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12. Elevating Soil Organic Carbon Levels: The Dynamics of Conservation Agriculture

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Abstract:

Intensive agricultural activities pose a wide range of environmental challenges, including land degradation, pollution, soil erosion, reduced fertility, loss of biodiversity, and increased greenhouse gas emissions, further exacerbating climate change. Promoting sustainable agricultural techniques like minimizing tillage, employing cover crops, and effectively managing crop residues has been recommended as a cost-efficient approach to tackle these problems.

Additionally, these methods facilitate the augmentation of soil organic carbon sequestration, leading to various associated advantages Conservation agriculture (CA), which embodies these principles, is extensively researched and enhances the physical, chemical, and biological properties of soil that are necessary to maintain soil health and enhance the resilience of agricultural ecosystems. However, the adoption of conservation agriculture worldwide faces persistent technical and socio-economic barriers. This document presents a body of contemporary knowledge on the potential agricultural, environmental, and socioeconomic benefits and drawbacks of implementing CA principles.

Keywords:

Intensive agricultural activities, loss of biodiversity, Conservation agriculture (CA), soil organic carbon sequestration.

12.1 Background:

Conservation agriculture (CA) is an agricultural method that emerged in the 1930s; in particular, Edward Faulkner's work on traditional farming in his Farmers Folly collection. [1] The method has been critically questioned. It gained popularity in the 1960s, especially in the American Midwest, through unprofitable farming in response to the environmental crisis of the 1930s Dust Bowl.

CA principles have been adapted around the world for agricultural development. In addition to reducing arable land, improving nitrogen (N) management includes organic amendments such as fertilizers, manure and agricultural products to reduce N_2O emissions when stones are used in soil fertilization.

Conventional monoculture farming practices, deep tillage and soil modification lead to development and compaction of soil structure and reduction of soil organic matter. This low growth affects soil biota, fertility, soil erosion and carbon dioxide (CO_2) emissions. As a management alternative to conventional agriculture, CA represents the highest standards of sustainability in agriculture.

12.2 Adopting Sustainable Farming: Transitioning to Conservation Agriculture (CA)

Conservation agriculture (CA) is a sustainable agricultural production system designed to protect both water resources and agricultural land while balancing agricultural, environmental, and economic considerations. This approach is clearly defined by the Food and Agriculture Organization [1,2]. CA revolves around three basic principles:

- First, it involves reducing mechanical soil disturbance through methods such as no tillage or minimum tillage.
- Second, it advocates for the maintenance of permanent soil cover through the incorporation of crop residues and/or cover crops.
- Finally, CA encourages crop diversification through rotation and association, which requires the inclusion of at least three different crops [6], including a league crop.

Conservation agriculture (CA) provides benefits at various levels, from global farmers to individual farmers:

- **Sustainability:** CA represents a sustainable approach to agriculture. It not only protects natural resources but also develops them. This method enriches the biodiversity of soil biota, flora and fauna in agriculture without affecting high productivity.
- **Enhanced Biodiversity**: CA thrives on biological processes and supports biodiversity at the micro and macro levels of agriculture.
- **Carbon Sequestration:** When used globally, idle land can act as a carbon sink, helping to control climate and climate change. Farmers working with CA can benefit from loans by supporting land management.
- **Labor Saving**: Farming is one of the most labor-intensive and environmentally polluting activities in agriculture. By avoiding large tracts of land, farmers can save time, labor and fossil fuels, thus increasing productivity and environmental impact.
- **Increase productivity:** Contrary to popular belief, CA is not a low-yield farming method. Its benefits are labor intensive and sustainable compared to modern agriculture. Fertility rates tend to increase and decrease over time.
- **Reduce costs**: CA is an important economic factor for farmers. The result is lower production costs and less labor and time, especially during peak demand periods such as land preparation and planting. It helps reduce equipment capital and maintenance costs in mechanical systems in the long run.

12.3 The Cornerstones of CA: Redefining Agriculture Through Three Key Principles

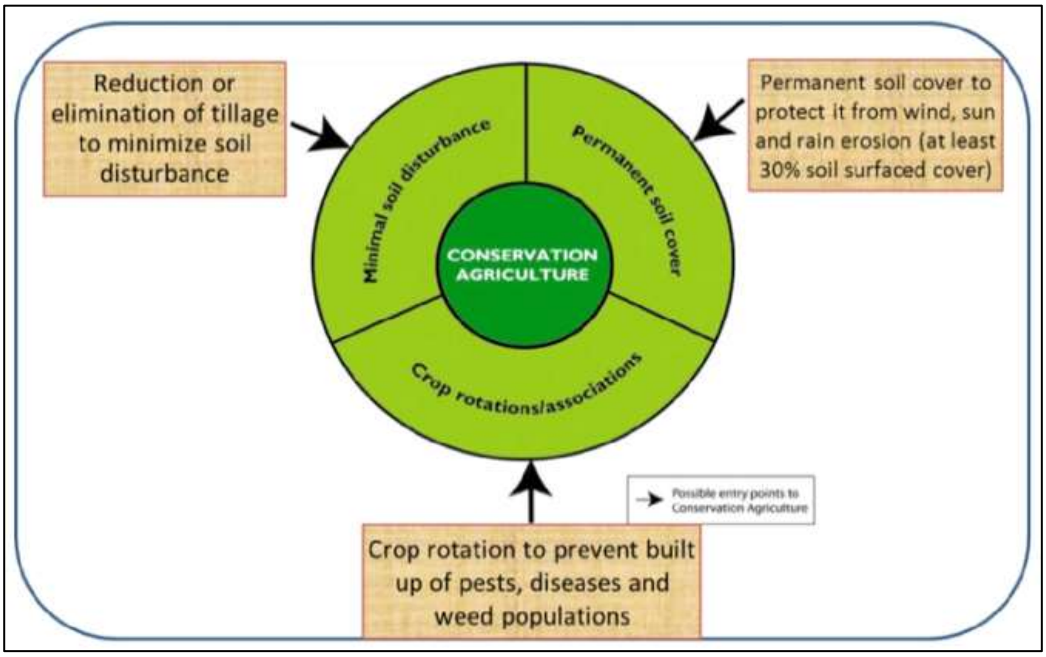

Figure 12.1: Cornerstones of CA

The three interrelated principles of conservation agriculture (CA) have demonstrated their universal applicability in various land-based crop production systems worldwide, regardless of farm size, crop types, or agricultural energy sources. CA systems extend their reach to cover a variety of agricultural scenarios, including rainfed and irrigated annual cropping systems, such as horticultural crops, root and tuber crops, and rice-based systems. They are equally effective in perennial cropping systems, including orchards and vineyards, as well as annual crops intercropped with trees, shrubs, agroforestry, plantations and a variety of pastures, rangelands and mixed systems. CA systems can be driven by organic or biological approaches as well as synthetic inputs.

By simulating a natural environment where mechanical disturbance to the soil is minimal, and soil formation processes are primarily carried out by soil life such as roots and various soil organisms, CA works biologically wherever the conditions for plant growth exist on Earth. The practical implementation of these principles may vary, including the specific equipment used for seeding and planting, which is influenced by soil type, location and situational factors, such as the choice of crops to be grown in the CA cropping system.

Applying these interconnected principles in practice forms the foundation for ecological sustainability and is based on sound ecological science. This foundation serves as a platform in which complementary practices can be seamlessly integrated, thereby enhancing the biophysical and biochemical processes that nourish and protect plants and support ecosystem function.

This approach enables and mediates ecosystem functions both at the regional level and across the wider landscape. It establishes optimal growth conditions, increases resilience against various biotic and abiotic stresses and ultimately achieves a balance between high biological and economic productivity and environmental sustainability.

12.3.1 Minimum Soil Disturbance Farming- Conversation Tillage:

Tillage plays a crucial role in agriculture, supporting various essential processes such as seed preparation, weed control, crop residue management and optimizing soil conditions for crops. [1,3]

However, conventional tillage practices can inadvertently alter soil properties, which can either benefit or hinder crop performance. Conservation tillage (CT), as defined by the Conservation Tillage Information Center (CTIC), represents a fundamental change in agricultural practices. Its primary goal is to prevent soil degradation without compromising crop yields. CT practices are designed to minimize soil disturbance, reduce soil and water losses, and ensure that at least 30% of the soil surface is covered with crop residues. The origins of CT can be traced back to the challenging times of the Dust Bowl era in the 1930s when catastrophic soil erosion events fueled the need for more sustainable agricultural practices. CT was identified to combat soil erosion and promote water conservation. Subsequent extensive research has highlighted numerous environmental benefits associated with CT. This includes significant savings in terms of soil organic carbon (SOC) content, maintained agricultural productivity and time, fuel and machinery required for seed preparation.

A. Special Types of Conservation Tillage (CT) Systems [1]:

- **No-Till Farming (NT):** NT is a unique CT system that revolutionizes planting and fertilization by reducing soil disturbance. It eliminates traditional mechanical seed preparation and relies on narrow strips for precise seed placement. While NT effectively controls erosion and increases water storage capacity, it contends with herbicide use and the risk of soil compaction.
- **Mulch Conservation:** Mulch farming focuses on minimal disturbance to the soil surface and conservation of crop residues. This approach often involves using live mulch derived from cover crop residues to protect the soil.
- **Strip or zonal tillage**: Strip tillage limits soil disturbance to crop rows while leaving the rest of the soil undisturbed. It includes designated seedling zones for optimal germination and water infiltration, often benefiting from modern technology such as GPS guidance.
- **Ridge conservation:** Ridge tillage minimizes soil disturbance before planting and selectively tills up to one-third of the soil surface during planting. This method, popular in corn and soybean production in the USA, relies on herbicides for weed control.
- **Reduced and occasional tillage:** Reduced tillage (RT) aims to reduce the number of annual tillages passes, especially for perennial crops. Occasional tillage introduces a one-time soil disturbance in a continuous no-till system, which addresses potential problems such as soil compaction and nutrient stratification. These diverse CT systems meet specific agricultural needs while prioritizing soil conservation.

12.3.2 Harnessing Permanent Plant Cover:

Perennial vegetation in sustainable agricultural practices involves the intentional growth of permanent, self-sustaining vegetation simultaneously with cash crops (such as intercropping) or during fallow periods. This serves the dual purpose of protecting the soil and enriching it.

In the case of natural vegetation, nature selects plant species that grow according to local climate conditions. These usually form wild species and are often referred to as weeds. In contrast, cover crops are intentionally planted and seeds are selected for their potential use. These cover crops may be legumes such as vetiver, which increase the nitrogen content of the soil, or may consist of grains such as rye or canola, which provide forage value or a human food source. In some cases, a combination of two or more species may be planted to maximize the benefits of this practice.

Spontaneous vegetation management often involves reduced tillage to minimize soil disturbance. In this scenario, plant debris remains on the soil surface, where it gradually decomposes and contributes to soil organic matter and nutrients, albeit at a slower rate. On the other hand, when a seed cover crop is harvested as its primary crop (e.g., grain or forage), residual plant material is intentionally left on the soil surface. This approach promotes the gradual decomposition of this organic matter, releasing carbon and essential nutrients into the soil. These environmentally friendly practices help improve soil health and long-term agricultural sustainability.

12.3.3 Enhancing Sustainability with Crop Diversification:

Crop diversification (CD) refers to a changed approach to agriculture that advocates moving away from monoculture farming practices, growing different crop species in the same field. Different strategies can be used to implement CD, including crop rotation (changing crops in different years), multiple cropping (growing different crops consecutively in the same year), and intercropping (growing different crops together in the same field).

Intercropping method can be divided into row cropping, where crops are planted in alternate rows and harvested together, or strip cropping, which involves mechanical separate harvesting of crops planted in wide rows. Alternatively, plants are planted in a mixed manner with no separation between rows or lines.

12.4 Potential horizons: The Way Forward for Conservation Agriculture

A. **Decreased production expenses:** The adoption of zero-till technology in CA can significantly reduce the cost of production for crops like wheat. Studies indicate potential savings of Rs. 2,000 to 3,000 ($33 to $50) per hectare. These cost reductions are primarily attributed to savings in diesel, labor, and input costs, especially herbicides.

B. **Reduced Incidence of Weeds**: Zero-tillage in CA systems tend to result in a reduced incidence of major weeds like Phalaris minor in wheat fields. This leads to decreased herbicide use, contributing to cost savings and potentially reducing environmental impact.

C. **Preservation of Water and Nutrients:** CA practices, particularly zero-tillage, have shown the potential to save water (up to 20% to 30%) and nutrients. In fields with laser leveling and bed planting, substantial water and nutrient savings have been observed. The soil under no-till retains more moisture, which can be critical for crop growth.

D. **Increased Yields:** When properly managed, zero-tillage in CA systems often leads to higher yields compared to traditionally prepared fields. CA's impact on crop yields is multifaceted, including soil health improvement, enhanced soil fertility, improved moisture retention, and rotational benefits. Yield increases of 200 to 500 kg per hectare have been reported for no-till wheat in specific systems.

E. **Environmental Benefits:** CA practices, such as zero-tillage and surface management of crop residues, offer significant environmental advantages. They can help eliminate the burning of crop residues, which is a source of greenhouse gases like CO2, CH4, and N2O. Additionally, proper residue management allows for the recycling of plant nutrients, reducing nutrient loss and environmental pollution.

F. **Crop Variety Expansion Opportunities:** CA systems open up opportunities for crop diversification. Through appropriate cropping sequences, rotations, and agroforestry systems, farmers can enhance natural ecological processes and adapt various crops to these new systems. Crops like mustard, chickpea, pigeonpea, and sugarcane can be well-suited to CA practices.

G. **Resource Improvement:** No-tillage, combined with surface management of crop residues, initiates processes that lead to soil structural improvement and increased recycling and availability of plant nutrients. Surface residues act as mulch, moderating soil temperatures, reducing evaporation, and enhancing biological activity in the soil.

12.5 Changing the Landscape: The Global Expansion of Conservation Agriculture:

The adoption and global spread of Conservation Agriculture (CA) represents a transformative change in modern agriculture. [4] Since 2008-09, CA has seen an annual increase of more than 10 million hectares, covering more than 205 million hectares of global cropland in 2018-19. It has spread to low-income countries, particularly Latin America and Asia, and is slowly gaining traction in West and Central Asia and Africa. CA principles apply to a variety of cropping systems, including perennial crops such as olives, vines and fruit trees, as well as plantation systems. Agroforestry systems that incorporate CA principles, known as “evergreen agriculture,” promote soil health, biodiversity, and sustainable agricultural productivity.

In the 1970s and 1980s pioneers, including farmers, agronomists and soil conservationists, played an important role in raising awareness about land and land degradation due to tillage agriculture. The establishment of the World Congress on Conservation Agriculture in 2001, sponsored by various agricultural development organizations, has played a crucial role in promoting CA globally. Despite some opposition to mainstream research and development systems, the adoption and spread of CA has been primarily driven by farmers and their communities. CA principles are applied in a variety of land-based farming systems, including various agricultural practices and cropping systems. CA has shown that sustainable intensification can be achieved using local resources, leading to the practice of uncertified organic CA systems. However, it faces challenges from multinational corporations and mainstream international agencies that promote traditional agricultural practices. In summary, CA represents a significant shift in modern agriculture, which is farmer-led and offers sustainable and regenerative solutions to address agricultural and environmental challenges. Despite the challenges, CA holds the potential for radical change in global agricultural land use systems.

12.6 Sustainability Cultivation: Practices for Agricultural Conservation

Figure 12.2: Conservation Agricultural Practices

A. Sustainable land management: Also known as lander agriculture, sustainable land management includes a variety of crop varieties and livestock products aimed at achieving consistently high yields while conserving soil and water resources. Conservation agriculture is a form of sustainable land management that meets the goal of producing more food while reducing environmental impact.

B. Green revolution vs. Zero or Mitigation Revolution: While the Green Revolution mainly benefits those with external income such as fertilizers and hybrid seeds, conservation agriculture, often referred to as ``zero or mitigation revolution", has "delivered benefits to all farmers and society." This multifaceted movement was created by the desire to increase food production while conserving resources and improving the quality of the environment. Agricultural conservation is an important part of food security, rural development and resource conservation strategies.

C. Minimal mechanical disturbance of the soil: The biological activity of the soil creates natural soil aggregates with different pore sizes, helping the proper penetration of air and water. Mechanical disturbance of the soil by planting or cultivation interferes with this biological process. Minimal soil disturbance is important to maintain the ideal composition of transpiration gases, adequate porosity for water movement, and to prevent weed seed germination. This includes permanent low soil disturbance, tillage, and direct seeding along with weeds.

D. Permanent organic soil cover: Protecting the soil from the harmful effects of rain and sun exposure is important in maintaining agriculture. A continuous supply of nutrients to soil microorganisms and plant roots is achieved through a permanent organic soil cover. This much is made using biomass from crop residues and covers plants.

E. Diversified crop rotation: Diversified crop rotation is necessary to provide nutrients to soil microorganisms and increase crop nutrient utilization. By rotating crops with different root depths and nutrient needs, a diverse crop rotation prevents runoff and increases soil biodiversity. Crop rotations that include seeds help fix biological nitrogen, disrupt pest life cycles, and increase overall biodiversity.

F. Cultivating Harmony: Pest, Weed, and Fertility Management in Conservation Agriculture Managing pests, weeds and soil fertility is a challenge in agriculture. Agricultural conservation practices should be carefully reviewed and revised before adoption. This aspect is the backbone of a successful farming system.

12.7 Cultivating Harmony: Pest, Weed, and Fertility Management in Conservation Agriculture

In a situation of scarce resources, sustainable solutions have been developed by farmers themselves. [8] They developed weed control methods, implemented strategic crop rotation, harnessed the power of organic fertilizers, and diversified crop options to enrich soil fertility. In particular, small-scale farmers have begun to integrate conservation agriculture and organic practices to increase the lasting impact of their businesses.

This integrated approach emphasizes the importance of a harmonious relationship between agricultural practices and the environment, moving agriculture towards a more sustainable and sustainable future.

A. Integrated Pest Management: Pest management in agriculture relies on integrated pest management (IPM) techniques. Even when new or unknown pests start to appear, crop rotation and cover crops play an important role in disrupting the life cycle of pests between crops.

B. Weed control balance: Although synthetic chemical herbicides may be necessary in the first year, they must be carefully managed to minimize adverse effects on soil health. Grazing practices include mulching, cover crops, crop rotation, and herbicides. In some cases, mechanical weeders adapted for tractors can be used through mulching. As farmers develop conservation practices, their reliance on herbicides decreases. Selecting appropriate cover crops also supports biological weed control.

C. Increasing soil fertility: Overcoming soil constraints such as acidity, salinity or toxicity is an important part of agricultural conservation. Soil organic matter (SOM) and the selection of plants and cover crops play an important role in regulating soil fertility, with SOM derived from root decay being particularly important. Incorporating livestock into the system can be a solution, especially for farmers with limited resources or access to mineral fertilizers. Organic and mineral fertilizers are also needed to maintain soil fertility.

12.8 Addressing Challenges in Conservation Agriculture Advancement:

A. Coding system complexity: Conservation farming systems show a higher level of complexity than conventional methods. A dominant limitation to the adoption of conservation agriculture is the lack of site-specific knowledge. Effective management of this system requires a deep understanding of the underlying processes and interrelationships between their components that significantly affect the performance of the system. For example, keeping crop residues on top of the soil acts as a protective mulch that reduces soil water evaporation and lowers soil temperature. At the same time, these residues form a source of easily decomposed organic matter that can change ecosystem dynamics and inhibit unwanted pests. Switching to no-till practices affects the depth and distribution of the root system, which in turn affects the water and nutrient and mineral cycles. Recognizing conservation agriculture as an integrated system requires the development of specific management strategies.

B. Developing a cooperative systems perspective: Developing a systems perspective depends on collaboration with farmers. Building a core consortium that includes scientists, farmers, extension and other stakeholders involved in a collaborative mode is essential for developing and disseminating new conservation agriculture technologies. This collaborative approach departs from traditional agricultural research and development because it involves setting research priorities, allocating resources in a structured framework, and establishing relationships and relationships with specialized partners in complementary fields.

C. Technological limitations: Although the basics of conservation agriculture, such as no-tillage and crop residue management on the soil surface, are well established, their seamless integration into diverse agricultural environments poses great challenges. Overcoming this challenge requires the development, standardization and widespread adoption of agricultural machinery designed to reduce soil disturbance during planting. It also involves establishing an efficient system for harvesting and managing crops.

D. Adaptation to site-specific needs: Developing strategies for agricultural conservation requires adaptation to harsh environments. It is important to recognize that agricultural practices are highly contextual. Gaining insights from different sites is important to understand why a particular technology or practice proves effective in certain situations and weak in others. This collaborative learning process accelerates the development of a comprehensive understanding of the complexities of resource management.

E. Focus on long-term research horizons: Conservation agriculture, evidenced by no-tillage and keeping crop residues above ground, improves the quality and sustainability of resources in the long term. In many cases, short years of evaluating the impact of conservation agriculture practices may not produce immediate results.

A deep understanding of the complex dynamics and interactions between physical, chemical, and biological processes is essential for developing advanced strategies for soil-water and nutrient management. Consequently, agricultural conservation research requires a long-term perspective to unravel the complex tapestry of these processes and relationships.

12.9 Conclusion:

Conservation Agriculture (CA) represents a holistic approach to modern agriculture that aims to solve a range of environmental problems while promoting sustainable food production. By reducing tillage, adding crop residues and supporting crop diversification, CA improves soil health and fosters a more harmonious relationship between agriculture and the environment.

The journey to general CA adoption is fraught with challenges. CA systems are inherently complex and require a deep understanding of their underlying processes and component interactions.

Collaboration between scientists, farmers and stakeholders is very important for the effective development and dissemination of CA technology. Technological limitations and site-specific needs further complicate the path to adoption.

Despite these challenges, the potential benefits of CA are significant. Reduced production costs, weed control, water and nutrient savings, increased yield and environmental benefits are just some of the rewards CA offers. CA's global expansion represents a transformative change in modern agriculture, driven by farmers themselves and offering sustainable and regenerative solutions to agricultural and environmental challenges.

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