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Review

Successful Experiences and Lessons from Conservation Agriculture Worldwide

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Abstract: Since 2008/2009, conservation agriculture (CA) cropland area has been expanding globally at an annual rate of more than 10 M ha per year. In 2015/2016, the total CA cropland area was 180.4 M ha, corresponding to 12.5% of global cropland area. In 2018/2019, the total cropland area was 205.4 M ha, corresponding to 14.7% of global cropland area. The spread of CA has been expanding in Asia, Africa, and Europe in recent years because farmers are becoming better organized in working together and networking. More attention and resources are being allocated by stakeholders towards supporting farmers to adopt CA and in generating new knowledge to improve their performance. Globally, expansion of CA remains largely farmer-driven and has become a multi-stakeholder movement comprising formal and informal CA networks at national and international levels involving individuals and institutions in the public, private, and civil sectors. Several lessons from the global spread of CA are elaborated responding to the questions: (i) Why are the three interlinked CA principles universally applicable? (ii) Why does CA work sustainably and optimally? (iii) Why does CA deliver ecosystem services? (iv) Why is CA a valid alternative agricultural paradigm for sustainable development? (v) What are the sufficient conditions for scaling and mainstreaming CA?

Keywords: paradigm; global; adoption; climate smart; networks; systems

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1. Introduction

The history of agriculture has essentially been a history of tillage in agriculture, and the culture of ploughing or tilling the soil to establish crops and to manage weeds has been a central part of agricultural development worldwide. After WWI, agriculture began to be intensified to achieve greater output. This was essentially based on the intensification of the use of tillage and of agrochemicals as part of crop nutrition and protection management of higher yielding crops under standardised mechanized systems. Initially, this change process began in North America, but after WWII, it spread to other industrialized countries in Europe and Eurasia as well as in Australia and New Zealand and in the independent countries of the tropics, with emerging economies such as in Latin America and South Asia as part of the Green Revolution drive from the West.

From 1960 to 2000, no-till production was being tested in all continents by researchers and larger-scale mechanized farmers, and limited scaling began in the 1980s and 1990s, mainly in countries such as the US, Canada, Brazil, Argentina, Paraguay, Uruguay, Bolivia, Venezuela, UK, Australia, New Zealand, Spain, Germany, Kazakhstan, Zambia, and South Africa. By 2000, these countries together covered some 65 M ha of no-till cropland systems. Prior to this period, soil and water conservation programmes in the US had led to the development of a range of soil and water management practices such as bunding, terracing, contour ploughing, reduced tillage as well as no-tillage, which were brought under a common term called 'conservation tillage'. During the period between 1970 and 1997, the no-till pioneers and champions, farmers, extension agronomists, and researchers had generated enough experience and expertise to be able to define the key components of a sustainable no-till system that was termed conservation agriculture (CA). This term was first proposed in Spanish at the IV RELACO (Latin-American Network for Conservation Tillage) meeting in Morelia, Michoacán, Mexico, in 1997 by the co-authors Rolf Derpsch and Theodor Friedrich [1]. The term was also adopted in 1997 by the Food and Agriculture Organization of the UN (FAO) to describe sustainable production systems. This led FAO in 1998 to define the three interlinked principles of CA as we know them today at its first regional CA workshop in Harare, Zimbabwe as follows [1,2]:

1. Continuous minimum or no mechanical soil disturbance: implemented by the practice of no-till seeding or broadcasting of crop seeds and direct placing of planting material into untilled soil; no-till weeding; minimum soil disturbance from any cultural operation, harvest operation, or farm traffic. Sowing seed or planting crops directly into untilled soil and no-till weeding reduces runoff and soil erosion; minimises the loss of soil organic matter through oxidation; reduces disruptive mechanical cutting and smearing of pressure faces; promotes soil microbiological processes; protects and builds soil structure and connected pores; avoids impairing movement of gases and water through the soil; and promotes overall soil health.
2. Maintaining a permanent mulch cover on the soil surface: implemented by retaining crop biomass, rootstocks, and stubbles and biomass from cover crops and other sources of biomass from ex-situ sources. Use of crop residues (including stubbles) and cover crops reduces runoff and soil erosion; protects the soil surface; conserves water and nutrients; supplies organic matter and carbon to the soil system; promotes soil microbiological activity to enhance and maintain soil health including structure and aggregate stability (resulting from glomalin production by mycorrhiza); and contributes to integrated weed, insect pest, and pathogen management and to integrated nutrient and water management.
3. Diversification of species in the cropping system: implemented by adopting a cropping system with crops in rotations, and/or sequences and/or associations involving annuals and perennial crops, including a balanced mix of legume and non-legume crops and cover crops. Use of diversified cropping systems contributes to diversity in rooting morphology and root compositions; enhances microbiological activity; enhances crop nutrition and crop protection through the suppression of pathogens, diseases, insect pests, and weeds; and builds up soil organic matter. Crops can include annuals, short-term perennials, trees, shrubs, nitrogen-fixing legumes, and pastures, as appropriate.

The mindset that is driving the global CA community of practice (CA-CoP) defines CA as an ecosystem approach to regenerative sustainable agriculture and land management based on the practical application of the context-specific and locally adapted three interlinked principles described earlier. CA systems are present in all continents, involving rainfed and irrigated systems including annual cropland systems, perennial systems, orchards and plantation systems, agroforestry systems, crop-livestock systems pasture and rangeland systems, organic production systems, and rice-based systems. Conservation tillage, reduced tillage, and minimum tillage are not CA, nor is no-till on its own [1]. A practice such as no-till can only be referred to as being a CA practice if it is part of an actual CA system as per the above definition. This is similarly true for soil mulch practice and crop diversification practice, both of which can only be considered to be CA practices if they are part of a CA system based on the application of the three interlinked principles [1].

CA areas in different countries were put together by FAO and made available through AQUATSTAT until 2013/2014. Since then, the authors have compiled the information on the global spread of CA for mainly the same national level sources comprising official statistics, regional and national no-till associations, Ministries of Agriculture, Non-Governmental Organizations (NGOs), and national experts. The information on the global spread of CA has been updated periodically such as in 2008/2009, 2013/2014, and 2015/2016 [2,3] and is available at the CA-Global website (https://www.ca-global.net/ca-stat, accessed 15 July

2021). The most recent update was undertaken by the authors for 2018/2019, and interim estimates of the global and regional spread of CA were presented by the authors at the 8th World Congress on Conservation Agriculture [1]. This review article provides the details of the update on the uptake and spread of CA around the world at the global, regional, and national levels for 2018/2019 and elaborates some of the successful experiences in CA adoption and spread [2]. The successful experiences offer lessons, and these are elaborated in terms of five key lessons. The article also records the CA adoption goal for 2050 set at the 8th World Congress on Conservation Agriculture and highlights the key action themes needing greater technical and organizational attention to accelerate the global uptake and spread of CA systems.

2. Successful Experiences of CA Uptake and Spread

2.1. Global Uptake

The historical chart of CA uptake at the global level is shown in Figure 1 [3]. The transformation of conventional tillage-based agriculture began in the 1930s after the 'Dust Bowl' that shook the farming communities in the midwestern US, causing the scientific community to rethink what was not going right with farming, particularly with regards to soil conservation. Minimization of soil disturbance with stubble mulching was a major breakthrough in the understanding of how the objective of crop production intensification could be combined with the objective of soil and water conservation at the practical level by farmers [1].

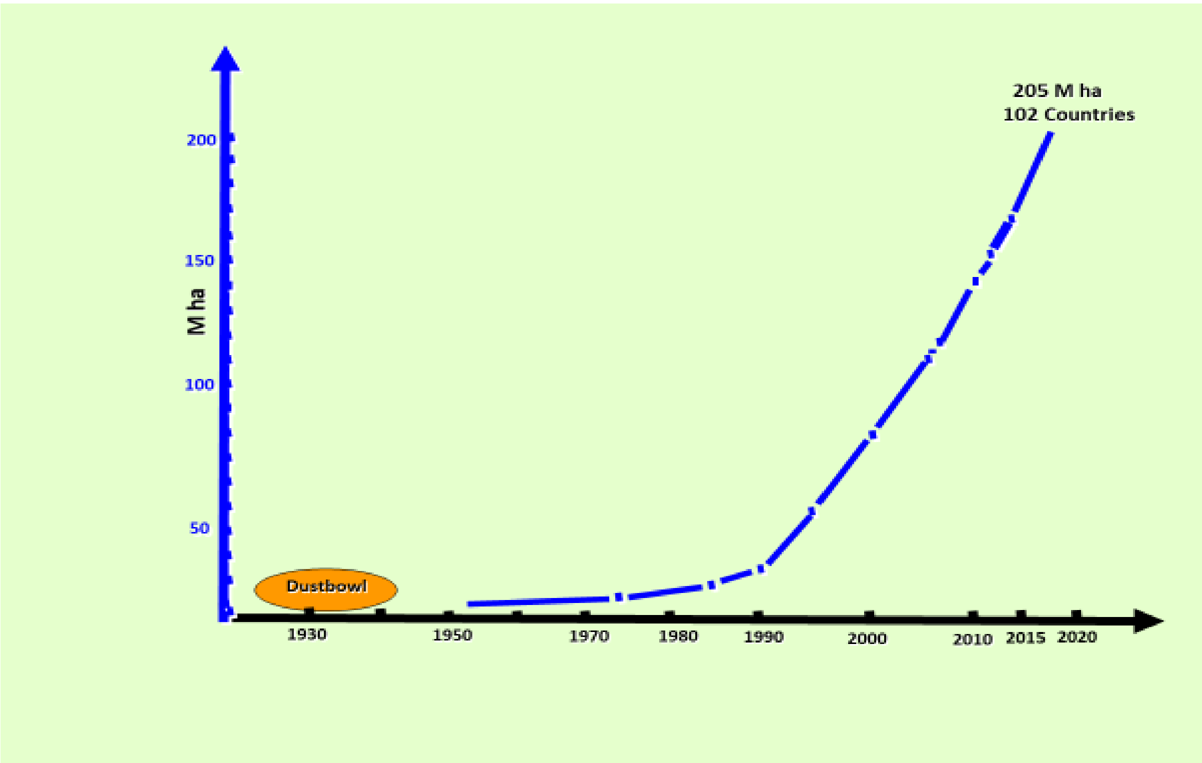

Figure 1. Historical chart of CA uptake at the global level [3].

Initially the intentions were to eliminate the erosion problem of tillage, for which the term conservation tillage became popular, determining the minimal necessary soil cover with crop residues to reduce erosion to acceptable levels. It took a few more years before the concept of tilling the soil was questioned per se, not only for the erosion problems it created, but also for other types of soil degradation processes it accelerated. In the late 1960s, pioneer farmers showed that no-till seeding through stubbles and crop biomass cover was the way to avoid or eventually reverse soil degradation and erosion [1]. Yet, like the current problems with climate change, the general global public is not aware of the ongoing soil degradation caused by tillage.

The global total CA cropland area in 2018/2019 was approximately 205.4 M ha, corresponding to about 14.7% of the total global cropland (also see Table 1). This represents an increase of 98.9 M ha or 92.9% from 106.5 M ha in 2008/2009, with the spread being more or less equally split between the Global South (50.5%) and the Global North (49.5%). The global CA cropland increased by some 48.6 M ha or 31.0% since 2013/2014 from 157 M ha, and some 25 M ha or 13.9% since 2015/2016, and from 180 M ha to 205.4 M ha in 2018/2019. Overall, the increase in the global CA cropland area since 2008/2009 has continued at an annual rate of approximately 10 M ha per year, from 106.5 M ha in 2008/2009 to 205.4 M ha in 2018/2019. Prior to that, the annual rate was about 5 M ha per year during the period from 1990 to 2008/2009. In 1990, the CA area of cropland was 11 M ha and in 2000, the CA area was 67 M ha.

Table 1. Global spread of CA cropland area ('000 ha) in different regions for 2008/2009, 2014/2015, and 2018/2019, and corresponding percent change [3].

Region	CA Cropland Area 2008/2009	CA Cropland Area 2013/2014	CA Cropland Area 2015/2016	CA Cropland Area 2018/2019	Percent Change in CA Area Since 2015/2016	Percent Change in CA Area Since 2013/2014	Percent Change in CA Area Since 2008/2009	Percent CA Cropland Area in the Region 2018/2019
S and C America	49,564.10	66,377.00	69,895.00	82,996.18	18.7	25.0	67.5	68.7
North America	40,003.80	53,967.00	63,181.00	65,937.22	4.4	22.2	64.8	33.6
Australia and New Zealand	12,162.00	17,857.00	22,665.00	23,293.00	2.8	30.4	91.5	74.0
Russia and Ukraine	100.00	5200.00	5700.00	6900.00	21.1	32.7	6800.0	4.5
Europe	1560.10	2075.97	3558.20	5601.53	57.4	169.8	259.0	5.2
Asia	2630.00	10,288.65	13,930.20	17,529.02	25.8	70.4	566.5	3.6
Africa	485.23	993.44	1509.24	3143.09	108.3	216.4	547.8	1.1
Total	106,505.23	156,759.06	180,438.64	205,400.04	13.8	31.0	92.9	14.7

A notable success was the establishment of the global CA Community of Practice (CA-CoP) in 2008 at an international conference held at FAO in July 2008 [4]. This has led to networking amongst CA associations internationally and sharing information on all aspects of CA with stakeholders. The doubling of the global rate of uptake since 2010 is another notable success. This reflects the fact that farmers worldwide are able to overcome local constraints to adoption of CA and move away from tillage-based production.

2.2. Regional Spread

The information on the spread of CA cropland area by regions in 2008/2009, 2013/2014, 2015/2016, and 2018/2019 is shown in Table 1 [3]. The change in the CA cropland area in the different continents since 2008/2009 has been: 67.5% (from 49.6 to 83.0 M ha) in South America; 64.8% (from 40.0 to 65.9 M ha) in North America; 91.5% (from 12.2 to 23.3 M ha) in Australia and New Zealand; 6800% (from 0.1 to 6.9 M ha) in Russia and Ukraine; 259.0% (from 1.6 to 5.6 M ha) in Europe; 566.5% (from 2.6 to 17.5 M ha) in Asia; and 547.8% (from 0.5 to 3.1 M ha) in Africa.

A notable success at the regional level has been the fourfold increase in the global share of the spread of CA across Europe (including Russia and Ukraine), Africa. and Asia. In 2008/2009, some 4.77 M ha, or 4.48% of the global CA area, was in Europe (including Russia and Ukraine), Asia, and Africa. By 2018/2019, the area increased to 33.17 M ha or 16.18% of total, on a larger global total CA area. This again reflects the fact that CA is expanding relatively faster in these continents, and increasing numbers of smallholder farmers in more countries are harnessing the benefits of CA. This trend is expected to continue in the coming years.

During the past decade, larger percentage increases occurred in these regions, but CA area continued to expand in the Americas, Australia, and New Zealand as well. In South America, the total CA area is approaching 70% of the total regional cropland area, and in Australia and New Zealand, CA area is approaching 75% of the total cropland area.

In North America, there has been a significant increase in CA area in the US [5] and Mexico [6]. In South America, there has also been a significant expansion of CA area in Brazil, particularly because the government over the past 10 years has facilitated the expansion of CA area, including cropping system diversification with legumes and trees, as part of its Plano ABC programme (the Brazilian Low Carbon Agriculture Plan or Plano de Agricultura de Baixa Emissão de Carbono [7,8]). In addition, countries in Central America have shown increasing interest to extend support to smallholders to adopt CA systems, including CA cropping with trees [6,9].

In Europe and Eurasia, there has been growing support to CA adoption generally. In the European Union (EU) countries, southern European areas in the Mediterranean region have made significant progress. The push for CA has been generally farmer-led, but there has been increasing level of government and EU support [10]. The expansion of CA has also included perennial systems including orchards and vineyards [11]. There has been a significant interest shown in the adoption of CA by most of the ex-Soviet states including Russia and the countries in the Caucuses and Central Asia [12,13]. Since 2008/2009, the European Conservation Agriculture Federation (ECAF) has expanded its membership, which now includes several eastern European countries.

In Africa, since 200820/09, there has been more than a five-fold increase in CA area and a three-fold increase in the number of countries actively promoting CA [14]. Notable successes have been recorded in South Africa [15], Zambia [16], and Ghana [17]. The establishment of the Adaptability of Agriculture in Africa initiative at COP 22 in Marrakesh, Morocco [18] has added momentum to the CA adoption in Africa, and so has the launching of the African Union-FAO initiative on Sustainable Agriculture Mechanization for Africa (SAMA) in 2018 [14], which is being operationalized by FAO and the African Conservation Tillage Network (ACT) in partnership with national governments and institutions. Support from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), the Norwegian Agency for Development Cooperation (Norad), the Canadian International Development Agency (CIDA), Centre de cooperation internationale en recherche agronomique pour le developpement (CIRAD), the Aga Khan Foundation (AKF), the International Maize and Wheat Improvement Center (CIMMYT), FAO, the International Fund for Agricultural Development (IFAD), the African Development Bank (AfDB), and EU has been important in generating momentum for CA research and extension. The Buffett Foundation has also been supporting the No-Till Training Centre in Ghana and the establishment of the Rwanda Institute for Conservation Agriculture (RICA).

In Asia, there is now a greater attention being accorded to CA in all regions, with several countries making significant progress. In West Asia, Iran has been scaling CA through its nationally coordinated programme [19]. In South Asia, India and Pakistan have made considerable gains [20]. In southeast Asia, nearly all the countries have begun to promote CA [21], and in East Asia, China has continued to provide leadership [22]. The Asia region now has a dedicated CA network—CA Alliance for Asia-Pacific (CAAAP) hosted at the Conservation Tillage Research Centre (CTRC) at the China Agriculture University, Beijing. Research and development support for CA from FAO, GIZ, CIRAD, CIMMYT, and the International Center for Agricultural Research in the Dry Areas (ICARDA) has been effective in generating interest and action in research and extension in the individual countries.

2.3. CA Adoption at National Level

Historical development of no-till systems and the modern version of CA that has been promoted over the past three decades are documented [2,3]. CA country areas for 2008/2009, 2013/2014, 2015/2016, and 2018/2019 are shown in Table 2.

Table 2. Extent ('000 ha) of adoption of CA worldwide by country in 2008/2009, 2013/2014, 2015/2016, and 2018/2019.

No	Country	CA Area 2008/2009	CA Area 2013/2014	CA Area 2015/2016	CA Area 2018/2019
1	USA	26,500.00	35,613.00	43,204.00	44,049.00
2	Brazil	25,502.00	31,811.00	32,000.00	43,000.00
3	Argentina	19,719.00	29,181.00	31,028.00	32,907.00
4	Canada	13,481.00	18,313.00	19,936.00	21,739.00
5	Australia	12,000.00	17,695.00	22,299.00	22,927.00
6	Paraguay	2400.00	3000.00	3000.00	3158.00
7	Kazakhstan	1300.00	2000,00	2500,00	3000.00
8	China	1330.00	6.670.00	9000.00	9000.00
9	Bolivia	706.00	706.00 *	2000.00	1858.03
10	Uruguay	655.10	1072.00	1260.00	1278.00
11	Spain	650.00	792.00	900.00	1000.00
12	South Africa	368.00	368.00 *	439.00	1607.08
13	Germany	354.00	200.00	146.00	352.89
14	Venezuela	300.00	300.00 *	300.00 #	300.00 +
15	France	200.00	200.00 *	300.00	720.00
16	Finland	200.00	200.00	200.00	120.00
17	Chile	180.00	180.00 *	180.00 #	180.00 +
18	New Zealand	162,00	162.00 *	366.00	366.00 +
19	Colombia	102.00	127.00	127.00 #	127.00 +
20	Ukraine	100.00	700.00	700.00 #	900.00
21	Italy	80.00	380.00	283.92	432.00
22	Zambia	40.00	200.00	316.00	552.67
23	Kenya	33.10	33.10 *	33.10 #	33.10 +
24	UK	24.00	150.00	362.00	562.00
25	Portugal	25.00	32.00	32.00 #	47.05
26	Mexico	22.80	41.00	41.00 #	149.22
27	Zimbabwe	15.00	90.00	100.00	100.00 +
28	Slovakia	10.00	35.00	35.00 #	365.00
29	Sudan	10.00	10.00 *	10.00 #	10.00 +
30	Mozambique	9.00	152.00	289.00	289.00 +
31	Switzerland	9.00	17.00	17.00 #	11.02
32	Hungary	8.00	5.00	5.00 #	24.29
33	Tunisia	6.00	8.00	12.00	14.00

Table 2. *Cont.*

No	Country	CA Area 2008/2009	CA Area 2013/2014	CA Area 2015/2016	CA Area 2018/2019
34	Morocco	4.00	4.00	10.50	12.83
35	Lesotho	0.13	2.00	2.00	2.00 +
36	Ireland	0.10	0.20	0.20	3.66
37	Russia	-	4500.00	5000.00	6000.00
38	India	-	1500.00	1500.00 #	3500.00
39	Malawi	-	65.00	211.00	211.00 +
40	Turkey	-	45.00	45.00	100.00
41	Moldova	-	40.00	60.00	180.00
42	Ghana	-	30.00	30.00 #	235.00
43	Syria	-	30.00	30.00 #	30.00 +
44	Tanzania	-	25.00	32.60	32.60 +
45	Greece	-	24.00	24.00 #	110.50
46	Korea, DPR	-	23.00	23.00 #	23.00 +
47	Iraq	-	15.00	15.00 #	12.00
48	Madagascar	-	6.00	9.00	9.00 +
49	Uzbekistan	-	2.45	10.00	120.00
50	Azerbaijan	-	1.30	1.30 #	37.50
51	Lebanon	-	1.20	1.20 #	1.20
52	Kyrgyzstan	-	0.70	50.00	60.00
53	Netherlands	-	0.50	7.35	17.50
54	Namibia	-	0.34	0.34 #	0.80
55	Belgium	-	0.27	0.27	0.27 +
56	Pakistan	-	-	600.00	1320.00
57	Romania	-	-	583.82	583.82 +
58	Poland	-	-	403.18	403.18 +
59	Iran	-	-	150.00	300.00
60	Estonia	-	-	42.14	42.14 +
61	Czech Republic	-	-	40.82	40.82 +
62	Austria	-	-	28.33	28.33 +
63	Lithuania	-	-	19.28	19.28 +
64	Croatia	-	-	18.54	18.54 +
65	Bulgaria	-	-	16.50	16.50 +
66	Sweden	-	-	15.82	26.00
67	Latvia	-	-	11.34	11.34 +
68	Uganda	-	-	7.80	7.80 +
69	Algeria	-	-	5.60	7.00
70	Denmark	-	-	2.50	38.50
71	Slovenia	-	-	2.48	26.00
72	Bangladesh	-	-	1.50	1.50
73	Swaziland	-	-	1.30	0.80

Table 2. *Cont.*

No	Country	CA Area 2008/2009	CA Area 2013/2014	CA Area 2015/2016	CA Area 2018/2019
74	Tajikistan	-	-	1.20	5.00
75	Vietnam	-	-	1.00	1.00 +
76	Cambodia	-	-	0.50	0.50 +
77	Laos	-	-	0.50	0.50 +
78	Luxemburg	-	-	0.44	0.44 +
79	Cyprus	-	-	0.27	0.27 +
80	Peru	-	-	-	2.89
81	Nepal	-	-	-	1.00
82	Armenia	-	-	-	0.30
83	Georgia	-	-	-	0.19
84	Belarus				400.00
85	Jordan	-	-	-	0.20
86	El Salvador	-	-	-	4.05
87	Guatemala	-	-	-	10.00
88	Honduras	-	-	-	171.00
89	Nicaragua	-	-	-	0.21
90	Sri Lanka	-	-	-	0.05
91	Burkina Faso	-	-	-	1.00
92	Cameroon	-	-	-	2.00
93	Myanmar	-	-	-	0.02
94	Rwanda	-	-	-	0.25
95	Burundi	-	-	-	0.20
96	Malaysia	-	-	-	7.50
97	Philippines	-	-	-	6.75
98	Timor Leste	-	-	-	1.00
99	Guinea	-	-	-	0.40
100	Ethiopia	-	-	-	7.50
101	DR Congo	-	-	-	2.06
102	Niger	-	-	-	5.00
	Total	106,505.23	156,738.96	180,438.64	205,400.04
	Percent difference		47.17 since 2008/2009	69.42 since 2008/2009 15.12 since 2013/2014	92.85 since 2008/2009 31.05 since 2013/2014 13.83 since 2015/2016

* Values taken from 2008/2009; # values taken from 2013/2014; + values taken from 2015/2016. Source: CA-Global website (https://www.ca-global.net/ca-stat, accessed 15 July 2021); 2008/2009 and 2013/2014 estimates from FAO-AQUATSTAT; 2015/2016 and 2018/2019 estimates obtained directly by authors from national sources.

The decade of the 1990s is considered as the decade when CA took off (Figure 1). During the first and the second decades of the new millennium, CA uptake by farmers spread out to Africa and Asia while it continued spreading in the Americas, Europe, and Australia. Smallholders had already been adopting CA systems, both manual and mechanized, in the tropics in South America in the late 1980s and 1990s, and smallholders in Africa and Asia also began to adopt CA systems during 1990s and the first decade in the new millennium.

The millennium opened with the first World Congress on Conservation Agriculture, which was held in Madrid, Spain. This helped to globalize the concept and principles of CA, and CA was promoted as part of sustainable production intensification by FAO and some donor agencies. Some centres of the CGIAR, particularly CIMMYT and ICARDA, began to conduct research on CA, and a number of national research systems also began to initiate CA research. More regional and national CA organizations and networks were established. Focus of attention also expanded to West Asia, South and South-East Asia, East Asia, and Africa, with countries such as Iran, Syria, India, Pakistan, China, South Africa, Mozambique, Zambia, Kenya, Ghana, and Morocco making significant progress in the expansion of CA area as well as in CA research to facilitate the effective application of the CA principles in specific contexts.

In July 2008, an international Consultation was organized by FAO in Rome to take stock and discuss the conditions that were necessary to achieve scaling of CA cropland systems. Experiences from all continents were discussed, and a global action plan was formulated to globalize the adoption and uptake of CA. To facilitate the implementation of the plan, a communication platform of Conservation Agriculture Community of Practice (CA-CoP) was established in early January 2009. The platform has enabled global CA stakeholders to be connected and exchange information on all aspects of CA from science and practice to sustainable agriculture development, conservation, and regeneration of natural resources and ecosystem functions.

By 2010, more than 105 M ha (7.0% of global cropland) were under CA cropland systems across 36 countries, covering all continents and most land-based agroecologies. Three more World Congresses of CA had also taken place in Brazil (2003), Kenya (2005), and New Delhi (2009). During the period from 1990 to 2010, global uptake of CA was approximately 9 M ha per year.

During the 2010–2020 decade, the rate of global uptake increased to 10.5 M ha per year, reaching more than 205 M ha (14.7% of global cropland) in 2019 across 100 countries. CA area in Africa, Asia, and Europe expanded more rapidly as more attention and resources were directed to promoting and supporting the uptake of CA cropland systems. During this decade, three more World Congresses of CA were held, in Australia (2011), Canada (2014), and Argentina (2017).

The expansion of CA uptake continues to be largely farmer-driven, and an increasing number of governments are now providing policy and institutional support to the uptake of CA cropland systems in addition to private sector machine and service companies.

In 2008/2009, global CA area was spread over 36 countries. In 2013/2014, the number of countries with CA area had increased to 53 countries, and in 2015/2016, to 77 countries. In 2018/2019, the number of countries with CA area had increased to 102. The corresponding increases in the number of countries from 2008/2009 to 2018/2019 was from 8 to 13 in South and Central America, from 11 to 31 in Europe, from 2 to 26 countries in Asia, and from 9 to 25 in Africa. This shows that much greater interest is being shown for CA systems in recent years by farmers globally in every region. In addition, the extent of support from public sector institutions and governments, although modest, has been increasing steadily. This trend is expected to continue, benefitting an increasing number of smallholder farmers.

Globally, the ten lead CA countries are: the US, Brazil, Argentina, Australia, Canada, China, Russia, India, Paraguay, and Kazakhstan. In South and Central America, the lead five countries are: Brazil, Argentina, Paraguay, Bolivia, and Uruguay; in Europe, Spain, France, Romania, United Kingdom, and Italy; in Africa, South Africa, Zambia, Mozambique, Ghana, and Malawi; and in Asia, China, India, Kazakhstan, Pakistan, and Iran.

3. Lessons Based on the Global Spread of CA

The following are some of the significant lessons based on scientific and empirical evidence obtained from the spread of CA-based cropland systems globally. Similar results are being obtained with perennial systems such as orchards, plantations, and CA croplands with trees. The list of lessons is long and there are many variations within these lessons, reflecting variations in biophysical, economic, environmental, social, institutional, research, and political conditions. We have selected the following five key lessons that emerge from the successful adoption and spread of CA globally, and they respond to the following questions:

(i) Why are the three CA principles universally applicable?
(ii) Why does CA operate sustainably, regeneratively, and optimally?
(iii) Why does CA deliver ecosystem services?
(iv) Why is CA a valid alternative paradigm for sustainable agriculture and land use?
(v) What are the sufficient conditions for scaling and mainstreaming CA?

3.1. The Three Interlinked CA Principles Are Universally Applicable

The three interlinked principles of CA have been shown to be universally applicable in all land-based crop production systems in all continents on all farm sizes and with all types of farm power. These CA systems include rainfed and irrigated annual crop systems such as horticultural crops involving root and tuber crops, and rice-based systems; perennial crop systems including orchards and vineyards; annual crops with trees and shrubs or agroforestry; plantations; and pasture, rangelands, and mixed systems. CA systems are being managed organically or biologically as well as with synthetic inputs [23,24].

The three principles emulate nature in which mechanical soil disturbance does not occur for vegetation to propagate and establish. Where vegetation growth is possible because of moisture availability, biomass produced always covers the ground and organic matter is converted into compost mulch on the ground surface and is incorporated into the soil through microorganisms and mesofauna. As one of the most important representatives of mesofauna, earthworms and termites play an important role in ingesting the biomass and mixing it with soil mineral particles to produce nutrient rich worm casts and excreta. Microorganisms also produce their own carbon-rich compounds, which help to bind soil mineral and non-mineral particles into stable aggregates that improve soil structure and porosity, water infiltration and retention and soil aeration.

CA is described as an ecosystem approach to regenerative sustainable agriculture and land management based on the practical application of three context-specific and locally adapted interlinked principles. They are often referred to as the three 'pillars' of CA that provide the foundation for CA's ecological sustainability at the system level without which economic and social sustainability are not possible.

The application of the three interlinked principles into practices provides the underpinnings for ecological sustainability and has been shown to have a robust ecological science foundation, providing a base upon or into which complementary practices can be integrated, thereby further strengthening the biophysical and biochemical processes of the system that nourish and protect plants and facilitating the functioning of the ecosystem. Thus, ecosystem functions at the field level as well as at the landscape level are enabled or mediated satisfactorily. Growing conditions for efficient growth are established, and resilience against biotic and abiotic stresses is also enhanced.

The above is illustrated in Figure 2, which shows a comprehensive CA production system and its components [25].

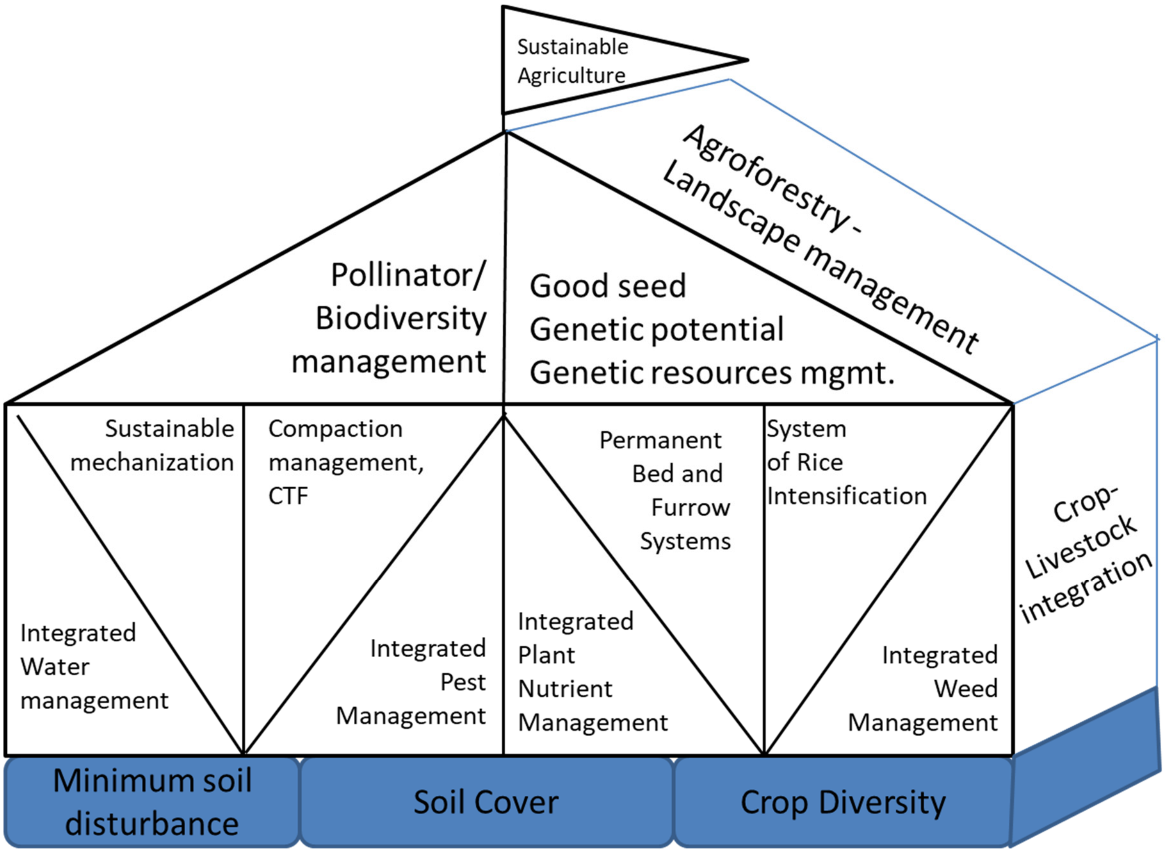

Figure 2. The three interlinked CA principles constitute the ecological foundation upon which sustainable agriculture can be built with complementary good agricultural practices [25].

3.2. CA Functions Sustainably, Regeneratively, and Optimally

CA systems operate sustainably, regeneratively, and optimally because CA promotes the following conditions and outcomes for the whole production system in which all CA principles have been applied adequately along with complementary practices of integrated crop, soil, nutrients, pests, water, and energy management.

- CA has ecological and biological foundations for sustainability [26].
- CA generates enhanced soil health status, biology, and functions [4].
- CA enhances biodiversity and therefore natural control mechanisms and feedback cycles [27].
- CA has diverse plant root systems that enhance soil systems [27,28].
- CA enhances environmental and ecosystem functions and delivers benefits to farmers and society [29].
- CA develops maximum efficiency and resilience [30].
- CA is able to regenerate and rehabilitate degraded agricultural lands [31,32].

Each of the above features of CA works synergistically with the others at the process and outcome levels to ensure superior and optimal overall performance. CA opens up the possibility for farmers to transform and regenerate the resource base, conserve the gains, and sustain the biological outputs as well as the ecosystem service outputs, allowing the system to operate at its optimal capacity.

The above is illustrated in Figure 3, which shows the propensity within CA systems to establish a dynamic cycle of regeneration, enhancement, and integration [33]. The outcomes include a production system that is self-enhancing, self-repairing, self-protecting, and self-regenerating as much as possible because its ecological and biological processes are interlinked in feedback loops.

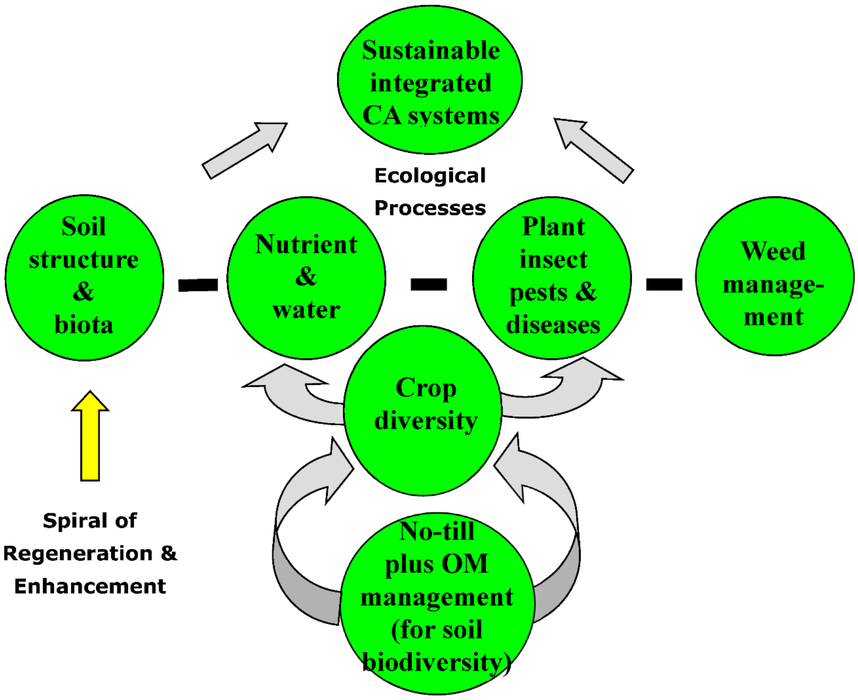

Figure 3. A spiral of regeneration and enhancement operating in integrated conservation agriculture systems based on the application of the three interlinked ecological principles adapted from [33].

3.3. CA Delivers Ecosystem Services

Ecosystem services are ecological and biological or organic services provided to society by nature [34]. They can be categorised into supporting services, regulating services, provisioning services, and cultural services, but in nature they are all interconnected (Figure 4). These services operate at the field and landscape levels. A major difference between the conventional tillage agriculture, which uses the plough and a number of tillage operations, and CA is in their ability to harness ecosystem services in the fields for production and across landscapes for society and environment. In conventional tillage agriculture, soils are degraded, and all soil health functions—biological, physical, hydrological, and chemical—are debilitated and prone to dysfunction.

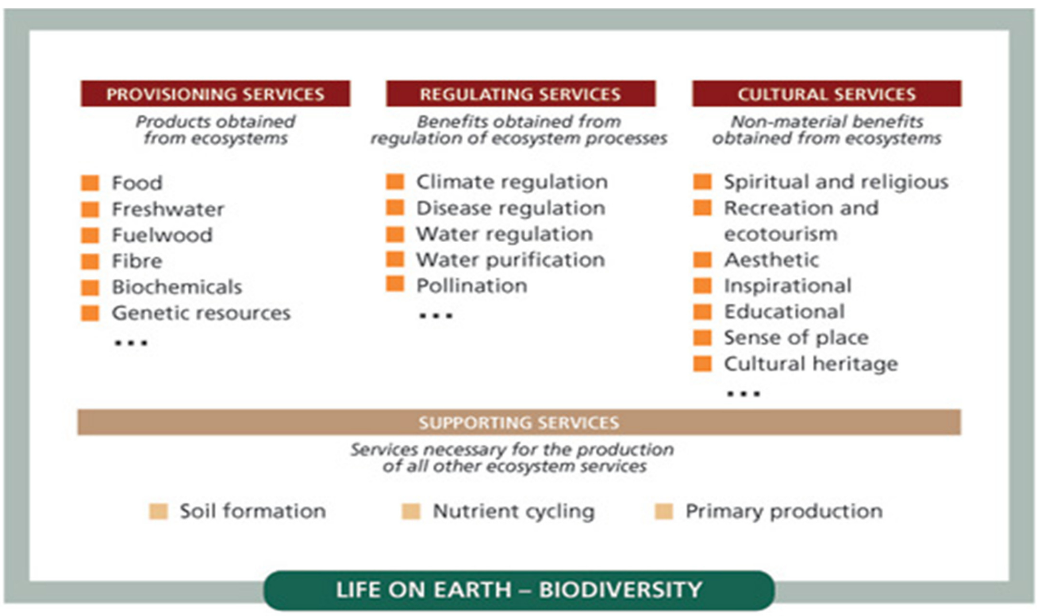

Figure 4. Categories of ecosystem services [34].

Examples of ecosystem services at the field and landscape levels have been described in [35,36]. Field level services covered biological, physical, hydrological, and chemical processes that interact amongst themselves and with the crops in the cropping systems affecting crop growth, development, productivity, and farm output. These provisioning services include all the biological products desired by society as well as above and below ground biodiversity. They also include the effects of soil biology on soil physical and chemical properties.

Regulatory services include landscape or watershed hydrology and services; stable stream and river flows with clean water; nutrient, water, and carbon cycling; and aquifer recharge and carbon sequestration. They also include biodiversity and wildlife food chains, and minimization of soil, water, and atmospheric pollution.

At the ecosystem level, ecosystem services at the field and landscape levels generate regional, national, and international level services for society including supporting services for biodiversity systems such as primary vegetation, wildlife habitats and migration systems, general circulation of the atmospheric regulation, thermal and moisture regulation in climate and weather systems, and large-scale nutrient, water, and carbon cycling.

Cultural services operate in terms of conservation area for wildlife and biodiversity, cultural and ecological tourism, and natural historical sites that have spiritual value.

Many of the ecosystem services described above operate at multiple levels, and they have been shown to function more optimally and sustainably when fields, landscapes, watersheds, and regional land use management is based on CA systems. Examples are given from Brazil, Spain, China, and Australia [35–37].

3.4. CA Is a Valid Alternative Paradigm for Sustainable Agriculture and Land Use

Global scientific and empirical evidence, as well as the extent of the global spread of CA, shows that CA is a valid alternative agricultural paradigm that is capable of addressing the weaknesses in the dominant tillage-based Green Revolution paradigm [38]. CA has shown the fuller potential of agricultural land use for farmers and their households and communities, the greater society, and the planet.

Contrary to tillage-based farming systems, natural resources such as soil, water, and biodiversity are not degraded in CA systems, but enhanced and improve over time. By reducing production costs while stabilizing, maintaining, or even increasing yield levels, CA improves the economic sustainability of farm households. Through diversified production systems, CA supports local supply of diversified food, gives small family farmers and rural entrepreneurs business opportunities, and enhances with this the social structure of rural areas, reducing the trend to urbanization. In this way CA is addressing sustainability in its three main areas—environmental, economic, and social.

Increasingly, CA is seen as a sustainable production base for climate smart agriculture and for carbon sequestration, responding to food security needs and adapting to and mitigating climate change. The private sector corporations appear more and more to provide support to agricultural transformation towards CA because it generally makes good business sense.

However, it seems that local manufacturing companies would need to become increasingly involved in producing the needed on-farm equipment and machinery for CA systems and associated supply chains. Many of the equipment and post-harvest processing used in conventional agriculture are relevant for CA systems. However, no-till direct seeders suited for all farm power and particularly for smallholder systems are an important area requiring further development. The same is true for non-chemical, non-soil engaging tools for weed management, and mechanized solutions for harvesting root and tuber crops with minimum soil disturbance.

The global CA movement is beginning to focus more on understanding the conditions necessary for mainstreaming CA, which involves the alignment of national policies and institutions towards supporting the transformation of tillage agriculture to CA systems but also engages in strategic research for improving the quality and performance of CA systems. Where mainstreaming is occurring, such as in countries like Canada, the US, Brazil, Australia, China, and South Africa, CA systems are able to play a bigger role for society in terms of sustainable food system and environmental management. Increasing farmers income and creating greater wealth from agriculture, reducing cost of production and consumer price of food, and enabling pro-poor development involving smallholder farmers and their communities increasingly contribute to sustainable food systems. Improved environmental management include providing ecosystem services such as cleaner water and carbon sequestration, enhancing biodiversity, and lowering pollution levels and flooding risks.

3.5. Sufficient Conditions for Scaling and Mainstreaming of CA

There are now several countries across the world where largescale adoption of CA has occurred. The top ten countries are: Canada, the US, Brazil, Argentina, Paraguay, Spain, South Africa, Kazakhstan, China, and Australia. In a number of these countries mainstreaming of CA is occurring. The word 'mainstreaming' means institutional and policy alignment in support of CA adoption. This goes well beyond the initial adoption of CA and its scaling at the grassroots level. Countries where CA is being mainstreamed include Canada, the US, Brazil, Argentina, Paraguay, Kazakhstan, China, and Australia.

For adoption of CA to become part of the national mainstreaming process, a set of necessary conditions must be established to create the sufficient conditions or an enabling environment for achieving a national transformation. A mainstreaming phase is essential to achieve a nation-wide paradigm shift.

The five necessary conditions for successful mainstreaming are [14,39,40]:

(i) The presence of champions and pioneer farmers, and champion institutions and champion institutional leaders.

Without adequate numbers of individual and institutional pioneers and champions, including farmers and extension agronomists and engineers, there will never be enough momentum to achieve and sustain an increase in the uptake of CA and address the challenges that can be expected to arise. Thus, major efforts must be made to inspire new generations of farmers, graduates, scientists, extension agents, institution heads, and stakeholders in the private, public, and civil sectors to become engaged at all levels in generating the momentum for change and CA-based transformation and agricultural development [41,42].

(ii) The presence of farmers coming together to form powerful farmer organizations for proactive actions and greater self-reliance.

Little will happen to spread quality CA if farmers themselves do not take action to work together and empower themselves and have a strong voice and visibility to accelerate the mainstreaming of CA in each country. Governments can provide support in enabling farmers to come together and establish associations to capture economies of scale in many areas within the value chains that would generate the momentum and efficiency in bringing about the needed agricultural transformation. Equally, increased levels of government support in terms of development investments, research, and extension can be used to enable farmers to establish associations in order to work together and improve their capacities to gain or generate new knowledge, apply new methods including mechanization, and improve market access and returns. In addition, working together, farmers can take advantage of delivering public goods to society more effectively in response to incentives including payments for environmental services where extra costs to farmers may be involved. Such public goods include clean water supply, reduction in flood risks, carbon sequestration, reduction in soil erosion and biodiversity loss, etc. [41,43–45].

(iii) The presence of education, research, and innovation systems supported by new communication technology that have aligned themselves to promoting the new paradigm.

Throughout the world, there are universities offering courses on sustainability, environment, soil, climate change adaptability and mitigation, climate smart agriculture, global food security and how to feed the world, and how to reduce wastage. Only a small number of universities teach CA. The same lack of emphasis on CA systems and practices apply to research and innovation and to new communication technology. Thus, students are exposed to facts, for example, regarding the objectives of soil tillage or concepts of pest control, which in the light of experiences with CA systems can be considered as myth or simply wrong [29,46]. CA requires embracing and internalizing new knowledge and skills that can be built in partnership with other knowledge systems. There is a need to build the skills, insights, and abilities of teachers and learners at all education levels and to link these efforts with wider global and national social movements to empower local self-reliant CA development efforts. It is thus important to establish long-term CA demonstration sites at the field scale in such areas to generate evidence that regenerative and more productive community-based crop-livestock management is possible and would benefit both crop farmers and livestock owners as well as reduce land degradation and improve the overall environment [47].

(iv) The presence of governance that creates policies and institutional support for CA paradigm change.

Most countries struggle with policies and institutional strategies to support a more sustainable way of farming. Only a handful of countries have attempted to develop a governance structure that is providing continuous support to promote the adoption and spread of CA, and the public and private institutional support it needs to improve its quality, generate graduates with CA knowledge, and promote CA participatory research and training. Unless national governance structure fully embraces and supports CA institutionally and policy wise, it is not possible to nationally mainstream CA. Several countries now have accepted CA at the national development policy level, which aligns institutions and resource allocation towards the promotion of CA. This involves establishing networks of CA institutions of excellence, each comprising a complex of collaborating institutions from the education, research, extension, and private sectors, and civil society all working closely with farmers on CA scaling and maintaining the gains made while improving quality of CA systems [48–51].

(v) The presence of effective capacity for farmers and their associations to partner with the private sector in ways that benefit both, as well as community and society at large, including nature.

Sustainable mechanization initiatives and extension support are needed to help minimize the use of agrochemicals, fuel, and farm power while intensifying productivity and ecosystem services with CA. It is generally true that established CA systems use considerably less seed, water, nutrients, pesticides, energy, and time compared to tillage systems, and with increased productivity, they generate employment along the value chain. In countries where farmers and the private sector have developed the capacity to partner effectively for sustainable agricultural development, mainstreaming support for CA uptake is established along the entire value chain [8,41,50].

These five necessary conditions are useful in examining the prospects for success in the transformation from conventional agriculture to CA along the value chain at the national level. Using these five criteria as a lens through which to look, one might be able to see where the gaps or weak points are located at the institutional level, thus directing attention to where it is needed.

Coming from the model of countries such as Brazil, Argentina, Paraguay, Uruguay, the US, Canada, Australia, and more recently South Africa, Zambia, Kazakhstan, China, and Morocco, one can see that the policy and institutional environment in the public and private sector for transformation of conventional tillage farming to conservation agriculture in countries worldwide needs a fundamental reform [24].

These five core criteria, which seem to us to be the key necessary drivers or conditions for agricultural change in each country and region across the world, together constitute the sufficient conditions. They can be used to monitor and evaluate where we need to focus our attention and where we need to make a faster, bigger difference in shifting to the CA paradigm. All five work together and create a foundation for maintaining and enhancing the momentum for change, innovation, quality, and impact [52].

4. Global CA Cropland Goal for 2050

The focus of the 8th World Congress on Conservation Agriculture in June 2021 was on the 'Future of Farming: Sustainable and Profitable Farming with Conservation Agriculture'. The Congress participants were convinced that CA must be the mainstay of the shift that the world has to make urgently towards sustainable farming and food systems, and that CA must become synonymous with sustainable farming.

The Congress set a notional goal for itself to increase the global CA cropland area to 50% of the total cropland by 2050, in particular to respond to the global challenge to mitigate advancing climate change and land degradation. This represents an area of 700 M ha [53]. Achieving this goal would require increasing the rate of expansion in CA cropland area by 50%, to 15 M ha per annum. It would also require a massive boost to the momentum of the global CA community's activities with a concentration on the following six themes:

1. Catalysing the formation of additional farmer-run CA groups in countries and regions in which they do not yet exist and enabling all groups to accelerate CA adoption and enhancement, maintaining high quality standards;
2. Greatly speeding up the innovation and mainstreaming of a growing array of truly sustainable CA-based technologies, including through engaging with other movements committed to sustainable farming;
3. Embedding the CA community in the main global efforts to shift to sustainable food and governance systems and replicating the arrangements at local levels;
4. Assuring that CA farmers are justly rewarded for their generation of public goods and environmental services;
5. Mobilizing recognition, institutional support, and additional funding from governments and international development institutions to support good quality CA programme expansion;
6. Building global public awareness of the steps being taken by the CA community to make food production and consumption sustainable.

5. Concluding Remarks

The global burden of chronic crises includes food insecurity, climate change, loss of biodiversity, environmental degradation, unsustainable diets, and human ill health. CA systems have a role to play in addressing all these crises. Increasingly, CA must be seen to be a central part of sustainable food systems and sustainable environmental management.

The CA global community must continue its effort to improve the quality and performance of CA systems but also undertake strategic research that would allow CA systems to operate biologically or organically, utilizing minimum input of synthetic agrochemicals or avoiding them. Already there are promising signs that such CA systems are possible, thus making it possible for farmers to adopt CA-based organic farming.

Equally important is the need to support smallholder farmers as they transform their conventional tillage systems to CA systems with improved returns and incentivized environmental benefits. Already more smallholders than large-scale farmers are practicing CA. However, the needs of smallholder farmers must be given greater attention than in the past. Equally important is the need to make farming an area of opportunity for women and youth, and transformation of conventional agriculture to CA has much to offer towards this goal, particularly when integrating precision GPS based practices and robotics in reducing drudgery and making farming more efficient and profitable.

Governments should be made aware that supporting CA systems will bring many benefits not only in the long run but in the short-term as well. For example, the application of CA technologies will allow efficient water infiltration into the soil, which will reduce the investment and running costs of infrastructure for cleaning drinking water. In addition, as rainwater infiltrates into the soil, erosion will be drastically reduced, and eroded sediments will not be carried to or deposited in unwanted places such as rivers, lakes, dams, and road infrastructure. When dams are affected by sedimentation, their effective life spans and operating efficiency are reduced, affecting electric power generation. All these benefits can be put at risk if the government does not facilitate the tools and processes necessary to initiate the mainstreaming of CA technologies.

At this point it is appropriate to remember that, similar to the problem of climate change, the general global public is not aware that the ongoing soil and biodiversity degradation caused by tillage is putting the survival of humankind on this planet at risk. Because of massive erosion during the 1930s in the US, President Franklin Delano Roosevelt said: "The nation that destroys its soil destroys itself". We can now also add: The society that destroys its soil and biodiversity destroys itself and the planet.

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