Conservation Agriculture and Soil Organic Carbon

Subjects: Soil Science

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Intensive agriculture causes land degradation and other environmental problems, such as pollution, soil erosion, fertility loss, biodiversity decline, and greenhouse gas (GHG) emissions, which exacerbate climate change. Sustainable agricultural practices, such as reduced tillage, growing cover crops, and implementing crop residue retention measures, have been proposed as cost-effective solutions that can address land degradation, food security, and climate change mitigation and adaptation by enhancing soil organic carbon (SOC) sequestration in soils and its associated co-benefits. In this regard, extensive research has demonstrated that conservation agriculture (CA) improves soil physical, chemical, and biological properties that are crucial for maintaining soil health and increasing agroecosystem resilience to global change.

reduced tillage | permanent soil cover | crop diversification | soil and water conservation | ecosystem services | carbon sequestration

1. Background and Rationale

The concept of conservation agriculture (CA) was born in the 1930s when Edward Faulkner first questioned the utility of ploughing in a manuscript called *Ploughman's Folly*, and it gained popularity during the 1960s in the mid-western United States as a means of preventing soil degradation after the Dust Bowl ecological disaster that occurred in the 1930s. Since then, research on adapting CA practices to cropping systems has been undertaken worldwide. In addition to reducing tillage intensity, CA also implies the application of organic amendments, such as manure, compost, and by-products from agro-industry [1], and the improvement of N management if mineral fertilizers are adopted to decrease N_2O emissions [2].

The exploitation of agricultural soils based on crop monocultures and deep tillage with inversion of the layers has resulted in progressive soil structure degradation and compaction and reductions in soil organic matter content. These detrimental developments have triggered negative cascade effects on the soil biota and fertility, increasing soil water and wind erosion and CO_2 emissions [3][4]. Among alternative management systems to conventional agriculture that aim at the sustainability of crop systems, CA represents one of the most advanced models.

2. Adoption of Conservation Agriculture (CA)

CA is defined by the Food and Agriculture Organization [5][6] as “a sustainable agricultural production system for the protection of water and agricultural soil that integrates agronomic, environmental and economic aspects”. CA is based on three principles (**Figure 1**): minimum mechanical soil disturbance through conservation tillage (i.e., no tillage, minimum tillage), permanent soil organic cover with crop residues and/or cover crops, and crop diversification through rotations and associations involving at least three different crops (including a legume crop). The benefits of CA are shown in **Table 1**.

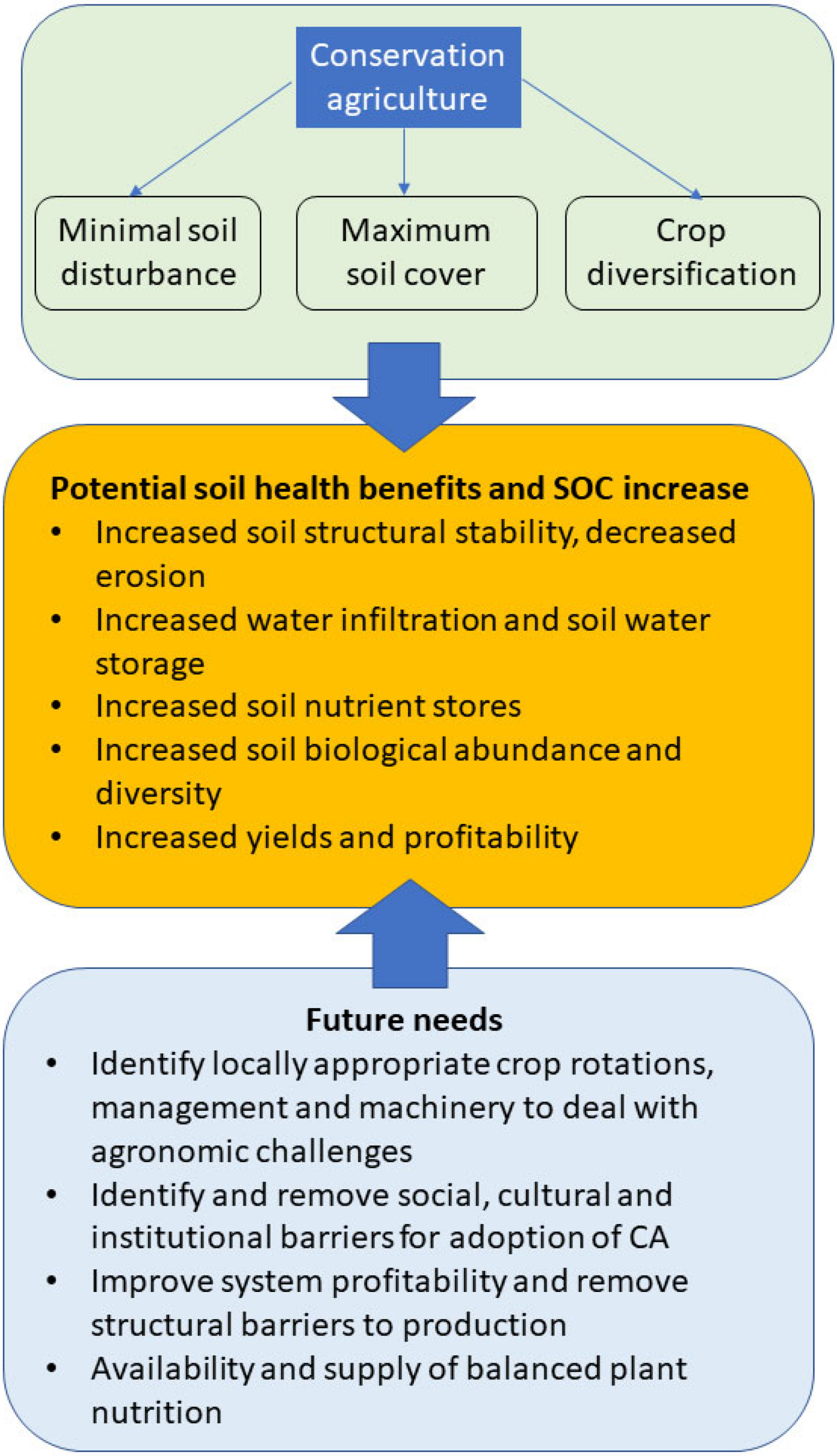

Figure 1. Principles of conservation agriculture, benefits of increasing SOC, and future needs. Modified from [7].

Kassam et al. [8] analysed the spread of the adoption of CA in 2015–2016 in different countries based on data available from government statistics, no-till farmer organizations, ministries of agriculture, non-governmental organizations, and research and development organizations.

The highest cropland areas were in South and North America (**Table 2**), with 69.9 and 63.2 M ha of cropland areas employed for CA, representing 38.7 and 35.0% of the total cropland employed for CA, respectively. However, CA represented 63.2% of the cropland area in South America and 28.1% in North America. The corresponding values for Australia/New Zealand and Asia were 22.7 and 13.9 M ha (12.6 and 7.7% of total cropland), representing 45.4 and 4.1% of croplands in the respective regions. Cropland areas employed for CA decreased in the order Russia/Ukraine > Europe > Africa from 5.7 to 1.5 M ha; i.e., from 3.6 to 1.1% of these regions' total cropland areas, respectively. Globally, the total cropland area employed for CA was 180.4 M ha, equivalent to 12.5% of total cropland.

Table 1. Benefits of conservation agriculture [9].

Target	Soil Cover	Minimal or No Soil Disturbance	Legumes in the Rotation	Crop Diversification
Simulate "forest floor" conditions	X	X		
Reduce evaporative loss of moisture from soil surface	X			
Reduce evaporative loss from upper soil layers	X	X		
Minimize oxidation of SOM and CO_2 loss		X		
Minimize compaction due to intense rainfall and the passage of machinery	X	X		
Minimize temperature fluctuations at the soil surface	X			
Maintain supply of OM as substrate for soil biota	X			
Increase and maintain nitrogen levels in the root zone	X	X	X	X
Increase CEC of the root zone	X	X	X	X
Maximize rain infiltration and minimize runoff	X	X		
Minimize soil loss in runoff	X	X		

Target	Soil Cover	Minimal or No Soil Disturbance	Legumes in the Rotation	Crop Diversification
Maintain natural layering of soil horizons through actions of soil biota	X	X		
Minimize weeds	X	X		X
Increase rate of biomass production	X	X	X	X
Speed up recuperation of soil porosity by soil biota	X	X	X	X
Reduce labour input		X		
Reduce fuel-energy input		X		
Recycle nutrients	X	X	X	X
Reduce pests and diseases				X
Rebuild damaged soil conditions and dynamics	X	[8] X	X	X

cropland,

Region	CA Cropland Area (M ha)	Total Cropland CA Area (%)	CA Area Cropland in the Region (%)
South America	69.90	38.7	63.2
North America	63.18	35.0	28.1
Australia/New Zealand	22.67	12.6	45.5
Asia	13.93	7.7	4.1
Russia/Ukraine	5.70	3.2	3.6
Europe	3.56	2.0	5.0
Africa	1.51	0.8	1.1
Global Total	180.44	100	12.5

3. Principles: Conservation Tillage, Permanent Plant Cover, and Crop Diversification

3.1. Conservation Tillage (CT)

Tillage is needed for different agricultural processes (e.g., seedbed preparation, weed control, crop residue management, improving soil aeration and avoiding soil compaction, optimizing soil temperature and moisture regimes). However, as a consequence, soil physical and chemical properties (structure, bulk density, pore size distribution, and fertility condition) are also altered, ultimately leading to good or poor crop performance [10]. Appropriate tillage practices, such as CT, aim to avoid soil degradation without compromising crop yields and while maintaining agroecosystem stability [11].

CT, as defined by the Conservation Tillage Information Center (CTIC, West Lafayette, Indiana, USA), excludes those tillage operations that invert the soil and bury crop residues. It consists of reducing the ploughing depth occasionally or continuously, applying shallower tillage with other implements, and/or reducing the intensity of seedbed preparation. Thus, it minimizes soil disturbance and reduces losses in soil and water, for which at least 30% of the soil surface must be covered by crop residues. Therefore, CT is a general term that includes specific operations, such as no-tillage, minimum tillage, reduced tillage, and mulch tillage practices [12][13][14]. Interest in CT systems increased globally after the 1930s following the Dust Bowl events, as they were seen as a way to halt soil erosion and promote water conservation [15]. However, extensive research has further demonstrated the multiple environmental benefits of adopting CT, such as enhancement of soil organic carbon (SOC) content, maintenance of agricultural productivity, and savings in the costs—in terms of time, fuel, and machinery—of seedbed preparation [13][14]. Moreover, it has been demonstrated that leaving crop residues on the soil surface also reduces evapotranspiration, improves infiltration, and suppresses weed growth [12][16]. According to the CTIC, there are five types of CT systems.

(1) No tillage (NT)

The NT system is a specialized type of CT consisting of a one-pass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed [17]. NT systems eliminate all pre-planting mechanical seedbed preparation except for the opening of a narrow (2–3 cm wide) strip or small hole in the ground for seed placement that ensures adequate seed–soil contact [11]. Retaining crop residues and leaving them on the soil surface is pivotal for soil and water conservation. Weed control can be managed using herbicides, a brush cutter, or biological control methods, such as crop rotation, inter-cropping, or vegetation strips. However, the use of herbicides may have detrimental effects on the soil system and its functions; thus, they should be applied with caution. Indeed, the new European agro-environmental policy framework discourages the use of herbicides; thus, use of mechanical or biological control methods should be boosted. Among the potential benefits of NT compared to other tillage systems are that it is more effective in controlling soil erosion, it improves soil water storage capacity, and it results in lower energy costs per unit of production and higher grain yields, especially in low-slope areas. However, as already stated, major disadvantages of NT are the heavy use of herbicides for weed control and the risk of soil compaction and nutrient stratification [18][19] in intensive agricultural systems (e.g., low residue input, machine traffic).

(2) Mulch tillage

Mulch tillage is based on the principles of causing the least disturbance to the soil and leaving the maximum percentage of crop residue on the soil surface. For this purpose, in addition to in situ crop residues, the use of live mulch derived from cover crop residues is becoming a common practice. This practice can be adopted in herbaceous and woody crop systems by either allowing spontaneous plant cover to become established or by growing cover crops in the fallow period (in the case of herbaceous crop systems) or in the inter-tree rows (in the case of woody crop systems). Regardless of the type of plant cover used, this practice consists of maintaining plant cover that can protect the soil for as long as possible without causing the problem of competition for water and nutrients with the main crop. To do so, in accordance with the crop type and climate conditions, the spontaneous or seeded plant covers are mowed before the water-limiting period starts, and their residues are left on the soil surface as mulch.

(3) Strip or zonal tillage

Strip tillage is a practice in which soil disturbance is limited to the crop rows while the rest of the soil is left undisturbed [20]. This tillage practice emerged as an alternative soil management practice in attempts to solve and mitigate the problems derived from conventional tillage or direct seeding methods [21]. The seedbed is divided into a seedling zone (5–10 cm wide), which is mechanically tilled to optimize the soil and micro-climate environment for germination and establishment of seedlings, and an inter-row zone, which is left undisturbed and protected by mulch or managed using chiselling to improve water infiltration and root development [22]. Today, strip tillage can benefit from the use of global positioning system (GPS) guidance equipment [23].

(4) Ridge till

Ridge tillage consists of leaving the soil undisturbed before planting and then tilling about one third of the soil surface when planting with sweeps or row cleaners. Crops are planted in rows on cultivated ridges, while weeds are controlled with herbicides. This tillage practice gained popularity as a conservation agriculture practice for maize and soybean production in the USA [17].

(5) Reduced and minimum tillage or occasional tillage

Reduced tillage (RT) is a soil management practice that consists of reducing the total number of tillage passes per year needed before seed planting (in both annual and perennial crops) or for soil aeration and decompaction (particularly in perennial crops). RT is also called minimum tillage and shallow tillage since, in some cases, it refers to reducing the depth at which the soil is tilled and/or using a cultivator or chisel plough to avoid soil inversion. Occasional tillage refers to the practice of one-time tillage, where tillage is conducted once every 5 or 10 years—depending on the soil, climate, and crop type—in an otherwise continuous NT system. This tillage practice is generally applied to mitigate the potential negative effects that tillage cessation may cause in some cases, such as soil compaction and nutrient stratification, particularly in rainfed perennial cropping systems [24][25].

3.2. Permanent Plant Cover

Permanent plant cover refers to those practices involving the growth of a permanent spontaneous or seeded plant cover within the crop system (intercropping systems) or between periods of normal crop production for soil protection and improvement. In the case of spontaneous plant covers, weeds grow in accordance with the pedoclimatic conditions of the area, and species are typically wild species. When the plant cover is seeded by employing what is known as a cover crop, species are selected for which the products can be harvested for food or feed. They may be leguminous (e.g., vetch) so that the cover crop can help to improve the N content, the crops may be used for forage or human consumption (e.g., rye, rapeseed), or mixtures of two or more species may be employed. Spontaneous plant cover can either be removed with a reduced tillage operation so that the plant residues are quickly incorporated into the soil or left on the soil surface; thus, the incorporation of the C and other nutrients will be slower. When seeded cover crops are harvested, their residues are usually left on the soil surface.

3.3. Crop Diversification

Crop diversification (CD) is a farming system that encourages the cultivation of different plant species in the same field as opposed to monoculture farming [26][27]. There are different options for implementing CD, such as crop rotations (at least two crops in different years), multiple cropping (different crops grown in succession during the same year), and intercropping (crops grown together on the same field). In intercropping, crops can be planted in alternate rows and harvested together (row intercropping) or in wide rows and mechanically harvested separately (strip intercropping), or they can be sown together (mixed intercropping); i.e., with no separation between rows or strips.

In addition to allowing a higher number of crops to be grown and alternated on a field, CD has several objectives [7]:

(a) Covering and protecting the soil from climatic agents in a continuous and effective way;

(b) Maintaining and improving soil structure through the action of the root systems of the plants;

(c) Stimulating biological activity in the soil and eliminating periods with no crop cover;

(d) Limiting environmental risks due to nitrate leaching, erosion and surface runoff, and loss of biodiversity.

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