crop control. Similarly, for intensive rice–wheat cropping, Singh *et al.* [136] found that green manure crops increased soil aggregation and infiltration while decreasing bulk density on a loamy sand soil. In Brazil's savannah biome, the cycles of pasture cover crops have marked soil health benefits, which benefit the following annual crop rotation cycle [81]. Generally 3 to 6 years of annual crops are alternated with 3 to 6 years of improved pastures that are under managed grazing. Depending on rain, supplemental irrigation and elevation, the annual crop rotations often consist of up to three annual crops such as maize or soybean sown in the first season (in September), followed by early maize or soybean in the short rainy season, followed by an irrigated crop, of dry beans (*Phaseolus vulgaris*), wheat, or a short-season cover crop, before repeating. Consequently, integrated crop/pasture livestock production systems under no-till are expanding through farmer–rancher partnerships driven by the positive rotation effects.

Further, the microbial processes of decomposition in the soil also reconfigure the chemical structure of remaining organic substrates and notably their affiliation with mineral components of the soil, creating physical arrangements or aggregates that improve soil physical structure, enhance aeration and infiltration and reduce erodibility. Through these and other mechanisms, the continual cyclical flux of carbon – from solar-driven photosynthesis into and through the soil – maintains soil health and multiple ecosystem functions [115, 137]. Soil structure is the arrangement of pores and cracks within a matrix of soil particles and organic matter. Chemical bonds that aggregate solid components of the soil result in the formation of these pores and cracks that enable water and gas flow through the soil matrix. The quantity, distribution and arrangement of pores determine the soil's water holding capacity, infiltration rate, permeability, root and earthworm penetration and soil respiration rate [119]. The continuity of the pores is important for both water and gas flow and storage through and in the soil matrix.

Soil, with its self-regenerating physical and biological characteristics, must therefore be viewed as an essential part of humanity's heritage and her future lifeline. While history can be a strong teacher, its lessons are often ignored. Soil erosion, for instance, is still a major problem in agricultural production systems. Efforts to control human-induced land degradation and soil erosion go back at least 10 000 years but have been largely based and intertwined with the tillage and monoculture concepts and systems that developed during this time [3, 99]. Efforts to control land degradation and soil erosion over this time have been reviewed by Montgomery [2, 6]. Soil erosion from agricultural land is induced by tillage. Soil that is loosened by any type of tillage is more easily transported by wind or water increasing the rate of erosion. Many of the conventional tillage practices used in growing crops lead to the loss of topsoil and destruction of the very soil characteristics that make agriculture possible. Tillage destroys much of the biological activity in the soil, leaving it lifeless, robbed of its fertility and susceptible to erosion by wind and rain. As a result, much of our best topsoil has been washed into rivers and streams, and deposited in an eternal grave at the bottom of the sea. Tilled soils are more vulnerable to raindrop impact, soil crusting, wind, water and tillage erosion, temperature and water extremes, carbon and biodiversity loss, increased runoff, decreased infiltration, increased evaporation, increased leaching and increased pollution [99]. Reduced soil disturbance and increased retention of crop residues on the soil surface improve soil porosity, water infiltration and holding capacity, and can reduce erosion from water and wind by 90% or more [119] resulting in less sedimentation in ditches, streams, rivers and lakes. Reduced sedimentation improves fish habitat and minimizes the need for dredging, expanding the longevity of dams. Less soil erosion also reduces offsite movement of agricultural chemicals tied to soil particles.

Soil water evaporation

The application of CA practices also provides a means for reducing soil water evaporation and thereby increasing water use efficiency. Any water loss as evaporation from bare soil is essentially wasted. CA systems provide continuous crop biomass cover from dead crop residue, dormant crop biomass, and living plant cover to protect the soil surface. Dead crop residue not only protects the soil surface from raindrop impact, but, if it is sufficiently thick, can substantially reduce soil evaporation [119, 138]. Disturbance of the soil through tillage reduces water storage and increases evaporative losses. Burns *et al.* [139] and Papendick *et al.* [140] showed that tillage disturbance of the soil surface (dust mulching) increased soil water evaporation compared to untilled areas. Tillage moves moist soil to the surface where its water is lost as evaporation, thereby offsetting increases in infiltration that may be associated with surface soil disturbance or roughness. Hatfield and Prueger (unpublished data, 1999) found that the total water evaporation fluxes in Iowa were 10 to 12 mm for a 3-day period following each cultivation operation in the spring. The total evaporation fluxes from no-till fields were less than 2 mm over the same period. Reicosky and Lindstrom (unpublished data, 1993) observed 18 mm evaporation from a moldboard plow treatment (250 mm deep) compared to 3.5 mm from no-tillage plots over a 24-h period. Commonly-used aggressive field cultivation operations in the spring could reduce soil water availability in the seed zone by as much as 20–30 mm. These studies demonstrate the importance of understanding the role of reducing tillage for efficient water use and crop growth as well as for mitigating soil erosion and environmental degradation.

Crop residues have been shown to benefit nearly all aspects of soil health, including chemical (soil organic carbon, pH, and cation exchange capacity), physical (soil structure, runoff, erosion, compaction, soil temperature and moisture content) and biological properties (biodiversity and biomass) presumably, due to provision of increased soil carbon [141]. The retention of carbon in the system and its potential benefits for soil health, is driven by total residue input, the C:N composition of the residue, and its decomposition rate [142], which are all influenced by tillage, soil type and climate [143]. Local conditions ultimately determine soil C levels and the extent to which crop residue management will be effective in promoting soil health.

Converting to no-tillage has also been shown to reduce irrigation water needs because soil water evaporation is reduced [144]. Conventional intercrop tillage typically involves a number of tillage passes. This is the case, for example, in the spring between winter wheat or triticale and corn (*Zea mays*) seeding in dairy silage production systems in the San Joaquin Valley, California, or virtually any conventional crop rotation in which spring tillage is performed [145]. Research in Nebraska has shown that these tillage operations dry the soil before planting to the depth of the tillage layer and that typically 8–19 mm of soil water may be lost per tillage pass [144]. In Nebraska, switching from conventional tillage to no-tillage under centre-pivot irrigation has been shown to save 80–130 mm of water annually, with added savings from decreased pumping costs [144]. Evaporation in a fully-irrigated trial was reduced by 173 mm due to the crop canopy and another 97 mm due to straw mulch. This savings of water in evaporation during the growing season because of the crop residue is important, but represents only part of the story. Additional benefits of crop residue extend beyond the growing season and include runoff reduction, reduced evaporation and increased snow capture, which could easily add 50 mm or more of soil water. More recent research by Klocke [146] in Kansas, showed that corn and wheat residues reduced evaporation by about 50% during about a 1 month period from mid-June to mid-July. This quantity is impressive because if it is extrapolated over 100 days of a growing season, water savings may be from 76 to 127 mm.

In addition to reducing evaporation, residue also keeps the soil surface cooler by protecting it from the sun. This cooler, moist surface allows better root development in the heat of summer, improving crop vigour, growth and development. High soil temperatures at planting in the Near East and South Asia can also have negative impacts on rhizobial survival on inoculated soybean seed (Kueneman E., personal communication, 2017). Having active roots near the soil surface may permit the use of water from light rain showers that don't soak into the soil profile. In the USA Midwest up to 50% of the maize evapotranspiration (ET) is lost by evaporation (E) during a normal growing season [147]. van Donk *et al.* [148] measured soil water content change to a depth of 1.68 m using a neutron probe to characterize the difference between residue covered and bare soils in corn canopies. They found the crop residue decreased evaporation between 65–100 mm in the 2007 growing season and 90–125 mm in 2008 growing season. Conventional tillage that was converted to no-tillage under overhead irrigation, yielded annual water savings of 203 mm [148].

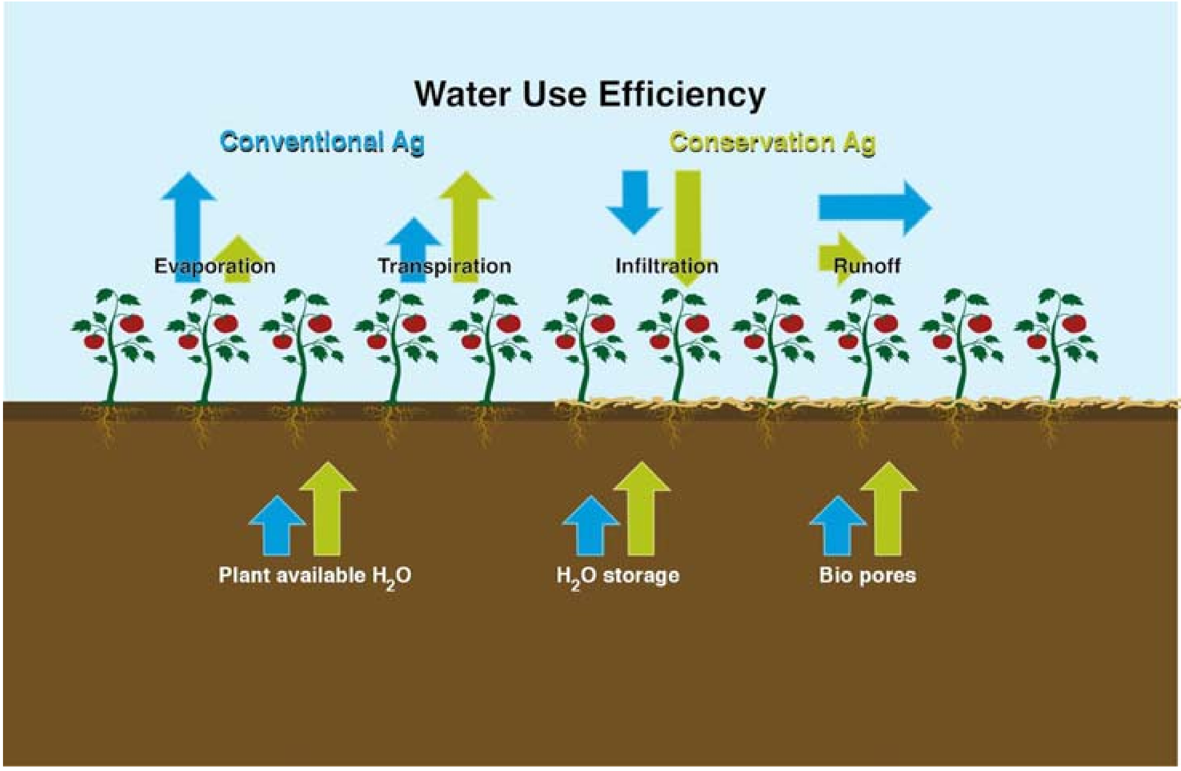

Figure 3 Possible mechanisms for improved soil–plant–water relations in CA systems (blue arrows) versus conventional agriculture (yellow arrows). The relative magnitude of the process or function is indicated by the length of the arrows.

Long-term no-tillage may conserve water by reducing winter evaporation and increasing snow trapping. In a typical annual cropping season, the use of CA practices that reduce soil water evaporation and runoff, and increase storage, could theoretically result in water savings of nearly 280 mm per year (D. Reicosky, unpublished data, 2018). The sum of these small amounts of water saved plus other synergistic benefits of increased carbon in CA systems may eventually lead to increased water use efficiency, ecosystem services and food security [118].

Soil water storage and plant-available water

An additional benefit of CA practices may be seen through the increases in soil water storage and plant-available water that may result from their sustained use in food production systems. Observations over thousands of years, as well as recent scientific studies, have shown that the productivity and functioning of a soil are directly related to its plant-derived organic matter content that is in the soil [27, 149, 150]. The plant thus depends on the soil and the soil depends on the plant. Plant-available water is defined as the difference between the water content of soil following drainage due to gravity ('field capacity') and the water content of the soil following further drying to a point at which it is essentially unavailable to plants. Management practices, such as those used in CA systems, that increase the bio-pore network in the soil increase soil water infiltration and storage and thereby the amount of water available to crop plants (Figure 3). CA practices that maximize solar energy capture and biomass production via plant photosynthesis, reduce soil water evaporation through the generation and preservation of surface residues, and increase the bio-pore network in the soil via crop and cover crop root growth, all serve to increase plant-available water [105, 151–153]. These practices effectively 'turn soils into sponges' and lead to more efficient water use [105]. While there is some recent debate about the benefits of SOM in this regard [154], in most situations, more organic matter in the soil generally confers higher water use efficiency. The challenge is to get more carbon stored deeper in the profile, rather than merely in the top 10–15 cm, which may be achieved with deeper-rooted cover crops [121, 124] as well as more perennially-based agricultural approaches [104].

This discussion on the various processes and properties that determine the hydrology of agricultural watersheds alludes to the complexity and interactions that affect overall water use efficiency. Figure 3 shows relative quantitative differences in these processes between conventional tillage and CA systems. The size of the arrows represents the relative magnitude for the two different agricultural systems. Conventional tillage systems that are designed primarily around annual crops can experience greater water loss through increased runoff, leaching losses and soil evaporation, in addition to off-season wind and water erosion [105, 155, 156]. By contrast, CA systems incorporating diverse rotations, cover crops and perennial and pasture crops where appropriate, ensure nearly continuous land cover, and as a result, can increase crop water use efficiency by simultaneously reducing evaporation and runoff and contributing to soil function improvements that create more and deeper water storage [105, 124, 156].

In rainfed systems precipitation is the primary source of freshwater, and the soil serves as the primary reservoir for capturing and storing water for agriculture. Thus, soil is a central component of ensuring a sustainable path towards global food and water security. However, to achieve both the productive capacity and environmental quality conditions needed for future food security, production systems and approaches that can meet these dual goals are needed. In rainfed systems in which multiple crops are grown throughout the year to maximize solar energy capture, crop and cover crop biomass production and residues, careful planning and crop sequencing is required to ensure that adequate water is available for all crops. Such approaches, however, may also lead to multiple co-benefits including increased resilience to both floods and droughts that are typical of climate extremes.

Examples of Conservation Agriculture Systems Worldwide

Over the last 30 or so years, CA approaches have been applied to production systems in several regions of the world. Indeed, in some areas, they now represent the dominant paradigm [78]. Globally, CA has been adopted on almost 160 million hectares and this area is increasing by about 10 million ha/year [85].

Canadian prairies

Adoption and consistent use of CA management practices throughout the vast Canadian prairie in Alberta, Saskatchewan and Manitoba provinces, beginning in the 1990s, has reduced reliance on the traditional summer fallow, enhanced soil health, increased soil water availability in near-surface layers [157, 158], and permitted the introduction of new crops, including oilseeds and legumes [157]. There is also evidence that no-tillage management itself, as an important part of these changed systems, has improved, becoming more reliable in recent years, and that changes in soil properties under no-tillage cropping tend to be positive [159]. No-tillage, in fact, has become the recommended cropping system throughout this region. As an example, no-till agriculture in Alberta, Canada, increased from about 5% of the seeded area in 1991 to over 80% by 2011. A comprehensive history of the development of no-till cropping systems in the Canadian prairie has been compiled by Lindwall and Sonntag [19].

Central Great Plains, USA

In the Central Great Plains (USA), where corn, soybeans and wheat predominate, CA approaches have also impacted agricultural management permitting both the intensification and diversification of cropping by initiating what has been termed 'a spiral of soil regeneration where interactions among more favorable water relations, residue production, and crop yield are continually improving soil health and, consequently, future crop performance' [160]. CA approaches successfully developed by South Dakota farmers in this area along with Dwayne Beck at the South Dakota State University's Dakota Lakes Research Farm over the past thirty years have led to CA management being used on over 90% of farmland throughout this region. It is important to point out that farmers in this region did not take on these practices out of dogmatic adherence to the underlying principles of CA. Rather, during the early 1990s they realized that different approaches were needed to the uneconomic alternate year summer fallow system, required to capture sufficient rainfall to produce a crop.

Brazil, Argentina and Paraguay

Similarly, in Brazil, Argentina and Paraguay, farmers of various production scales have been obliged to develop and refine similar types of CA systems in face of the large soil erosion losses that were common near the end of the 20th century [11]. Current estimates of the uptake of CA systems on field crops throughout this region of South America indicate adoption on over 80% of land planted to maize, soybean, wheat, upland rice, *Brachiaria* spp. pasture grass, and many short-season cover crops. Initially the expansive wet-dry savannas (Cerrados biome) of central Brazil were mostly comprised of unproductive native bush/grasslands. Clearing and burning the bush enabled modest expansion of semi-managed rangelands, but with low carrying capacity for cattle. Production of annual crops was limited due to soil acidity and low phosphorus availability. In the 1970s, research coupled with farmer experimentation, revealed that applications of lime to raise pH to at least 5.5, combined with phosphorous-rich fertilizer, resulted in good crop growth. Annual crop production in the Cerrados expanded exponentially. However, wide use of disc plows in the Cerrados resulted in rapid loss of soil organic matter, structure and severe soil erosion. Conversion to reduced tillage approaches reduced soil degradation and production costs. Brazil became the leader of most CA innovations in the Southern Cone countries of Argentina, Chile, Paraguay and Uruguay. Extensive bushlands were cleared with chains stretched between two caterpillar tractors. Soils were initially heavily tilled by disc harrows, then often sown with upland rice or maize for several years before the inclusion of soybean in cropping systems became common. The development of soybean varieties adapted to the short daylengths of the tropics and sub-tropics coupled to excellent international prices was a huge driver of Cerrado-use expansion. By the early 1980s, it was apparent that discs plowing of these lands resulted in massive soil erosion [161]. With conventional tillage, soil losses reported from thirty experiments were more than 23 metric tonnes (MT)/ha/annum, while loses in zero till treatments were about 6 MT/ha/annum – approximately an 80% reduction [162]. Farmers shared experiences and support from the federal government and state-funded research and extension programmes led to the expansion of CA systems. Private sector support from the agro-related industries was substantial and very important in the rapid adoption that occurred. From the beginning of the 1980s, mechanized CA expanded with soybean (*Glycine max*), maize and other crops in the Cerrado. Advantages to adopting CA practices included policy supports through access to credit. Reduced production cost was also pivotal [161, 163]. Soil erosion per unit of land was reduced and silting of rivers and reservoirs diminished. CA has extended along the margins of the Amazon biome, often as mechanized farmers acquire relatively inexpensive, degraded pasture lands. More than 10 million ha of zero tillage CA is now practiced in Brazil [85]. While much of the CA in Brazil is the practice of relatively large mechanized agriculture, smallholder systems have also proven successful. The biology at work in CA is scale-neutral, but the approaches to CA by smallholders are nuanced and sometimes very different [87]. A significant number of smallholder family farmers in Brazil's southern states of Paraná, Santa Catarina and São Paulo have also adopted CA, including use of animal traction powered mechanization. Another very interesting development in Brazil is the creation of Integrated Crop Livestock Zero Tillage – ICLZT [161]. Millions of hectares of nutrient-depleted, degraded pasture lands were marginally productive and the costs of renovation by incorporation of chemical fertilizers were prohibitive. By alternating cycles of annual crops, pasture crops were improved and farmers/ranchers were able to bring the pasturelands back into high productivity. By application of no-tillage, land could be easily converted to cycle between pastures and annual crops. Pasture species such as *Brachiaria* spp. maintained for 3 to 6 years as pasture, create excellent root biomass when soil fertility is high. The annual crop cycle benefits from this SOM contribution and from breaks in pest cycles. The pasture crop cycle benefits from the residual fertilizer nutrients that were applied to 3 to 6 years of the high value annual crops. Synergies between annual crops and improved pastures is the target of much innovative research [164] and Brazil's national research organization, EMBRAPA, has hosted three international conferences in the last decade on ICLZT to enable knowledge and experience sharing.

Adoption of CA systems has similarly expanded in savannahs of Paraguay, Eastern Bolivia and especially Argentina. Argentina led in the inclusion of herbicide tolerant (HT) soybean and maize varieties within the CA system, whereas Brazil's regulatory framework was more restrictive vis-à-vis the planting of GMO crops. However, it is no secret that until recently a number of Brazilian farmers bought GMO soybean seed in Argentina. CA systems do not depend on use of HT varieties, but the simplicity of weed control, especially in situations where applications of other herbicides were not effective, makes the combination of CA and HT adoption attractive for many CA farmers. About 95% of soybeans sown in Argentina were no-tillage and HT by 2001. Brazil's adoption of HT crop varieties is now open and extensive. Medium- and large-holder farmers in south-eastern Bolivia and much of Paraguay, where soils are similar to those of the Brazilian savannas, have also adopted CA approaches primarily for economic reasons. Smallholder farmers in Paraguay were early adopters as well, but when financial assistance stopped, some returned to conventional animal traction with plows (Dirk Lange, personal communication, 2016).

Southeast Asia

In the 1980s, at the time of the Rice Wheat Consortium's (RWC) inception throughout Bangladesh, India, Nepal and Pakistan, reduced tillage-based CA was already exploding in the Cerrados of Brazil. RWC agronomists, who were aware of CA development in Brazil, could see the need for practices that enabled soil health to return to the structurally-tortured, over-tilled soils in the Indo-Gangetic Plains (IGP). The incipient CA research at IITA, a sister Centre in the Consortium Group for International Agriculture Research (CGIAR), also influenced agronomists at the International Research Center for Wheat and Maize (CIMMYT) and International Rice Research Institute (IRRI), who were launching the RWC in the IGP. RWC partner scientists demonstrated benefits of CA through reduction in production costs and the opportunity to plant wheat early enough to reduce heat stress associated with late-planted wheat. Proper land levelling prior to the onset of CA, enhanced water application and water use efficiency. Provision of laser land levelling gained acceptance through empowerment of service providers (SPs) (farmers who purchase no-till equipment and then rent their services of land levelling and no-till planting to the farming community, after first using the equipment on their own farms). Training and empowerment of SPs was a big step forward. One of the most pivotal dimensions of the RWC was to embrace a holistic systems approach to development needs and opportunities, including a refreshing appreciation for improved agronomy, as part of the solution. Previously donors, probably shortsightedly, argued that agronomy was too site-specific for the input of international research institutions.

Mottaleb *et al.* [165] reported that India alone now has about 2 million ha of smallholder no-tillage wheat, but notes that adoption is relatively slow. Less than a fifth of the IGP wheat acreage is under no-till. This is in part because many farmers are still unaware of CA opportunities, training is demanding, and there is a scarcity of trained SPs with the right equipment, who plant on a contract basis. A mechanization industry is growing throughout the IGP, especially in Eastern India and Bangladesh, but requires further investment and support for its acceleration. Not all provisions of mechanization through SPs are soil health 'smart'. Subsidized rotovators, for example, are making 'drastic' tillage popular in preparation for both rice and wheat. Farmer education concerning the long-term negative effects of this approach, such as increasing the compaction (plow pan) associated with most rototillers, is important.

Donors and policy makers who are concerned about the recent global meta-analysis study on smallholders' inability to benefit from CA [166] should consider the abundance of carefully-conducted farm-level research in the IGP [167]. Such studies thoughtfully consolidate and reconfirm regional experience and refereed documentation supporting benefits from CA in the region [168–176]. On-farm yields and incomes have been significantly higher under CA management compared to conventional tillage, regardless of sowing time. Cost of production under conventional tillage is almost always significantly higher than with CA, primarily because of energy and labour costs associated with multiple passes of land preparation.

Across many studies, an income advantage of approximately $100 USD/ha can be expected for CA wheat [167]. The potential long-term CA benefits of improved soil structure cannot be expected when rice, as a monsoon rotation crop in the same production systems, is established with intensive soil tillage (puddling). The double CA system of rice and wheat both under no-till has not yet been broadly adopted. This is primarily due to the tradition of transplanting rice seedlings into puddled soils, which destroys soil structure.

Both the Sustainable Resilient Farming Systems Innovation Program, an Australian government-funded project in Eastern India, and the Cereal Systems Initiative for South Asia (CSISA), a USAID and BMGF-funded programme involving several national programmes and the CGIAR, are working with farmers in selected nodes on this double-crop CA approach. Eventual wide adoption of no-till direct seeded and/or mechanically transplanted rice into non-puddled soils will likely be driven primarily by the increasing costs of labour for hand-transplanting rice seedlings. Studies by Erenstein and Laximi (2008) [171] suggest that farm families with above average resources in this region are more inclined to adopt CA innovations. Presumably they have the means to hire no-till planting services, though they could as easily have chosen to have their land roto-tilled. The extreme poor are frequently not adopters. One may conclude that training of better-off smallholders will generate more adoption and more impact. Alternatively, if resources are focused on enabling the SPs to use no-tillage, prices for the service may be reduced as supply increases, and some poor smallholders may take the option to plant wheat no-till, instead of paying for rototilling.

Western Australia

Australian scientists also found CA to have large potential in some production systems and subsequently its adoption expanded there soon after. GPS-enabled controlled traffic guidance technologies have been coupled to CA to reduce soil disturbance and risks of compaction as is being done in other regions of the United Kingdom and Canada [177]. CA cropping also has been extensively adopted for cereal production in the drylands of southwestern Australia [178, 179]. In this region, the benefits of surface residues are increased availability of soil water during germination and early growth of the subsequent crop (K. Flowers, Personal communication, 2017). Conservation of soil moisture as well as improved soil structure and soil health have been reported as a major impetus for increased adoption of no-tillage practices in this region [180]. An important component of CA systems in Australia has been the adjunct use of controlled traffic systems that restrict tractors and the risk of soil compaction to traffic zones in a field thereby preserving undisturbed crop growth zones. McHugh et al. [181] showed that in some soils and environments, removal of traffic not only slows or arrests soil structural decline, but it actually leads to restoration towards natural conditions. The widespread and widely reported adoption of similar systems in other parts of Australia as well as in the United Kingdom and Canada on a range of soil types and across a variety of climates indicates that the elimination of traffic compaction, even in the presence of conventional tillage disturbance, results in improved soil structure, infiltration, water storage, biology and crop yield, emphasizing the critical negative impact of traffic on productivity [78, 182, 183]. Numerous publications have also shown that controlled traffic techniques are scalable and adaptable across a wide variety of production systems and as such, make important contributions to soil sustainability in agricultural production [78, 177, 184] that are major contributions enhancing conservation agriculture systems.

Africa

In the late 1970s, soil physicists and agronomists at the International Institute of Tropical Agriculture (IITA) conducted large experiments on CA and conventional tillage and their impact on soil erosion and crop productivity throughout Africa. CA was clearly advantageous if and when soils were kept covered with crop residue or with external mulch [3]. A benefit from CA was that soil surface crusting, that previously constrained seedling emergence stopped being a problem and seedling emergence improved sharply. Permanent soil cover became a corollary of the principles of CA that have been mentioned above. Efforts to introduce smallholder CA in Zimbabwe, Zambia, Mozambique and Malawi have increased adoption. A dearth of appropriate smallholder no-tillage planters is one of the principle constraints. Mechanized no-tillage is common in South Africa and more recently increasing in Ghana. Corbeels *et al.* [185] reviewed adoption of CA in Africa. Giller *et al.* [80] also appraised CA research and farmer adoption. They raised concerns about the difficulties of farmer adoption and erratic yield results in reported trials and highlighted the need to ensure that low plant nutrients and other factors such as the limited availability of cover crop seed are addressed before one can expect CA to have a consistent impact. Trials are often run on experiment stations with badly compacted and depleted soils. In addition, no-till treatments in research trials are generally planted later than they should be, due to waiting for conventional tillage plots to be prepared so sowing of all plots can occur on the same day. In most cases, the CA plots could (and should) have been planted a week or two earlier when it was ideal to benefit from the full rainy season. About 10 cm of topsoil needs to be moist before plowing and seedbed preparation in conventional systems. Early seasonal rains at planting are frequently erratic. Consequently, trial planting is often delayed, and CA systems are disadvantaged in the comparison.

The South Asia approach of training farmer SPs and empowering them with access to low-cost, smallholder no-tillage planters could also be enabled by government policies and support in Africa. The private sector needs to be encouraged and empowered to acquire (import initially) and service new equipment. Development bank and donors could help governments and private sector partners to ensure sustainability through profits.

Across the spectrum of introduction of CA into smallholder systems globally, it is apparent that in addition to the poor availability of appropriate equipment, e.g. no-till planters, herbicide sprayers, land levellers (for irrigated systems), mowers to enable planting into high stubble, etc., rather subtle and detailed management practices also determine success or failure. Timing of operations is key, as are correct adjustment of planters, height of stubble and control of weeds. Learning and applying CA practices is relatively knowledge-intensive. Extension systems in developing countries are not organized to train trainers and empower them to work with farmer groups in this level of knowledge-sharing. Participatory approaches to learning, such as FAO's 'farmer field schools' may provide the mechanism for farmer learning/discovery, but funding for this remains elusive. The 'service provider' model gaining popularity in South Asia may also be part of the solution to scaling-up adoption of smallholder CA in developing countries.

California, USA

The Great Central Valley of California is one of the most productive agricultural regions of the world with typically seven or eight of the highest farm-gate revenue-producing counties in the USA [60]. Although these levels of productivity stem from decades of successful refinement in management practices, the core agronomic characteristics for annual crop production throughout the region have changed very little since they were first developed in the 1930s [132, 133]. Even in this historically productive agricultural region that has been characterized by intensive, weed-free cultivation practices for over 90 years, a growing number of farmers are now beginning to explore and develop CA approaches. It is estimated, for instance, that use of strip-tillage and no-tillage for silage corn production in the Valley has increased from less than 1% acreage in 2004, to now over 45%. A small number of tomato and other vegetable farmers in the area are now routinely using cover crops and reduced disturbance tillage in their fields as a means to improve water movement across wide planting beds that are irrigated with subsurface drip tape [186]. These farmers use these practices not out of a fixed allegiance to any of the principles of CA *per se*, but out of the recognition that they need to improve the performance of their current systems.

Conservation Agriculture Systems as a Unifying Concept

The vigorous discussions and very creative thinking that have been directed to the goal of production systems improvement by many groups of scientists, farmers and a wide variety of dedicated contributors in recent years have been very useful and productive. Each of the alternative systems visions that have been proposed has value and adds important dimensions to decisions on what should be done moving forward. A variety of insights will be relevant in meeting the challenge of global food security in the future. Discovery and predictive sorts of tools systems agronomy and ecological intensification approaches offer nimble and robust agronomic research protocols to rapidly identify the specific suite of practices that will give highest returns and least risk across landscape variations in soil properties, climate, and other management variables. The understanding and respect that come from organic, regenerative, soil health, and conservation agriculture systems thinking for how cycles of energy, water, nutrients, and biodiversity ultimately impact and guide how we produce food over the long haul is also important. We propose that a very long-term perspective (10 – 20 generations) on the types of systems that will be required is needed. This looking very carefully at the constraints that are likely to exist in the future and avoiding dogmatic prescriptions for what ought to be possible in every environment or field.

Recently, there have been two interrelated sources of concern related to how CA systems are defined, implemented and evaluated across diverse regions, and how they actually perform [166, 187], as well as how they have been promoted or, at times, been rather dogmatically prescribed [76]. A detailed expose of these concerns is beyond the scope of this review, however, it is important to note that the vigorous and at times acrimonious debate that has been undertaken about CA in recent years has been useful in focusing attention on what may be the best ideas for moving food production systems forward in all environments. The first of these critiques relies on a vast global meta-analysis of 610 studies across 48 crops and 63 countries comparing no-till with conventional tillage practices. This concluded that the productivity of no-tillage alone is lower than conventional tillage. However, when all three CA principles are used in concert with CTF, the negative impacts on yield are minimized. In the majority of the replicated experiments, no-till plots were not planted at their optimal time, they were sown later when the conventional plots could be sown. This calls into question the validity of meta-analysis conclusions and has been a stumbling block for replicated research for decades, in that field research has often looked at practices, rather than systems. If researching the system, the timeliness of CA would be recognized and used to advantage. Lower productivity was raised as a caution to CA promotion efforts particularly in Sub-Saharan Africa and South Asia where a high number of the world's poor and most vulnerable people live. The second concern is that CA dogmatically promoted. Rather than attempting to impose practices on local production contexts, knowledge, tools and adaptive systems that surface directly from the local context are needed. This point is well made and is also quite important to the development and adoption of improved systems. CA is very dependent on production of biomass to protect the soils, but the generation of ample biomass without fertilizer is almost impossible on already impoverished and degraded soil. In Africa, fertilizer prices are high, and farmers are poor. Poor adoption outcomes are predictable, but that does not mean the concepts are biologically wrong.

Given that each of the large groups of workers around the world that have created the various frameworks for alternative future food production systems have invested considerable thought, research, and publicity on their respective endeavours and are strongly vested in their efforts, it is unlikely a global, unified vision for how future food production systems might best be achieved will be reached. Market access and trade-related protocols, such as 'organic' or 'GlobalGAP' will also increasingly dictate how farmers farm. In many respects, the process of putting forth alternative conceptual frameworks, as has happened during the past two decades by so many earnest people and organizations has done much to clarify and strengthen the urgent need to persevere in this quest with added perspective, flexibility, and collective resolve. CA adoption may not be the right choice for all farmers. There is however, an immutable primacy to what has been formulated as the core concepts of CA as potential means not only for approaching the eternal efficiencies of natural ecosystems, but also for providing theoretical guidance for alternative future food production systems. Understanding natural resources and then achieving the ability to flexibly emulate natural water, energy, nutrient and biodiversity cycles in agroecosystems will thus inevitably figure largely in whatever systems agronomy or SI directions farmers ultimately pursue.

We add here a word regarding the growing and dramatic trend that agricultural technology development will have in future food production systems. CA systems recognize the soil as a natural living system that requires carbon flow throughout. Understanding the biological complexities from a management perspective of the soil system will thus require understanding of 'biological technologies'. In addition, while not systematically covered in this review, we recognize the inevitable contributions that a range of technological innovations are having and will continue to have in these systems. There are areas of the world such as the Netherlands, the Salinas Valley in California and segments of the Great Plains of the USA where a wide range of new crop production technologies such as the use of robotics in crop establishment, pest management and harvesting are having huge transformative and indeed revolutionary impacts on the way food is grown. The tiny country of the Netherlands, for example, has become an agricultural powerhouse, – the second largest global exporter of food by dollar value after the USA, – with only a fraction of the land available to other countries [188]. This has been achieved by using the world's most efficient agricultural technologies in largely indoor glasshouse soilless culture of a wide variety of crops. The potential of these technologies and of those that do not yet exist to transform and greatly improve the performance of production systems is staggering and will certainly continue to provide efficiency and labour-saving benefits. It will be, we believe, the eventual coupling or merging of these technologies with the underlying and largely biological or ecological principles and practices of CA that will provide the greatest advances and prospects for meeting future food production demands.

This paper has focused on the need to amplify and accelerate adoption of good agriculture practices that enable productivity increases on a sustainable basis. Society's choices on practices in agriculture will determine food security and planetary health for, and beyond, the foreseeable future. We made the case that for many production environments the three principle elements of minimum-tillage-based CA generally provide the best-bet approach, if widely adopted, to reach tangible goals of improving farm incomes while ensuring that soil health, water utilization and quality, air quality and bio-diversity are protected. Organic approaches have merit but the current reliance on soil tillage (for weed control) make organic less optimal, overall. In addition, we wish to emphasize the beneficial role that CTF might have when coupled with CA systems in recognition of machinery compaction in farming systems which is becoming more important as machines become bigger and heavier. We use the platform of this review article to discuss the addition of CTF to the CA definition which is something that has been widely proposed (J. McPhee, personal communication, 2018). We are not suggesting that every farm on the planet should convert to CA systems. We do hold that it will be good for very many, and thereby, for the planet and food systems. By appraising the current status of natural resource degradation and the implications of longer-term abuse, we then emphasized the need to, when practical, embrace practices that mimic natural systems that have proven stable outcomes. We emphasized that current soil tillage practices are not sustainable when conducted on a large scale. This level of tillage must be reduced *now* to recover soil functionalities, including the re-sequestration of atmospheric carbon. The CA approach contributes to climate change adaptation and mitigation. We also discussed the history of CA adoption and how CA adoption is one of the major tools for SI of crop production, contributing to strategic goals such as Climate-smart Agriculture, Poverty Reduction and Food Security. We reviewed the current debates concerning CA, as well as concerns that agriculture development choices need to be nuanced to fit local context – addressing the risks of over-promoting CA without insuring the fit to local conditions, especially the harsh farm-family constraints in developing nations. Special extension needs are required to scale up adoption of knowledge-intensive innovations such as CA, where timing of field operations is so critical. Our intentions were to highlight the longer-term views of sustainable agricultural practices, which must be inculcated *now* to prevent disasters of a greatly degraded natural resource base that is unable to recover to support needs of our species.

We are mindful in our focus on agricultural practices that many other dimensions, including policy, equity, finance, risk management, extension education and food waste prevention are also paramount for the changes needed. Soil, water, air resources and the biota that are part and parcel of agroecosystems, are not forever expendable. In addition, relationships between CA, soil health, the health of our food production systems, and human health are all very closely linked [189–191]. Thus, we highlighted needs for regenerative, restorative systems and lastly, provided evidence for the need for wide-scale adoption of CA systems and respecting the cycles of natural systems.

The broad adoption of combined innovations to address sustainable food security is often 'knowledge intensive'. Farmers need to understand their choices – and the implications of those choices – in the immediate as well as longer terms. However, adequate investment in 'innovation adoption' with the needed research support is often lacking. Then too, the complexity means broad adoption development innovations take more time and funding. Donor fatigue is the grand nemesis of sustainable development. Donors are continually striving to be at the cutting edge of the development-curve to justify their investments. In this context, innovations such as 'Farming Systems Research', 'Sustainable Intensification', 'Climate-Smart Agriculture' and 'Water-Smart Agriculture' are often offered to rally foci for the development community. However, smart donors will increasingly move away from these buzz words, and instead will focus on outcomes in the long-term. Nevertheless, the concepts that underpin CA systems, as presented in this article, are among the core elements for sustainable agricultural development in a near-future that will be required for increasing availability and access to nutritious food, but doing so without over expanding available water and land resources. Human health ultimately results from the health of our soils as well as the environment.

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