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Conservation Agriculture for Carbon Security in Drylands

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Abstract

Dryland ecosystems covering over 40% of the world's land are among the most fragile, facing land degradation, declining soil fertility, and unpredictable climates. These regions often experience low rainfall, high evapotranspiration, and poor soil quality, making sustainable farming a major challenge. Conservation Agriculture (CA) has emerged as a promising solution, built on three key practices: minimal soil disturbance, continuous soil cover, and crop diversification. CA not only improves soil health and productivity but also plays a critical role in capturing and storing carbon in the soil a key strategy in fighting climate change. In drylands, where natural carbon inputs are limited, CA boosts soil organic carbon (SOC) through increased biomass, better root growth, reduced erosion, and stabilization of organic matter. Techniques like reduced tillage, cover cropping, crop residue retention, and rotation help store carbon long-term while enhancing nutrient cycling and microbial activity. Evidence from dryland areas in Africa, India, Australia, and Latin America shows that CA can raise SOC levels, lower greenhouse gas

emissions, and improve land resilience. However, its success varies depending on soil type, climate, crops, and management. Barriers such as limited technical knowledge, socioeconomic constraints, and competition for residues often slow adoption. Despite these hurdles, CA remains a climate-smart approach offering multiple benefits better water retention, improved biodiversity, and more stable yields. To realize its full potential, long-term support through policies, incentives, and farmer-focused extension services is essential. This paper explores the mechanisms, benefits, and limitations of CA in drylands, with a focus on its impact on soil carbon and sustainable agriculture.

1. Introduction

Covering about 41 percent of the land surface of the planet, the dryland spaces, including the arid, semi-arid, and dry sub-humid areas. Such areas are largely found in the developing world and in them, lay some of the most vulnerable in the world with their economy based largely on agricultural production (Wang et al., 2022). Nevertheless, the intrinsic features of drylands like low and unevenly distributed rainfall, high evapotranspiration, low soil fertility and common incidence of droughts are major threats to the sustainable agricultural productivity, and food security. Organic carbon in soils (SOC) is the basis of soil health, fertility and productivity (Pandao *et al*., 2023). It enhances soil texture, water holding capacity, assists in nutrient levels and it promotes microbial processes. However, because of the ongoing processes of land deterioration, cropping over, denudation and the overall unreasonable agricultural process, the levels of SOC in arid areas often fall to rock bottom levels. Consequently, dry land soils are susceptible to erosion, decrease in water infiltration, and diminishing productivity, and this worsens the susceptibility of such lands to climate change (Naorem et al., 2023). Conservation agriculture (CA) in this case can be seen as a sustainable method of land management that can help in repairing the soils as well as storing carbon into the atmosphere. Conservation agriculture rests on three closely inter-relationship principles which include no-till or limited soil disturbance, permanent soil cover, and diversified crop rotations.

The practices are especially adapted to the dryland conditions because they aid in the improvement of the water use efficiency, soil erosion and strengthen cropping systems amid moisture-affected conditions (Srinivasrao et al., 2021). The possibility of CA to trap carbon in dryland soils is an issue that is raising awareness as a climate-smart agricultural practice. CA enhances SOC accumulation and stabilization by adding organic matter to the soil and decreasing carbon emission. In addition, its co-benefits, i.e. increased soil fertility, reduced cost of production, and biodiversity enhancement, are also favourable to its performance in sustainable development (Francaviglia et al., 2023). Although very promising, adoption of conservation agriculture in the drylands has been met by a number of challenges that are socio-economic barriers, poor access to information and resources as well as presence of inter-crop residue competition as animal feed sources. That is why it is important to know all the mechanism, advantages and constraints of CA to scale it up in adoption.

2. Dryland Soils and Carbon Dynamics

One of the characteristics of dryland soils is that it has coarse texture, low organic matter and little fertility. These are shallow, poorly structured and easily crust, compacted and eroded soils. In drylands, low, and erratic precipitation combined with high temperatures results in low biomass production and other organic materials being added to the soil, which limits the amount of soil organic carbon (SOC) built up (Morya et al., 2023). Due to this, dry land soils generally contain lesser SOC stocks as the humid places. Organic carbon in soil is a very important part of soil health, and it determines physical, chemical, and biological attributes. SOC is crucial in improving soil structure, water holding capacity, nutrient cycling and microbial processes all of which are key towards the ability of crop production to be sustained in drylands by utilizing limited water supplies. The carbon cycle within the dryland soils entails the input of organic matter by the plant residues, the root biomass, and by microbial biomass, as well as the process of decomposition, mineralization and stabilization of carbon which dictates the destiny of carbon within the soil.

The dryland carbon processes however are very susceptible of land management practices and climatic conditions (Devi et al., 2023). Sustainable agricultural practices and land management like infrequent tillage, retention of crop residues, under-grazing and forest cover preserve the organic matter longer to hold the carbon and erosion and oxidation causes carbon loss in the soil. Moreover, dryland ecosystems have been more prone into desertification and long-term degradation as they are delicate and this process destroys the SOC reserves further. The scarcity of moisture in drylands also impacts on the rate of release and decomposition of organic matter as well as the turnover of carbon, most of the time in a slow way.

But in case of having moisture, the process of decomposition can be very quick and there will be a burst of the release of CO_2. SOC in drylands is very erratic and exposed to the external shocks. The process of stabilization of carbon in dryland soils will mostly be determined by the process of interaction with soil minerals, soil clumps, and protection through soil pores. Those particles that have a fine texture, like those that are clay based, normally tend to stabilize SOC better since they have a higher surface area through which carbon can be bound (Hanan et al., 2021). Many dryland soils are however sandy and do not have such stabilizing power. The dynamics between climatic conditions, vegetation cover, soil attributes and land management is complex and unrevealed to optimize carbon sequestration measures in drylands. Improving the SOC in these areas will help in mitigating the climate condition, improving soil fertility as well as in stability of dryland agriculture systems.

3. Conservation Agriculture Principles and Practices

Conservation Agriculture (CA) is a sound farming method aimed to recharge the health of the soil, raising production and resilience to climate variability especially in vulnerable ecosystems such as drylands. It is established on three main connected principles: (1) should only disturb soil minimally, (2) should maintain Soil cover to be permanent and (3) rotate or intercrop crops and diversify. When implemented in combination, these principles provide maximum biological health to the soil, safeguard natural resources as well as promote sustainable farming in the long run.

3.1. Minimal Soil Disturbance

It referred to zero tillage, or reduced tillage, this principle involves keeping the minimum disturbance to soil that comes of the mechanical process to sustain the soil structure along with the organic matter. The rate of organic matter degradation is faster in conventional soil tillage practice and leads to more carbon emissions particularly in drylands where the existing soil organic carbon levels are low (Cooper et al., 2021). Reduced tillage preserves ground characteristics of aggregating and reduces tillage soil erosion and assists in the preservation of soil moisture which is crucial in arid and semi desert conditions.

3.2. Permanent Soil Cover

The soil should always be covered with some form of vegetation or the leftovers of the crop that is growing, this ensures that the soil is not ventilated to the wind and water erosions, which tend to be frequented in dry areas. The cover of soil also moderates the temperature of the soil, minimizes prevalence of losses through evaporation and facilitates the biological activity. Retention of residue is also vital in the drylands because it helps in the accumulation of soil organic carbon, improves water entry and decreases the growth of weeds (Dharmawan et al., 2023). But the ever-present limit is crop residues competition as fodder; so, the integrated residue management approaches are necessitated.

3.3. Crop Diversification

Rotation and intercropping with legumes or strong rooted species enhance nutrient cycling; disturb pests and disease cycles, and biodiversity of soil. In arid lands, drought-tolerant crops such as millets, pulses and oilseeds can be used in rotations to enhance resilience of the systems. Leguminous crops especially contribute to the enrichment of the soil with nitrogen and increase of organic matter, which assists in carbon sequestration. A combination of these CA practices enhances the fertility, soil structure and water-holding capacity of the soil, which provide an environment favorable to long-term storage of carbon. They also minimize chemical inputs and fossil-based operations making the emissions of greenhouse gasses further reduced. Conservation agriculture practice demands that legacies of land use, such as soil type, climate and social-economic limitations are taken into consideration in implementing conservation agriculture in dryland regions (Srinivasrao et al., 2021). To enable farmers to adopt CA practice in large scale, there is need to support farmers with training, extension services and provide them with the right machinery and inputs to maximize the carbon sequestration potential of CA practice.

4. Soil Carbon Sequestration mechanisms in drylands through Conservation Agriculture

Conservation Agriculture (CA) and Carbon sequestration in dry restores and maintains the carbon sequestered in the soils through a complex of biological, physical, and chemical processes that enhances the carbon input and carbon loss reduction as well as renovation of the carbon storage in the soil (Reicosky et al., 2021). These mechanisms play a critical role in the degraded soils of the dry lands and in reducing climate change in resource-limited realms.

4. 1. More of the Carbon Input

CA practices, especially crop diversification and retention of residues, enable organic matter to be fed back to the soil. Diverse rotations and cover crops add extra root and shoot biomass, exudates and above-ground residues, as primary sources of carbon. In arid regions such as drylands where biomass production would be low, small increments of organic inputs make large impacts on SOC concentrations (Devi et al., 2023). Leguminous cover crops also produce more biomass and have some sort of nitrogen fixation capability, thus allowing better goodness in carbon and nitrogen cycling.

4. 2. Minimized Carbon Loss Conservation tillage reduces the disturbance of soil hence decreasing the oxidation of organic materials and the consequent emission of carbon dioxide (CO_2). Conventional cropping promotes an increase in microbial activity and lays the organic matter open to erosion. Conversely, practices as no-till or reduced tillage increase the retention of existing SOC through the preservation of soil structure, and protection against water and wind erosion, two primary routes of carbon emissions in drylands (Srivastava et al., 2025). The temperature extremes are also cushioned by the protective residue cover, avoiding the evaporation keeping the microclimate favorable to microbial activity and organic matter preservation.

4. 3. Better Aggregated Soil Structure

Soil Aggregation is one of the main physical procedures of carbon preservation. CA increases the stability of soil aggregates and enhances the formation of soil aggregates leading to increased organic binding agents like polysaccharides and fungal hyphae. These aggregates paved the way to physically shield SBK against microbial decomposition. Soils may also be weakly aggregated in dry lands, and aggregation created by CA can highly enhance soil stability and water infiltration to allow long-term carbon retention in storage.

4. 4. Chemical Stabilization of Carbon Soil mineral

This occurs when organic carbon is stabilized by particles of carbon soil minerals, particularly, clays and iron/aluminium oxides, in forming stable organo-mineral complexes. Although much dryland soils are sandy and have a low percentage of clay, still CA practices can enhance the generation of microenvironments favorable to carbon stabilization by enhancing the addition of organic matter and stimulating mineral weathering. Gradually, these interactions give a stronger chemical defense of SOC. A combination of these mechanisms shows the way in which CA can aid the change of dryland soils into the carbon sinks (Francaviglia et al., 2023). CA sequesters carbon by increasing the nutrient content of the soil because of the increase in the biomass input and the decreased rate of decomposition, and the carbon protection of soils leading to improved soil fertility, and resilience and productivity of dryland agroecosystems.

5. Empirical Evidence from Dryland Regions

Numerous studies in the dryland zones of the whole world have confirmed the productive efforts of Conservation Agriculture (CA) on soil carbon stocking. Despite some differences in carbon storage due to climate conditions, soil condition, level of management and crop systems, the general picture remains the same i.e. it is possible to increase significantly the level of soil organic carbon (SOC) through the adoption of CA practice in these delicate ecosystems. Field experiments in long-term studies conducted in India using CA in arid areas like semi-arid tropics in Madhya Pradesh and Andhra Pradesh have seen positive results in SOC levels. Experiments by Indian Council of Agricultural Research (ICAR) showed an increase of 1525 per cent in SOC in 57 years by no-till cultivation in residue retention and crop rotation systems compared to conventional tillage. The rain fed cotton chickpea system in Central India, Under residue retention in reduced tillage system, soil availability of both surface SOC and soil moisture were improved. Surveys in Zambia and Zimbabwe in Sub-Saharan found that CA-based systems, including maize-legume rotations and minimum tillage yielded positive beneficiaries in modified SOC content (0.3 to 0.5 Mg C ha 1 yr 1). These systems also enhanced infiltration of soil and crop yields which were economically and environmentally beneficial. Thierfelder and Wall (2010) reported SOC enhancements in CA even in smallholder systems with low inputs, a fact that proves the usefulness of CA to the resource-pinched farmers.

In Australia’s drylands, stubble retention and reduced tillage in Western Australia and New South Wales have increased soil organic carbon (SOC) by 10–30% over the past 20 years, mainly in the top 0–10 cm of soil. This highlights the role of surface residue in reducing erosion and boosting carbon input. In Latin America's drylands, especially in Brazil and Argentina, widespread adoption of no-till soybean–wheat rotations has significantly increased SOC, with sequestration rates ranging from 0.4 to 1.0 Mg C ha^{-1} yr^{-1}, depending on rainfall and cropping intensity. Despite regional differences, CA consistently enhances SOC in drylands. However, success depends on factors like soil texture, cropping system, residue management, and socio-economic conditions. Achieving long-term carbon gains requires sustained efforts, farmer training, and strong institutional support.

6. Benefits and Setbacks of Conservation Agriculture in Drylands

Conservation agriculture (CA) has several co-benefits in addition to soil carbon sequestration especially in the dryland ecosystems where environmental stress, and resource scarcity reduce agricultural productivity. Nevertheless, due to its potential, CA implementation in dryland is associated with multiple practical, social, and economical challenges opposed to the popularization of this type of agricultural practice.

7. Dry lands Co-benefits of CA

7.1. Better Soil Health and Fertility

Examples of CA practices, which include keeping the residues and crop rotation, contribute to soil organic matter, increase nutrient cycling, and enhance useful microbecial dynamics. This will have a better outcome in the soil structure, porosity, and the capacity of soil to hold water- which is essential in drylands in relation to crop productivity in areas of water scarcity (Singh et al., 2021).

7.2. Water Conservation and Efficiency

Soil cover using crop residues decreases evaporation and that minimum tillage enhances infiltration and decreases runoff. These effects aid in moisture conservation, lengthens the growing season in droughts, and enhances efficiency of water use, all of which are of importance in arid and semi-arid areas (Dharmawan et al., 2022).

7.3. Yield Stability and Resilience

CA yields may be low in some cases at first until the impacts of the technique start to be realized; however, CA enhances stability in crop yields in the long term, particularly under climatic stress of drought (Wang et al., 2022). The production is further stabilized by the crop diversification which assists in reducing the pressures of pests and diseases.

7.4. Mitigation and Adaptation to Climate Change

High soil carbon sequestration, lowering tillage and synthetic fertilizer emissions are also means to mitigate climate change through CA. At the same time, facilitation of soil and crop system resilience facilitates the response to the growing climate variability.

7.5. Biodiversity Booster: CA promotes biodiversity above and below the ground. Permanent cover and crop diversification provide a conducive environment to beneficial organisms such as pollinators, Earth worms and microbes.

8. Some Issues in the CA Adoption

8.1. Residue Competition

Most drylands areas require crop residues to use as livestock feed, energy sources, or material to be used in buildings; therefore, it is not easy to keep residues on fields. This restrains one of the most important aspects of CA.

8.2. Knowledge and Start up Investment

Conservation agriculture may be considered as a shift that needs additional machinery like zero-till seeders, as well as know-how of integrated techniques. The farmers might not have access to these resources and technical training especially those who are resource poor farmers (Lee et al., 2022)

8.3. Short-term Yield uncertainty

In the first years of CA adoption farmers might experience stagnating or falling yields

9. Conclusion

Conservation Agriculture offers a practical and sustainable path forward for managing land and building climate resilience, especially in vulnerable dryland regions. By focusing on key principles like minimal soil disturbance, maintaining continuous soil cover, and rotating crops, CA helps tackle pressing challenges such as water scarcity, soil degradation, and poor agricultural productivity. One of its major strengths lies in improving SOC levels achieved through more biomass input, less erosion, and stronger soil structure. Over time, carbon becomes more stable in the soil, which not only boosts soil health but also improves its ability to retain moisture and support consistent crop yields. These benefits are vital for millions of smallholder farmers who depend on dryland farming for their livelihoods.

Beyond this, CA brings added advantages like better nutrient cycling, enhanced biodiversity, and lower greenhouse gas emissions, making it a truly climate-smart farming approach. However, widespread adoption is still a challenge. Farmers often face hurdles such as competition for crop residues, limited access to suitable tools, lack of training, and weak institutional backing. To overcome these, we need a collaborative effort—stronger connections between research and extension services, hands-on training tailored to farmers, better access to appropriate technologies, and policies that encourage long-term sustainability. Most importantly, CA practices must be adapted to fit the local environment, economy, and culture to ensure they are effective and embraced by farming communities.

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