Egypt. J. Soil Sci. **Vol. 65**, No. 4, pp: 1855-1871 (2025)

Egyptian Journal of Soil Science
http://ejss.journals.ekb.eg/

Transforming Agriculture in Global Drylands by Adopting Negative Emission Technology and Restoring Soil Health

Rattan Lal

Cfaes Rattan Lal Center for Carbon Management and Sequestration, The Ohio State University, Columbus, OH 43210, USA

GLOBAL drylands (GDLs), covering ~41.3% of the Earth's land surface, have low soil moisture availability and their soils are prone to degradation and desertification. The low agronomic yield of crops in GDL is attributed to harsh environmental conditions, degraded/depleted soils, and limited water supply. Yet, upscaling of proven best management practices (BMPs), fine-tuned for soil/site-specific situations, can enhance productivity and promote sustainable agriculture. Soils of dryland ecosystems also have a large potential to sequester atmospheric CO_2 as soil inorganic carbon (SIC) and soil organic carbon (SOC). In general, stock of SIC in GDLs is more than that of SOC. With upscaling of BMPs, GDLs can be transformed from being a source to a major sink of atmospheric $CO_{2.}$ Sequestration of SIC in drylands occurs through autotrophic microbial pathways, formation of secondary carbonates, and leaching of bicarbonates in irrigated ecosystems. Sequestration of SOC occurs through increasing input of biomass C, conserving soil and water, and decreasing risks of soil degradation and desertification. The rate and magnitude of sequestration of SOC and SIC can be increased through upscaling of BMPs including conservation agriculture, cover cropping, afforestation, and integration of crops with trees and livestock .Policies are needed at local, state and national level to promote adoption of BMPs through payments for ecosystem services and other incentive measures.

Keywords: Global drylands, Carbon farming, Dryland agriculture, Negative emission technology, Resource use efficiency.

I. Introduction

Global drylands (GDLs) cover ~41.3% of the Earth's land surface or 62 m km^2 and represent the world's largest biome (Garcia-Palacios et al., 2019) that support a large and growing population (Devkota et al., 2025). Population of GDLs represent 30.8% of the world population (> 2.3 B) (Wong et al., 2023), and it is projected to reach 5 B by 2100. GDLs are also dominant drivers of the global biogeochemical cycling (Osborne et al., 2022), especially the carbon (C) cycle (Lal, 2019). GDLs cover a large area in Sub-Saharan Africa (SSA), Middle East and North Africa (MENA) region; South Asia (SA), Central Asia (CA) and North Asia (NA), and other regions. GDLs are expanding because of climate change, and the area may increase by about 10% by 2100 (World Atlas of Desertification, 2025). Dryland expansion is occurring in diverse regions, including western U.S., Brazil, Europe, Asia and Central Africa. Under the projected climate change, 3% of the world's humid areas may be converted to drylands (UNCCD, 2024). Thus, the risks of soil degradation are also increasing (Lewin et al., 2024). Agronomic yield of crops in GDLs is low and faces many challenges, especially those affecting small holder farming systems (Stringer et al., 2017).

The large land mass of arid and semi-arid biomes are characterized by harsh environmental conditions, comprising of depleted soils, low precipitation and extremely high evapo-transpiration. Thus, these regions have a negative soil moisture budget and a short growing season for crops. Agricultural productivity of GDLs is limited by a combination of drought stress, heat wave and saline conditions. Most of the crop production in GDLs is dryland farming dependent on natural rainfall which ranges from 200 to 500mm per annum. The predominant factors which limit agronomic productivity of GDLs are: low rainfall, low soil water storage and frequent drought stress, accelerated soil erosion by water and wind, high soil salinity, and low soil biodiversity (Zarea, 2011).

Soil degradation and land desertification are serious risks to livelihood of billions of people living in GDLs. Thus, improving the agronomic productivity of dryland agriculture (DLA) is critical to achieving food and nutritional security and advancing the Sustainable Development Goals (SDGs) of the United Nations Agenda 2030. Agronomic productivity of DLA is especially low in SSA (Kraaijvangheer et al., 2016) and SA

*Corresponding author e-mail: lal.1@osu.edu
Received: 04/09/2025; Accepted: 13/11/2025
DOI: 10.21608/EJSS.2025.420628.2349

(Shrinivasarao et al., 2012). However, increasing biomass production and crop yield, sequestering carbon (C) in soil and reducing emissions from farm operations can achieve negative emissions in DLA by understanding the processes affecting C dynamics and by adopting negative emission technology. Farm operations which contribute to emission of greenhouse gases (GHGs) in DLA include plowing, the use of nitrogen (N) and other fertilizers, application of herbicides and pesticides, and applying supplemental irrigation. Therefore, it is pertinent to understand the water /fertilizer interaction so as to enhance use efficiency of both in these water and nitrogen limited eco-regions. Attempts at increasing agronomic productivity of DLA since 1960s have involved intensive tillage, increased input of agro-chemicals, and expansion of land areas under supplemental irrigation. However, these practices have aggravated risks of soil degradation by erosion (hydric and aeolian), compaction, salinization, and emission of GHGs while aggravating the risks of drought and reduction in agronomic yield. Consequently, these practices have also decreased the resource use efficiency (RUE) of DLA including those of N, water and energy. The low RUE is being further aggravated by the current and projected anthropogenic climate change or ACC (Yang et al., 2021; Wang et al., 2022; Lin et al., 2024). The ACC-induced changes in temperature and rainfall (amount and pattern) may shorten the growing season, decrease plant available water in the root zone (green water) and aggravate variability in agronomic productivity. Agricultural production in DLA involves a range of commodities: food, feed, fiber, and fuel (bio), and most have low agronomic yield. The key limiting factor in DLA is the low water productivity (Kirkegaard et al., 2014; Palaniappan et al., 2009; Ritchie and Basso, 2008).

Identification of challenges and opportunities to upscaling of some proven best management practices (BMPs) is the first step. In this context the importance of DLA cannot be over-emphasized because of its large land mass and large population. Fixation of C in soils of DLA has multiple benefits, which needs to be explored and harnessed. Production of biofuel, along with sequestration of C in soil has strong implications to mitigation of and adaptation to ACC. Important among sustainable management practices for DLA; including conservation agriculture (CA), cover cropping, biochar, degradable plastic mulches, supplemental irrigation based on the use of drip sub-fertigation in conjunction with the selective use of organic amendments etc., need to be evaluated under site -specific conditions. Therefore, the objective of this article is to deliberate the technological options and strategies to transform DLA from a problem to a solution to advancing food and climate security, as well as advancing SDGs of the U.N. Agenda 2030**.**

II. Carbon Dynamics in Soils of Dryland Agriculture

Soil C in agroecosystems of arid and semi-arid regions play an important role in the global C cycle (Lal, 2019). Total soil C stock of GDLs comprises of soil inorganic C (SIC) and soil organic C (SOC). In contrast to soils of the humid and sub-humid regions, however, soils of DLA contain more SIC than SOC. Therefore, sequestration of atmospheric CO_2 into natural land-based sinks of GDLs is a win-win option to restore soil health while also mitigation of and adaption to the ACC. Soils under DLA can be managed to sequester atmospheric CO_2 both as soil inorganic carbon (secondary carbonates or SIC) and as SOC. The sequestration of C as SIC is primarily an abiotic process. Desert lands are estimated to sequester SIC during the night (see Sectin IIIa) and the magnitude of SIC sequestration can be as much as 1 Pg C/yr (Lal, 2019a; Lal, 2024). Sequestration of SIC may also be facilitated by leaching of bi-carbonates in irrigated lands and formation of secondary carbonates through microbial processes (Lal et al., 2000) as is explained in details in the following sections. The sequestration of SOC can be achieved by creating a positive C budget so that the input of biomass C exceeds the losses due to acceleration soil erosion, microbial decomposition and some leaching especially in irrigated land. The sequestration of SOC is a biotic process and depends on input of biomass carbon (e.g., crop residues, root biomass, compost and other soil amendments and cover cropping). These practices come under the overall topic of Negative Emission Technology (NET), and are explained in the following sections.

III. Adopting Negative Emission Technology (NET) in Dryland Agroecosystems

The argument that achieving C neutrality of agroecosystems is a global goal (Kingwell, 2021; Yang et al., 2022) may not be a good enough target. Agriculture is the only industry which goes beyond neutrality and has a large C negative budget. For example, adoption of proven BMPs can produce as much as 8 ton of biomass (grains plus straw) in DLA, and up to 10 ton of biomass in sub-humid and humid agroecosystems. Based on the hidden C cost of farm operations (Lal, 2004a), net C sequestration in agroecosystems creates a negative soil ecosystem C budget. The negative C budget thus created can be large in DLA(Lal,2004b;Lal et al.,2000) Global agriculture, and especially the DLA, must be strongly C-negative, and this target can be achieved through: i) reducing emissions from farm operations, ii) sequestering C in land-based sinks (SOC and SIC in soil, and C in biomass of plants including trees and perennials), iii) adopting conservation agriculture or CA, iv) managing soil fertility and creating positive nutrient budget by adopting practices of integrated soil fertility management, and vii) alleviating drought by water conservation in the root zone and using supplemental irrigation. Technical potential of C sequestration in soils of the world is estimated at ~2.5 Pg (billion ton) C/yr (Lal et al., 2018) equivalent to around 25% of the fossil fuel emissions, of which about 1 Pg may be in soils of GDLs (Lal et al., 1999). The most limiting factor to achieving this potential is the drought stress, which is aggravated by less rainfall, reduced streamflow and deep and falling groundwater level. Thus, the strategy is to harness C-sink capacity and sequestering C in land-based sinks by improving water use efficiency (WUE) ,producing more crop per drop of water and more productivity per unit input of nitrogenous and other fertilizers. The key issue in DLA is the low RUE which must be enhanced by upscaling of stie specific BMPs.The C sequestration potential (SOC and SIC) can be enhanced by increasing RUE and especially WUE (Monger et al,2015; Jia et al., 2020; Sharfifar et al.,2025; Batool et al.,2024) in DLA.

(1) Sequestration of Soil Carbon in Drylands

Agroecosystems are structurally and functionally diverse but play an important role in determining the trend and variability of the terrestrial C sinks and their ramifications (Smith et al., 2019).Whereas soils of GDLs contain more SIC than SOC, yet the sequestration of SIC in GDLs has not received the attention as that for SOC management because the latter has more beneficial effects on crop growth, and soil properties and processes. Nonetheless, it is important to realize that sequestration of SIC in GDLs is a complex process governed by a wide range of factors (i.e., climate, land use, irrigation, and nutrient management) (Naorem et al., 2022). Soils of GDLs may also fix atmospheric CO_2 by autotrophic microbial pathways. Zheng et al. (2022) observed that the dominant phyla of autotrophic microbes in soils of DLA include Actinobacteria and Proteobacteria and their composition may be correlated with total phosphorus (P) and soil pH. Additionally, the formation of secondary carbonates and leaching of bicarbonates with supplemental irrigation are among mechanisms of soil C sequestration in DLA (Lal et al., 2000). Technical potential of C sequestration in GDLs may be as much as 1 Pg C/yr (Lal et al., 1999; Lal et al., 2000; Lal, 2000; Lal, 2010 a). While additional research is needed to identify site-specific land use and management options, translating known science into action by upscaling and upscaling adoption of proven BMPs is a high priority. Among these BMPs, enhancing WUE is critically important. In this context, sequestration of SOC and SIC in salt affected soils of GDLs is a win-win option (Lal, 2010 b).

(2) Enhancing Water Use Efficiency

Rainfed agriculture is widely practiced in GDLs. Thus, increasing soil water storage, combined with prudent nutrient management, is critical to enhancing RUE and advancing green development in arid regions such as the Loess Plateau of China (He et al., 2021), and elsewhere. The widespread problem of drought is also being aggravated through losses of water by high runoff and evaporation, such as in cultivation of wheat (Mohammadi et al., 2011) and other cereals. Historically, increase of the wheat yield in the world have occurred at 20-88 kg/ha/yr (O'Leary et al., 2018), but ACC can reduce the rate or reverse these gains (Yang et al., 2021) because of changes in temperature and precipitation during the growing season. Thus, the numerous and interacting factors affecting the productivity of DLA must be addressed by adopting innovative options (Chinwamurombe and Matarynka, 2021). In addition to adaptation and mitigation strategies of ACC, WUE must be increased by improving overall water productivity (Li et al., 2020). Some technological options of improving WUE and water productivity are outlined in Fig. 1 including some proven technologies for ecological (rather than sustainable) intensification, increasing SOC and SIC content, conservation of green water in the root zone, genetic improvement and choice of appropriate species suited for GDLs, and management of soil salinity (Fig.1).

It is pertinent to identify site-specific agronomic management (Ritchie and Basso, 2008). Important among BMPs for Vertisols of south/central India (dark clayey soil with high concentration of expanding type clay minerals of a high swell-shrink capacity) has been intensively studied. Pertinent BMPs include retention of crop residues as mulch, combination of farm yard manure (FYM) and chemical fertilizers (Srinivasarao et al., 2012).Among all these straw return/retention to the soil (Guo et al., 2024), preferably as surface mulch, can sustain productivity by strengthening coupled cycling of water, C and nutrients (Lal.2004a;b).

(3) Understanding the Fertilizer-Water Interaction

Soil water availability and WUE also depend on the accessibility of essential plant nutrients. Sustainable management of DLA is aimed at reducing the adverse effects of low and highly variable rainfall, soil degradation by erosion and salinity, and severe nutrient deficiencies (Arrue et al., 2019). In this regard, a judicious input of fertilizer N is necessary to improving crop yield and advancing local food security (Guo et al., 2012).An eefficient utilization of all available nutrient resources is likewise critical for enhancing the productivity and resilience of DLA systems (Wienhold et al., 2000). Because of the strong water-energy nexus in DLA, it is prudent to integrate sustainable water management with renewable energy technology (i.e. solar energy) to reduce emission of GHGs and conserve green water in the root zone. Khattak et al. (2025) advocated the use of strategies which consider water-C dynamics and coupled cycling with water. An effective water use also depends on innovative strategy of salinity management in soil (Panell and Ewing, 2006) which reduces the effective supply of green water and the land area affected is increasing because of ACC and uncertain climate.

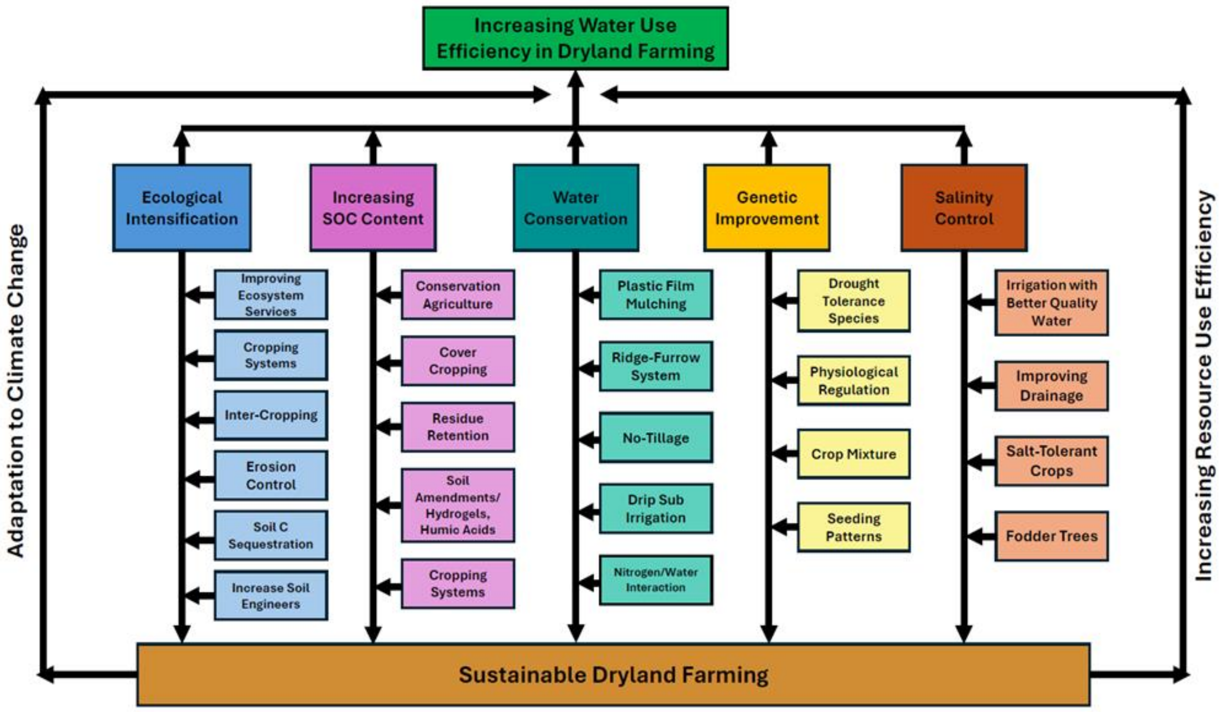

Fig. 1. Factors and practicing for increasing resource (water) use efficiency in dryland farming for adaptation to and mitigation of anthropogenic climate change.

IV. Sustainable Management of Dryland Agriculture

Being the largest biome of the world with >2. 3B people, improving agriculture in GDLs is critical to addressing SDGs of the U.N. There are many options of improving agriculture, but an effective pathway depends on the site-specific situation. Garcia-Palacios et al. (2019) argued that agriculture in these harsh environments must be managed through ecological intensification (EI) rather than sustainable intensification. The strategy is to enhance RUE, decrease leakage of chemicals into the environment, while producing more from less. The strategy of EI is to replace some external agricultural inputs (e.g. fertilizers, pesticides, supplemental irrigation) with practices which optimize ecosystem services (ESs) and enhance crop production. This technology involves low-cost interventions which have big impacts on productivity of DLA (Chander et al., 2019). Some potential technological options are briefly described below;

1- Conservation Agriculture

Whereas DLA is of worldwide importance it has long been neglected (Stewart and Koohafkan, 2004). Yet these lands are under pressure (Isnahane, 2025) because of increasing population. Thus, there is a strong and an urgent need for global evaluation of current and future threats to drylands (Lewin et al., 2024). These threats are being aggravated by land misuse and soil mismanagement which are driven by growing demands of the increasing population. Plow-based conventional tillage, widely practiced in GDL, has adverse effects on soil including crusting, compaction, accelerated erosion, decrease in water infiltration, and increase in drought stress, high soil surface temperature, and decline in soil physical health. Thus, there is a growing interest in adoption of system-based CA in GDLs (Serraj and Siddique, 2012). The latter involves several pillars including: i) elimination of moldboard plowing, ii) use of crop residue mulch, iii) adoption of complex rotations, iv) using integrated soil fertility management options, and v) combining crop production with trees and livestock (Lal, 2015) (Figure 2).

Examples of benefits of CA on soil properties and productivity in diverse agroecosystems of DLA are outlined in Table 1. References collated and cited in Table1 are from diverse agro-ecoregions. These are examples of the applicability of CA in diverse soils, climate, cropping systems, and land scape. Furthermore, the references cited also show the benefits of CA beyond agronomic yield. Specific practices of CA include reduced or no-till, crop residue retention, diverse crop rotations, these practices lead to soil and water conservation, SOC sequestration, productivity gains, yield stability and increase in profitability. Examples cited in Table 1 indicate that is a scale natural practice and is applicable to small, medium and large farms.

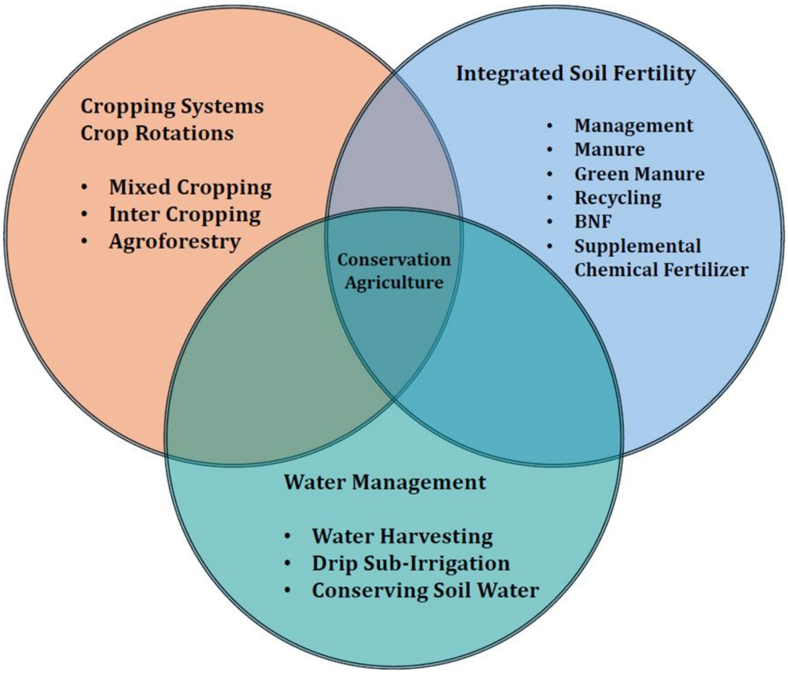

Fig. 2. Components and pillars of conservation agriculture involving water and soil fertility management along with complex cropping systems and crop rotations.

Table 1. Some examples of positive impacts of conservation agriculture in rainfed farming in global drylands.

Region/Location	Crop	Technology and Its Impact	Reference
Central Asia	-	Crop residue retention	Kenzier et al. (2012)
China	Maize-Wheat	Straw retention increased yield and protein yield by 1-4 and 24.0% respectively by NPS treatment	Guo et al. (2024)
China	Maize	NT with plastic mulching increased yield	Dai et al. (2021)
Pakistan	Diverse	NT reduced cumulative CO_2 flow and increased SOC sequestration	Wang et al. (2020)
China	-	NT with residue retention improved SOC storage	Rehman et al. (2023); Wang et al. (2020)
Northern Great Plains, USA	Wheat, Barley	NT enhanced soil health and sustained crop yield	Sainju (2021)
Pakistan, Punjab	Wheat, Mung bean	NT with legume crop rotation improved SOC storage	Naz et al. (2022)
China	Wheat	Rotational NT conserved water and improved yield	Zhang et al. (2021)
South Africa	-	Wholistic approach to farming	Strauss et al. (2021)
China	-	NT is a climate smart agriculture	Lin et al. (2024)
India	-	Conservation tillage improved soil physical health	Indoria et al. (2017)
China	Corn	CA practices had the greatest yield benefit	Ren et al (2023)

In drylands of India, for example, Indoria et al. (2017) observed that CA can improve soil physical properties. As documented by the examples in Table 1, benefits of CA have been reported in Central Asia (Kienzler et al., 2012), South Africa (Strauss et al., 2021), China (Dai et al., 2021; Wang et al., 2020; Zhang et al., 2021) and elsewhere (Zarea, 2011; Rehman et al., 2023; Chizari and Ommani, 2009). As a component of sustainable agriculture, CA is normally practiced in conjunction with crop residue mulch, animal manure, green manure, legume-based rotation (Chizari and Ommani, 2009), and of course use of cover crops. Properly implemented, CA is a climate-smart or better a climate-resilient agriculture.

2- Cover Cropping

A cover crop is the one that is grown during the off-season for its biomass to cover the ground rather than for its grains. Historically DLA has relied heavily on the summer fallow to conserve water, but these regions can benefit from growing a cover crop rather than keeping the ground under bare fallow. Indeed, cover cropping can have numerous beneficial impacts on soil health and on productivity of the following grain crop in DLA. Table 2 lists some examples where the effectiveness of soil and water conservation and nutrient management practice has been enhanced by cover cropping.

Table 2. Impact of cover cropping on soil health and agronomic productivity.

Region/Land	Cover Crop	Food Crop	Impact	Reference
Texas USA	Crimson clover, hairy vetch, wheat pea	Cotton	24-48% higher SOC content	Hux et al. (2023)
Southeastern Great Plains, USA	-	-	Improved sustainability and SOC accumulation	Ghimire et al. (2018)
Northern Great Plains, USA	-	Wheat, Barley	Less available water and immobilized N	
Colorado Plateau, USA	-	Wheat	Cover	Eash et al. (2021)
Southern Great Plains, USA	-	Wheat, sorghum		Simon et al. (2022)

General benefits of cover cropping on soil and agronomic productivity have been reported by Simon et al. (2024) and Kasper and Siinger (2024). The available literature shows that cover cropping enhances the effectiveness of CA even under water-liming DLA by restoring soil functions such as high SIC/SOC and total N content (Hux et al., 2023). Replacing fallow in the previous dry season by cover cropping (Williams et al., 2022) in DLA can also sequester C and generate another income stream for farmers (refer section V). Thus, an important strategy for DLA has been to replace summer fallow by growing a cover crop in the off-season to provide additional soil health benefits (Simon et al., 2022). Nonetheless, in some cases, less available soil water and immobilization of N by cover cropping can reduce crop yield, such as that of wheat (Eash et al., 2021).

3- Biochar

Positive effects of biochar on soil functions and agronomic productivity have been documented on depleted and degraded soils of the tropics (Li et al., 2024; Table 3). Whereas, use of biochar has been widely promoted for soils of low fertility and acidic pH in humid and sub-humid agroecoregions (Lehmann and Rondon, 2006). Despite its positive effects,its use is not common in DLA. One of the constraints in DLA is the lack of an abundant supply of biomass to produce biochar. Therefore .growing crops for biofuel production and pyrolyzing the biomass is an option to produce biochar as a byproduct of generating bioenergy. In China, Chen et al. (2015) suggested growing of Camelina (*Camelina sativa*) for biofeedstock production. Biochar feedstock can involve use of agricultural by-products and other waste which have limited uses (i.e., rice husk, municipal solid waste). An important option is to use biochar in combination with chemical fertilizers that may save fertilizer use by enhancing the use efficiency of fertilizers and save irrigation water by improving water conservation, use of biochar can improve soil physical, chemical and biological properties (Table 3).

Table 3. Positive effects of biochar application on soil health and agronomic productivity in global drylands.

Location	Crop	Soil	Impact	Reference
North China Plains	Maize	Inceptisol	Biochar compound fertilizers can substitute chemical fertilizer	Zheng et al. (2017)
Iran	Nigella, Sativa	Low SOC	Biochar with NT improved oil yield by 23-29%	Kiani et al. (2024)
Southwestern Australia	What	-	P fertilizer saving of 50% and yield increase of 10%	Blackwell et al. (2010)
Pakistan	-	Sub-tropical	What straw biochar increased recalcitrant SOC content	Sultan et al. (2019)
India	-	Alfisol	Biochar improved soil physical, chemical and biological environment	Pandian et al. (2016)
Pakistan	Legume-cereal	-	Increased crop yields	Azeem et al. (2019)

4- Soil Fertility Management

There exists a strong water-nutrient interaction in crops grown under DLA. Over and above the adoption of water-saving practices, RUE for crop production in semi-arid regions can also be enhanced by judicious management of plant nutrients. Indeed, grain yield of crops under DLA can be improved by promoting synergy between genotype, environment and management. A balanced application of macronutrients (N, P, K, Ca, Mg) is essential to improving soil fertility and crop nutrition (Ryan, 2020). In the Loess Plateau of China, Liu et al. (2025) observed that total seasonal precipitation and N fertilizer placement depth (35 cm in drier and 25 cm in wetter season) improved grain yield of maize. Jia et al. (2020) observed that ridge-furrow planting with 200 kg/ha of N application improved RUE and maize yield. In southern USA, Sainju (2024) reported that cultivation of wheat with CA at higher rate of N fertilization (100kg N/ha) enhanced SOC and total N content of soil. Bouras et al. (2023) reported that P application minimized the adverse effects of high salinity. Application of micro-nutrients is also critical for enhancing crop yield and productivity in DLA. Melash et al. (2023) observed that foliar-based iron (Fe) application improved the grain yield of durum wheat from 2.0 to 3.2 Mg/ha. Rather than using chemical fertilizers, soil fertility can also be managed by organic farming. In South India, Palaniappan et al. (2009) recommended inter-cropping systems along with green manuring with sunhemp for increasing soil fertility. In China, Wang et al. (2024) observed that agriculture based on organic farming can advance "dual-carbon" goals and promotion of sustainable agriculture development. Similarly, lignite-derived humic amendments are also being considered for improvement of DLA (Ma et al., 2022). In the eastern Washington state of USA, Wachter et al. (2019) reported that integrating perennial crops (such as alfalfa and forage grasses) into organic farming systems can improve soil quality, profitability and supply of N to succeeding grain crops.

5- Plastic Film and Gravel Mulching

Conserving soil water in the root zone by reducing evaporation and controlling weeds lead to a wide spread use of plastic film mulching under diverse biophysical environments of the tropics , such as for rice and maize production in China. Table 4). However, most studies on biochar and its impact on agronomic yield have been done in China and elsewhere in North Asia. In this context, it is pertinent to note most studies cited in Table 4 are from China and neighbouring counties.

Table 4. Soil-water conservation by use of plastic film mulch.

Location/Region	Crop	Impact	Reference
Loess Plateau of China	-	Ridge-furrow system with plastic mulching improved yield	Li et al. (2020)
Loess Plateau of China	Wheat	Film mulching is a carbon-friendly technology	Xue et al. (2018)
Northeast China	Maize	Increased maize productivity and sustainability	Hossain et al. (2022)
China	-	Microplastic improved soil multifunctionality	Wang et al. (2024)
China	Rice	Direct seeded rice production is improved by biodegradable film mulching	Gao et al. (2023)
Loess Plateau, China	-	Increased yield by 11% and net economic return by 12%	He et al. (2018)

It is important to note that all examples listed in Table 4 regarding the use of plastic film mulching are from China and especially from the North China Plains and the Loess Plateau regions. Whereas the positive effects on water conservation and weed control are notable, micro plastic pollution has become a serious global issue and DLA managed with plastic film mulching is one cause of this problem. Thus, degradable plastic film (Gao et al., 2023) can have an important role in improving DLA in water-scarce areas. Similar to plastic mulch, gravel mulch is also used widely in China where it has been used for centuries. Among benefits of gravel mulch are conservation of water, moderation of soil temperature, and reducing risks of aeolian and hydric erosion, and thus increase in agronomic productivity (Wu et al., 2024). However, long term use of gravel much can also cause soil degradation by decreasing SOC content and other properties (Qi et al., 2025).

6-Supplemental Irrigation and water management

Increasing water productivity is critical to enhancing agronomic productivity in GDLs in regions with annual rainfall of 200-500 mm and necessitates integration of scientific technologies with indigenous farming methods (Inanga et al., 2005), especially with regard to water conservation and management. In DLA, supplemental irrigation has a strong effect on agronomic productivity and quality of some products. Some examples of the use of supplemental irrigation on increasing productivity are outlined in Tables 5 and 6.

Table 5. Impacts of supplemental irrigation on productivity and secondary salinization.

Region	Effect	Reference
Global	Irrigation increased grain yield by 142%, and net energy gain by 152%	Nasseri (2025)
NSW, Australia,		Kadkoi et al. (2020)
Texas High Plains USA	Center pivot irrigation declined ground water supply	Bhandari et al. (2022)

Table 6. Some examples of supplemental irrigation in improving productivity of dryland agriculture.

Region/County	Crop	Impact	Reference
Global	Cereals	Irrigation increased grain yield by 142%	Nasserai (2025)
Iran	Wheat	Stable yield performance of irrigation with saline water	Mohammadi et al. (2011); Bouras et al. (2023)
India	Cereals	Drip sub-fertigation	Singh et al. (2022)
India	Cereals	Sustainable water management to explore water-energy nexus	Khattak et al. (2025)

Yet, traditional irrigation can improve agronomic productivity. Based on meta-analysis of 628 observations on energy inputs and production inputs, Nasseri (2025) observed that irrigation increased grain yield by 142%, energy input by 120%, energy output by 133%, and net energy gain by 152% compared with unirrigated control. Additionally, with average application of 4134m^3/ha (41.3cm of water), energy use was higher by 118% in human labor, 87% in machinery, 85% in N fertilizer, 61% in fuel, 43% in seed, and 116% in herbicides compared with unirrigated land. In the irrigated perimeter of the Tagia region of Morocco, Bouras et al. (2023) observed that P fertilization can mitigate some negative effects of irrigation with the saline water. For dryland Alfisols (Red Soils) of South India, Palaniappan et al. (2009) suggested pitcher-pot irrigation for horticultural crops (i.e., amla, sapola, and mango) as a low-cost drip irrigation system. Supplemental irrigation must be upscaled in SSA where there is a strong need to improve crop yield in drought-prone regions. Despite numerous benefits of supplemental irrigation, it increases risks of salinization. Excessive use of water can lead to build up of salts in the surface horizon and causing secondary salinization. As much as 20% of irrigated croplands in DLA has been salinized. There are also some implications of salinity to human health (Jardine et al., 2007). Excessive irrigation can also lead to water shortage (Lu et al., 2025), and rapid decline in water table as widely observed in Punjab states of India and Pakistan, and Ogalala aquifer in USA (Nilahayane et al., 2023). Thus, limited irrigation is also recommended (Bhandari et al., 2022).

7- Using Amendments for Soil Water Conservation and Management

In addition to irrigation, conservation of water in the root zone is critical to enhancing water productivity. The WUE Initiative in Australia was aimed at increasing WUE of grain-based production systems by 10% in areas with annual rainfall of 300 to 700mm. The soil application of acrylamide-based hydrogels can also enhance soil water conservation in DLA (Muhammad et al., 2025). Nackley et al. (2024) assessed the benefits of Tectonite Dust amendment in central Oregon for increasing soil fertility and water holding capacity, soil health and crop yield by improving structure, nutrient availability and water retention.

8-Seeding Rate and Planting Patterns Such as Ridge Furrow System and Clump Planting

Among agronomic practices, seeding rate and planting patterns strongly affect crop stand and agronomic productivity. For durum wheat, Melash et al. (2023) observed a linear increase in biomass (21.5%) and grain yield (23.5%) with a high seeding rate. For fox millet, Meng et al. (2020) observed that ridge-furrow planting and increasing planting density in furrows increased the grain yield and crop water productivity. Rather than monoculture, maize with peanuts inter-cropping can improve soil fertility, agronomic productivity and C emission efficiency. In dry farming regions of China, Han et al. (2024) observed that maize-peanut rotation inter-cropping advanced SDGs. Rather than a single seedling per hill, bunch planting, growing more seedling at one point, can improve WUE and minimize risks of drought (Stewart, 2004; Unger et al., 2023). Similarly, Lascano and Nelson (2024) recommended that planting dryland crops in a circular pattern would store more water in soil compared with conventional straight rows.

V. Carbon Farming in Dryland Agriculture

The current and projected ACC may lead to changes in rainfall patterns and amount, and increase of evapotranspiration. Thus, adaptation to ACC by improving SOC content and by increasing resilience of crops grown in DLA to abiotic and biotic stresses can improve productivity while improving soil quality (Venkatesarlu and Shaknar, 2012) (Figure 3).

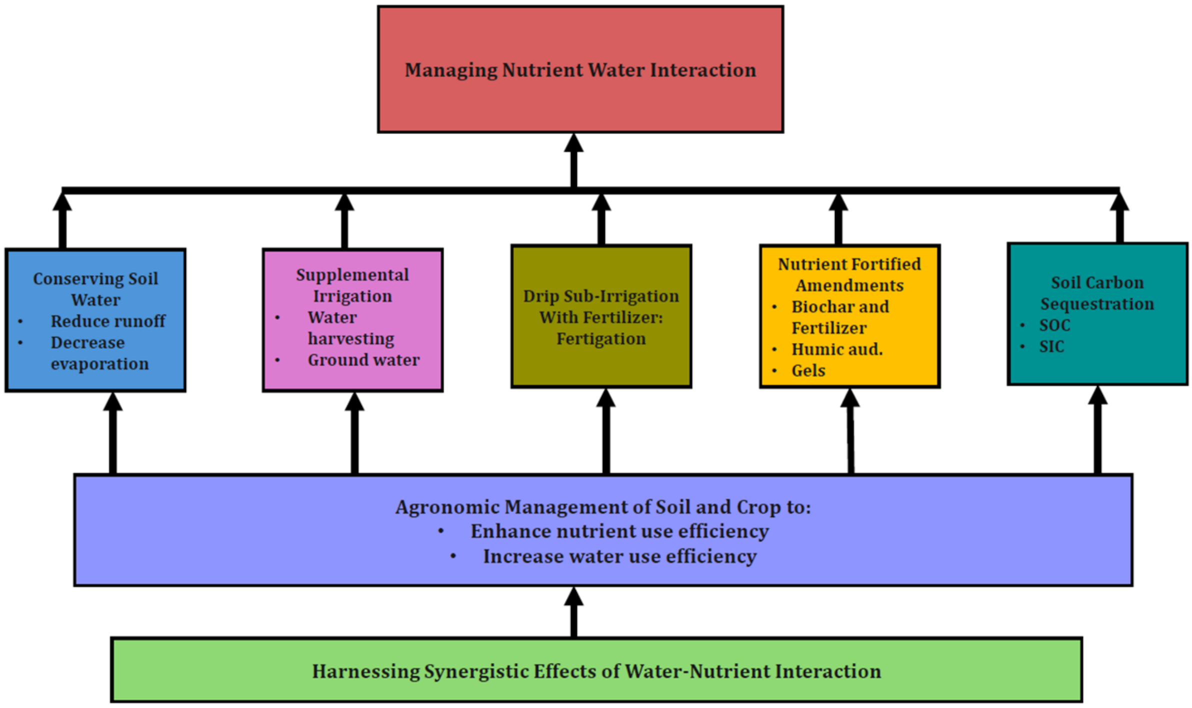

Fig. 3. Managing the water-nutrient interactions under traditional and improved systems by enhancing use efficiency of water, nutrients and other inputs.

The SOC content under DLA is low and regressively declining under traditional systems of cultivation. Low level of SOC content is a yield-limiting factor in GDLs because of low water holding capacity and rather meagre reserves of plant macro and micro-nutrients. In this context, it is pertinent to enhance adaptive capability of crops by improving soil quality and functions which depend on SOC content. Sequestration of atmospheric CO_2 by retention of crop residue as mulch and input of organic amendments (cattle manure) is a land-based solution to restoring soil health. Sequestration of SOC can be achieved by recycling of organic residues as well as afforestation of denuded lands by perennial plants that have deeper and most extensive root system. In semi-arid environment of southern India, Srinivasarao et al. (2012a, b) assessed the mean SOC sequestration of 0.57 Mg C/ha /yr by improved management of Alfisols for production of groundnut. In western Australia, Wocheslander et al. (2016) observed that C sequestration under reforestation was 2.5 Mg/yr over the 22-year life span of tagasaste treatments. Of this, 1.6 Mg C/ha/ yr was in biomass and 0.9 Mg C/ha/ yr in soil to 0.9m depth. A modeling study in Nigeria, Sudan and Argentina by Farage et al. (2007) showed that annual rate of C sequestration ranged from 0.08 to 0.17 Mg C/ha/ yr over the 50-year period. Most effective practices for SOC sequestration included use of farmyard manure or FYM (0.09 Mg/ha/ yr), maintaining trees (0.15 Mg/ha/ yr) and using CA (0.04 Mg/ha/ yr). Based on a study in Western Australia, Hoyle et al. (2013) reported that SOC stock ranged from 33 to 128 Mg/ha, but the attainable capacity was 59 to 140 Mg/ha, which could be achieved within 100 years. Thus, the additional storage capacity of C by as much as 5 to 45 % (7-27 Mg C/ha) can be achieved by adoption of site-specific BMPs. Legume-based rotations can enhance SOC stock in dryland wheat systems of Oregon to offset some of its annual emission (Ramirez et al., 2025). Legume-based rotations can also improve water retention and nutrient cycling (Vanderpol et al., 2022). Grain legumes and dryland cereals (including chickpea, cowpea, common beans, groundnut, lentil, pigeon pea, and soybean) can be grown in rotation with finger millet, pearl millet, and sorghum in drylands of Africa and SA (Kuyah et al., 2023). Controlled grazing and establishing fodder trees can also enhance SOC stock in depleted and degraded soils (Yaebiyo et al., 2024).Some examples of SOC sequestration rate by adoption of BMPs are shown in Table 7.

Table 7. Managing biogeochemistry of soils of arid climate by soil carbon sequestration via adoption.

Country/Region	Carbon Sequestration Rate with Improved Management	Reference
USA	Continuous cropping increased productivity and soil C sequestration at 78 kg C/ha/yr	Robertson et al. (2018)
India	Integrated nutrient management increased soil C sequestration at 287 kg C/ha/yr and rates for different cropping systems ranged from 141 to 287 kg C/ha/yr	Aravindh et al. (2023)
USA	NT did not result in increase in C sequestration and judicious tillage is an option for sustainable production	Wuest et al. (2023)
China	Leguminous grasslands sequestered more SOCK and gramineous grasslands by 0.64 Mg C/ha/yr	Liu et al. (2017)
Australia	Permanent pasture increases deep SOC sequestration over decade or longer	Eyles et al. (2015)
Northwest China	N fertilizer with manure had 3 to 42% lower C footprint than control	Yang et al. (2022)
Central India	Combination of farmyard manure and chemical fertilizers increased SOC stock at the rate of 0.79 Mg C/ha/yr and increased crop yield	Srinivasarao et al. (2012)
Northeast and North China	Soil tillage and fertilization had a strong influence on SOC density	Zhuo et al. (2022)
Western Australia	Roth C model indicated an additional SOC storage capacity of 5-45% (7-27 Mg C/ha) depending on specific land use to 3m depth over 1 year	Hoyle et al. (2013)
Pakistan	Continuous no-till increased SOC and different fractions	Rehman et al. (2023)
China	Input of manure and straw increased different SOC fraction	Qi et al. (2025)

Increasing soil C content, especially SOC, is called C farming when it increases farm income through trade of C credits or via payment of ecosystem services or ESs (Farrell and Vadckattu, 2023; Dumbrell et al., 2016). The idea of C farming is to enable farmers to adapt to ACC (Asseng and Pannell, 2013) by increasing SOC stock which also enhances soil structure and soil nutrients (Zhang et al., 2021) and generates another income stream. However, farming C is a viable option only if farmers are rewarded according to the societal value of C. The low C price such as \$15/MgCO_2e in western Australia (Flugge and Abadi, 2006) and elsewhere may not be adequate to motivate farmers for adopting BMPs. Social value of soil carbon must be assessed and farmers paid accordingly (Lal, 2014). The overall strategy is diversification of cropping system that also influences soil microbial biodiversity and improve soil health (Williams et al., 2023). Leguminous species can sequester more carbon than gramineous species in water-scarce GDLs (Liu et al., 2017).

Researchable Priorities

Despite fragile soils and harsh climate, GDLs have a large potential to advance SDGs of the Agenda 2030 of the United Nations. However, GDLs face a range of natural and anthropogenic challenges (Stringer et al., 2017) which must be addressed. Addressing these challenges will require greater interdisciplinarity and knowledge co-production to advance SDGs (Stringer et al., 2017). The traditional farming systems of DLA must be improved by investment in science and technology that can help sustain farming systems of GDLs (Carberry et al., 2011). GDLs are also vulnerable to degradation even after minor disturbances aggravating challenges to restoration (Sevjcar and Kildisheva, 2017) which must be addressed by research on the following issues:

I. Develop and conduct on-farm validation and testing of soil quality index (SQI) for these fragile soils (Parr and Papendick, 1997) by understanding biogeochemistry of GDLs (Osborne et al., 2022).
II. Establish relationship between SOC stock, water productivity, and yield of diverse crops and eco-regions in site-specific farming systems (Wuest et al., 2023; Robertson et al., 2018).
III. Evaluate water footprint and water productivity of diverse farming systems and eco-regions using innovative drip irrigation systems (Singh et al., 2022).
IV. Assess changes in soil biotic activity and diversity (macro, meso, and micro-organisms as soil engineers) under diverse farming systems (Jouquet et al., 2018).
V. Identify plant species turnover in global drylands in relation to climate changes and determine thresholds in environmental conditions driving shifts t in plant species
VI. Develop and test techniques of ecological intensification under diverse eco-regions of GDLs (Garcia - Palacias et al., 2019).

VII. Evaluate practical techniques of management of secondary salinization (Pannell and Ewing, 2006), and minimize risks of salt build up in the root zone with focus on management of soil physical properties and processes (Indoria et al., 2017)
VIII. Identify industrial by-products which can be used as soil amendments in DLA (Ma et al., 2022) such as hydrogels (Muhammed et al., 2025).

IX. Assess water-nutrient-C nexus or interplay in DLAs (Khattak et al., 2025) to enhance RUE and overcome challenges to advancing agricultural sustainability in water -limited environments through restoration of soil health and water conservation (Nilahyane et al., 2023).

IX. Develop and assess measurement and monitoring to reduce risks of desertification (Winslow et al., 2011).
X. XI. Establish measurement systems to quantify changes in climate under DLA systems (Huang et al., 2017) and to promote technology for adaptation and mitigation of climate change (Kakuman et al., 2016).
XI. XII. Develop strategy and legal options to minimize risks of plastic pollution in GDLs (Zhang et al., 2024).
XII. Identify mechanisms (SOC vs. SIC) of C sequestration (Eyles et al., 2015) and how to upscale adoption of BMPs.
XIII. Promote adoption of BMPs in Sub-Saharan Africa to enhance productivity (Kurkulasuirya et al., 2006).
XIV. Site-specific identification of crops and cropping systems, both for dryland and irrigated farming, leading to soil C sequestration through regenerative agricultural systems for reducing environmental footprints while enhancing soil health (Xie et al., 2025).
XV. Implementation of Soil Health Act at county, state and national level to reward farmers for ecosystem services and respect-rights-of soils and rights-of-nature (Lal, 2019)

Conclusions

GDLs and DLA, being have a vast potential to enhance agronomic production advance SDGs. Despite the large potential, DLA has not received the attention that it deserves. Whereas there is a need for additional research in soil and crop management of DLA, a high priority must also be given to upscaling of proven BMPs such as CA, supplemental irrigation, soil fertility improvement, development and identification of improved varieties and species among others. Carbon farming, growing SOC and SIC in soil as a commodity that can also create another income stream for farmers is a high priority. Farmers must be paid according to the societal value of carbon and site-specific situation which in mid 2020s is about US$50 per credit. Payment for ESs can be a part of Soil Health Act implemented at state, national and international level.

List Of Abbreviations

GDL Global Drylands
DLA Dryland Agriculture
RUE Resource Use Efficiency
ACC Anthropogenic Climate Change
GHG Greenhouse Gas
BMP Best Management Practices
C Carbon
SDGs Sustainable Development Goals
SSA Sub-Saharan Africa
SA South Asia
CA Conservation Agriculture
NET Negative Emission Technology
ESs Ecosystem Services
FYM Farmyard Manure

References

Aravindh, S., Chinnadurai, C., Malathi, P., Sanjivkumar, V., Pandian, P. S., Thiyageshwari, S., & Balachandar, D. (2023). Nutrient management and cropping pattern influence the carbon sequestering ability of semi-arid tropical soils. *Environmental Sustainability*, *6*(1), 87-98.

Arrúe, J. L., Álvaro-Fuentes, J., Plaza-Bonilla, D., Villegas, D., & Cantero-Martínez, C. (2019). Managing Drylands for Sustainable Agriculture. In M. Farooq & M. Pisante (Eds.), *Innovations in Sustainable Agriculture* (pp. 529–556). Springer International Publishing. https://doi.org/10.1007/978-3-030-23169-9_17

Asseng, S., & Pannell, D. J. (2013). Adapting dryland agriculture to climate change: Farming implications and research and development needs in Western Australia. *Climatic Change*, *118*(2), 167–181. https://doi.org/10.1007/s10584-012-0623-1

Batool, M. Chiacek, L., and R.S. Algahandi 2024. Soil inorganic carbon formation and sequestration of secondary carbonates in global carbon pools: A Review. Soil Systems 2024, 8(1), 15. https://doi.org/10.3390/soilsystems.0010015.

Bhandari, K. B., Acosta-Martínez, V., Pérez-Guzmán, L., & West, C. P. (2022). Soil health within transitions from irrigation to limited irrigation and dryland management. *Agricultural & Environmental Letters*, *7*(1), e20077.

Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2010). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: An agronomic and economic perspective. *Soil Research*, *48*(7), 531–545. https://doi.org/10.1071/SR10014

Bouras, H., Mamassi, A., Devkota, K. P., Choukr-Allah, R., & Bouazzama, B. (2023). Integrated effect of saline water irrigation and phosphorus fertilization practices on wheat (*Triticum aestivum*) growth, productivity, nutrient content and soil proprieties under dryland farming. *Plant Stress*, *10*, 100295. https://doi.org/10.1016/j.stress.2023.100295

Carberry, P. S., Bruce, S. E., Walcott, J. J., & Keating, B. A. (2011). Innovation and productivity in dryland agriculture: A return-risk analysis for Australia. *The Journal of Agricultural Science*, *149*(S1), 77–89. https://doi.org/10.1017/S0021859610000973

Chander, G., Reddy, T. Y., Kumar, S., Padmalatha, Y., Reddy, S., Adinarayana, G., Wani, S. P., Reddy, Y. V. M., & Srinivas, K. (2019). Low-cost interventions for big impacts in dryland production systems. *Archives of Agronomy and Soil Science*, *65*(9), 1211–1222. https://doi.org/10.1080/03650340.2018.1560426

Chen, C., Bekkerman, A., Afshar, R. K., & Neill, K. (2015). Intensification of dryland cropping systems for bio-feedstock production: Evaluation of agronomic and economic benefits of *Camelina sativa*. *Industrial Crops and Products*, *71*, 114–121.

Chimwamurombe, P. M., & Mataranyika, P. N. (2021). Factors influencing dryland agricultural productivity. *Journal of Arid Environments*, *189*, 104489.

CHIN. *Fresenius Environmental Bulletin*, *29*(9), 7219-7227.

Chizari, M., & Ommani, A. R. (2009). The analysis of dryland sustainability. *Journal of Sustainable Agriculture*, *33*(8), 848-861.https://doi.org/10.1016/j.indcrop.2015.02.065.

Dai, Z., Hu, J., Fan, J., Fu, W., Wang, H., & Hao, M. (2021). No-tillage with mulching improves maize yield in dryland farming through regulating soil temperature, water and nitrate-N. *Agriculture, Ecosystems & Environment*, *309*, 107288. https://doi.org/10.1016/j.agee.2020.107288

Devkota, K. P., Devkota, M., Mabhaudhi, T., Nangia, V., Attaher, S., Boroto, R. J., ... & Siddique, K. H. (2025). A blueprint for building resilience and food security in MENA and SSA drylands: Diversifying agriculture with neglected and underutilized species. *Food and Energy Security*, *14*(1), e70046.

Dumbrell, N. P., Kragt, M. E., & Gibson, F. L. (2016). What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. *Land Use Policy*, *54*, 29–37. https://doi.org/10.1016/j.landusepol.2016.02.002

Eash, L., Berrada, A. F., Russell, K., & Fonte, S. J. (2021). Cover crop impacts on water dynamics and yields in dryland wheat systems on the Colorado Plateau. *Agronomy*, *11*(6), 1102.

Eyles, A., Coghlan, G., Hardie, M., Hovenden, M., & Bridle, K. (2015). Soil carbon sequestration in cool-temperate dryland pastures: mechanisms and management options. *Soil Research*, *53*(4), 349-365.

Farage, P. K., Ardö, J., Olsson, L., Rienzi, E. A., Ball, A. S., & Pretty, J. N. (2007). The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modelling approach. *Soil and Tillage Research*, *94*(2), 457–472. https://doi.org/10.1016/j.still.2006.09.006

Farrell, M., & Vadakattu, G. (2023). Growing soil organic carbon in dryland agricultural systems. *Microbiology Australia*, *44*(1), 18-21.

Flugge, F., & Abadi, A. (2006). Farming carbon: An economic analysis of agroforestry for carbon sequestration and dryland salinity reduction in Western Australia. *Agroforestry Systems*, *68*(3), 181–192. https://doi.org/10.1007/s10457-006-9008-7

Gao, H., Liu, Q., Gong, D., Liu, H., Luo, L., Cui, J., ... & Mei, X. (2023). Biodegradable film mulching reduces the climate cost of saving water without yield penalty in dryland rice production. *Resources, Conservation and Recycling*, *197*, 107071.

García-Palacios, P., Alarcón, M. R., Tenorio, J. L., & Moreno, S. S. (2019). Ecological intensification of agriculture in drylands. *Journal of arid environments*, *167*, 101-105.

Ghimire, R., Ghimire, B., Mesbah, A. O., Idowu, O. J., O'Neill, M. K., Angadi, S. V., & Shukla, M. K. (2018). Current status, opportunities, and challenges of cover cropping for sustainable dryland farming in the Southern Great Plains. *Journal of Crop Improvement*, *32*(4), 579–598. https://doi.org/10.1080/15427528.2018.1471432

Guo, J., Jiang, P., Zhang, J., Dong, S., Tian, W., Li, J., Li, F., Lv, J., Yao, Y., Hou, Y., Wu, S., Shaaban, M., Huang, M., & Li, Y. (2024). Straw Return Substituting Potassium Fertilizer Increases Crop Yield, Efficiency, and Quality in Maize-Wheat Rotation System. *Agronomy*, *14*(6), 1266. https://doi.org/10.3390/agronomy14061266

Guo, S., Wu, J., Coleman, K., Zhu, H., Li, Y., & Liu, W. (2012). Soil organic carbon dynamics in a dryland cereal cropping system of the Loess Plateau under long-term nitrogen fertilizer applications. *Plant and Soil*, *353*(1), 321–332. https://doi.org/10.1007/s11104-011-1034-1

Han, F., Javed, T., Hussain, S., Guo, S., Guo, R., Yang, L., Liu, X., Cai, T., Zhang, P., Jia, Z., Shah, A. A., Chen, X., & Ren, X. (2024). Maize/peanut rotation intercropping improves ecosystem carbon budget and economic benefits in the dry farming regions of China. *Journal of Environmental Management*, *353*, 120090. https://doi.org/10.1016/j.jenvman.2024.120090

He, G., Wang, Z., Cao, H., Dai, J., Li, Q., & Xue, C. (2018). Year-round plastic film mulch to increase wheat yield and economic returns while reducing environmental risk in dryland of the Loess Plateau. *Field Crops Research*, *225*, 1-8.

HE, G., WANG, Z., SHEN, J., CUI, Z., & ZHANG, F. (2021). TRANSFORMATION OF AGRICULTURE ON THE LOESS PLATEAU OF CHINA TOWARD GREEN DEVELOPMENT. *Frontiers of Agricultural Science & Engineering*, *8*(4), 491–500. https://doi.org/10.15302/J-FASE-2021428

Elouafi, I. (2025). Drylands under pressure: Science and solutions for global stability. *Science, 387*(6735), eadv6563. DOI: 10.1126/science.adv6563.

Hossain, M. E., Zhang, Z., Dong, W., Wang, S., Liu, M., Liu, E., & Mei, X. (2022). Plastic film mulching improved maize yield, water use efficiency, and N use efficiency under dryland farming system in northeast China. *Plants*, *11*(13), 1710.

Hoyle, F. C., D'Antuono, M., Overheu, T., & Murphy, D. V. (2013). Capacity for increasing soil organic carbon stocks in dryland agricultural systems. *Soil Research*, *51*(8), 657-667.

Hoyle, F. C., D'Antuono, M., Overheu, T., & Murphy, D. V. (2013). Capacity for increasing soil organic carbon stocks in dryland agricultural systems. *Soil Research*, *51*(8), 657-667.

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., ... & Wang, G. (2017). Dryland climate change: Recent progress and challenges. *Reviews of Geophysics*, *55*(3), 719-778.carbon stocks in dryland agricultural systems. *Soil Research*, *51*(8), 657-667.

Hux, B. A., DeLaune, P. B., Schirmarcher, M. T., Gentry, T. J., & Mubvumba, P. (2023). Winter cover crop impact on soil health in Texas Rolling Plains dryland cotton. *Agrosystems, Geosciences & Environment*, *6*(1), e20352. https://doi.org/10.1002/agg2.20352

Inanaga, S., Eneji, A. E., An, P., & Shimizu, H. (2005). A recipe for sustainable agriculture in drylands. In K. Omasa, I. Nouchi, & L. J. De Kok (Eds.), *Plant Responses to Air Pollution and Global Change* (pp. 285–293). Springer Japan. https://doi.org/10.1007/4-431-31014-2_32

Indoria, A. K., Rao, C. S., Sharma, K. L., & Reddy, K. S. (2017). Conservation agriculture–a panacea to improve soil physical health. *Current science*, 52-61.

Jardine, A., Speldewinde, P., Carver, S., & Weinstein, P. (2007). Dryland salinity and ecosystem distress syndrome: human health implications. *EcoHealth*, *4*(1), 10-17.

Jia, Q., Xu, R., Chang, S., Zhang, C., Liu, Y., Shi, W., Peng, Z., & Hou, F. (2020). Planting practices with nutrient strategies to improves productivity of rain-fed corn and resource use efficiency in semi-arid regions. *Agricultural Water Management*, *228*, 105879. https://doi.org/10.1016/j.agwat.2019.105879

Jouquet, P., Chaudhary, E., & Kumar, A. R. V. (2018). Sustainable use of termite activity in agro-ecosystems with reference to earthworms. A review: Sustainable use of termite activity in agro-ecosystems with reference to earthworms: a review. *Agronomy for Sustainable Development*, *38*(1), 3.

Kadkol, G., Smith , A., Cullis, B., & Chenu, K. (2020). Variation in Australian durum wheat germplasm for productivity traits under irrigated and rainfed conditions: Genotype performance for agronomic traits and benchmarking. *The Journal of Agricultural Science*, *158*(6), 479–495. https://doi.org/10.1017/S0021859620000817

Kakumanu, K. R., Kuppanan, P., Ranganathan, C. R., Shalander, K., & Amare, H. (2016). Assessment of risk premium in farm technology adoption as a climate change adaptation strategy in the dryland systems of India. *International Journal of Climate Change Strategies and Management*, *8*(5), 689-717.

Kaspar, T. C., & Singer, J. W. (2011). The use of cover crops to manage soil. *Soil management: Building a stable base for agriculture*, 321-337. https://doi.org/10.2136/2011.soilmanagement.c21.

Kemanian, A. R., & Stöckle, C. O. (2010). C-Farm: A simple model to evaluate the carbon balance of soil profiles. *European Journal of Agronomy*, *32*(1), 22–29. https://doi.org/10.1016/j.eja.2009.08.003

Khattak, W. A., Sun, J., Zaman, F., Jalal, A., Shafiq, M., Manan, S., ... & Du, D. (2025). The role of agricultural land management in modulating water-carbon interplay within dryland ecological systems. *Agriculture, Ecosystems & Environment*, *378*, 109315

Kiani, H., Khalesro, S., Mokhatssi-Bidgoli, A., & Sharifi, Z. (2024). Biochar and conservation tillage affect the agronomic performance and fatty acid composition of Nigella sativa L. under both irrigated and dryland conditions. *Scientific Reports*, *14*(1), 2648.

Kienzler, K. M., Lamers, J. P. A., McDonald, A., Mirzabaev, A., Ibragimov, N., Egamberdiev, O., Ruzibaev, E., & Akramkhanov, A. (2012). Conservation agriculture in Central Asia—What do we know and where do we go from here? *Field Crops Research*, *132*, 95–105. https://doi.org/10.1016/j.fcr.2011.12.008

Kingwell, R. (2021). Making agriculture carbon neutral amid a changing climate: the case of South-Western Australia." Land, 10(11), 1259.

Kirkegaard, J. A., Hunt, J. R., McBeath, T. M., Lilley, J. M., Moore, A., Verburg, K., Robertson, M., Oliver, Y., Ward, P. R., Milroy, S., & Whitbread, A. M. (2014). Improving water productivity in the Australian Grains industry—A nationally coordinated approach. *Crop and Pasture Science*, *65*(7), 583–601. https://doi.org/10.1071/CP14019

Kraaijvanger, R., Almekinders, C. J. M., & Veldkamp, A. (2016). Identifying crop productivity constraints and opportunities using focus group discussions: A case study with farmers from Tigray. *NJAS - Wageningen Journal of Life Sciences*, *78*, 139–151. https://doi.org/10.1016/j.njas.2016.05.007

Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Deressa, T., Diop, M., ... & Dinar, A. (2006). Will African agriculture survive climate change?. *The World Bank Economic Review*, *20*(3), 367-388.

Kuyah, S., Muoni, T., Bayala, J., Chopin, P., Dahlin, A. S., Hughes, K., Jonsson, M., Kumar, S., Sileshi, G. W., Dimobe, K., & Öborn, I. (2023). Grain legumes and dryland cereals contribute to carbon sequestration in the drylands of Africa and South Asia. *Agriculture, Ecosystems & Environment*,

Lal, R, JM Kimble, H Eswaran, BA Stewart (eds). 2000. *Global Climate Change and Pedogenic Carbonates*. CRC/Lewis Publishers: Boca Raton, FL.

Lal,R. 2004a.Carbon emission from farm operations.Env.Int.30:981-990.

Lal,R. 2004 b..Carbon sequestration in dryland ecosystems. Env. Management 33(4):528-544

Lal, R. (2010). Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. *Food security*, *2*(2), 169-177.

Lal, R. (2014). Societal value of soil carbon. *Journal of Soil and Water Conservation*, *69*(6), 186A-192A.

Lal, R. (2015). A system approach to conservation agriculture. *Journal of Soil and Water Conservation*, *70*(4), 82A-88A.*355*, 108583. https://doi.org/10.1016/j.agee.2023.108583.

Lal, R. (2019). Rights-of-soil. *Journal of Soil and Water Conservation*, *74*(4), 81A-86A. https://doi.org/10.2489/jswc.74.4.81A.

Lal, R. (2019a). Carbon cycling in global drylands. *Current climate change reports*, *5*(3), 221-232.

Lal, R. (2024). Carbon farming in global drylands. In *Climate Change and Sustainable Agro-ecology in Global Drylands* (pp. 56-76). GB: CABI.

Lal, R., Smith, P., Jungkunst, H. F., Mitsch, W. J., Lehmann, J., Nair, P. R., ... & Ravindranath, N. H. (2018). The carbon sequestration potential of terrestrial ecosystems. *Journal of soil and water conservation*, *73*(6), 145A-152A.

Lascano, R. J., & Randall Nelson, J. (2014). Circular planting to enhance rainfall capture in dryland cropping systems at a landscape scale: measurement and simulation. *Practical Applications of Agricultural System Models to Optimize the Use of Limited Water*, *5*, 85-111.

Lehmann, J., & Rondon, M. (2006). Bio-char soil management on highly weathered soils in the humid tropics. *Biological approaches to sustainable soil systems*, *113*(517), e530.

Lehmann, J., da Silva Jr, J.P., Rondon, M., Cravo, M.S., Greenwood, J., Nehls, T., Steiner, C. and Glaser, B.: 2002, 'Slash-and-char – a feasible alternative for soil fertility management in the central Amazon?', *Proceedings of the 17thWorld Congress of Soil Science*, (pp. 1–12) Bangkok, Thailand. CD–ROM Paper no. 449.

Lewin, A., Murali, G., Rachmilevitch, S., & Roll, U. (2024). Global evaluation of current and future threats to drylands and their vertebrate biodiversity. *Nature Ecology & Evolution*, *8*(8), 1448-1458.

Li, F.-M., Li, X. G., Javaid, M. M., Ashraf, M., & Zhang, F. (2020). Ridge-furrow plastic film mulching farming for sustainable dryland agriculture on the Chinese loess plateau. *Agronomy Journal*, *112*(5), 3284–3294. https://doi.org/10.1002/agj2.20310.

Li, X., Wu, D., Liu, X., Huang, Y., Cai, A., Xu, H., ... & Zhang, W. (2024). A global dataset of biochar application effects on crop yield, soil properties, and greenhouse gas emissions. *Scientific Data*, *11*(1), 57. https://doi.org/10.1038/s41597-023-02867-9.

Liang, J., Zhao, Y., Chen,L. and Liu,J.2024.Soil inorganic carbon storage and spatial distribution in irrigated farmland of the North China Plains.Geoderma 446: May 2024,116887. https//doi.org/10.1006/j.geoderma.2024.116887.

Lin, B. J., Wei, Y. X., Chen, Z., He, C., Oladele, O. P., Xue, J. F., ... & Zhang, H. L. (2024). Climate Change and Sustainable Agro-ecology in China's Dryland: A Case Study. *Climate Change and Sustainable Agro-ecology in Global Drylands*, 253-270.

Liu, F., Wu, P., Li, Y., Ma, S., Li, N., Mo, F., & Jia, Z. (2025). Coupled effects of rainfall-induced soil moisture and nitrogen placement depth on maize productivity and resource utilization in the Loess Plateau. *Field Crops Research*, *333*, 110036. https://doi.org/10.1016/j.fcr.2025.110036

Liu, Y., Tian, F., Jia, P., Zhang, J., Hou, F., & Wu, G. (2017). Leguminous species sequester more carbon than gramineous species in cultivated grasslands of a semi-arid area. *Solid Earth*, *8*(1), 83-91.

Lu, X., Zou, M., Gan, G., & Kang, S. (2025). Excessive irrigation-driven greening has triggered water shortages and compromised sustainability. *Agricultural Water Management*, *311*, 109405.

Ma, B., Bao, Y., Ma, B., McLaughlin, N. B., Li, M., & Liu, J. (2022). Residual effect of Bentonite-Humic Acid Amendment on Soil Health and Crop Performance 4–5 years after initial application in a Dryland Ecosystem. *Agronomy*, *12*(4), 853.

Ma, B., Ma, B.-L., McLaughlin, N. B., Li, M., & Liu, J. (2022). Improvement in dryland crop performance and soil properties with multiple annual applications of lignite-derived humic amendment. *Soil and Tillage Research*, *218*, 105306. https://doi.org/10.1016/j.still.2021.105306

Melash, A. A., Bogale, A. A., Mengstu, S. G., Aberra, D. A., Tsegay, A., & Mengistu, D. K. (2023). Sustainable management practices for durum wheat production: Analyzing specific agronomic interventions on productivity, grain micronutrient content, and quality. *Heliyon*, *9*(8). https://doi.org/10.1016/j.heliyon.2023.e18733

Meng, X., Lian, Y., Liu, Q., Zhang, P., Jia, Z., & Han, Q. (2020). Optimizing the planting density under the ridge and furrow rainwater harvesting system to improve crop water productivity for foxtail millet in semiarid areas. *Agricultural Water Management*, *238*, 106220. https://doi.org/10.1016/j.agwat.2020.106220

Mohammadi, M., Karimizadeh, R., & Abdipour, M. (2011). Evaluation of Drought Tolerance in Bread Wheat Genotypes under Dryland and Supplemental Irrigation Conditions. *Australian Journal of Crop Science*, *5*(4), 487–493. https://doi.org/10.3316/informit.281651288962837

Monger, C. Khresat, Cole, D.R. and Kraimer, R.A. 2015. Sequestration of inorganic carbon in soil and groundwater. Geology 43(5): 375-378. DOI: 10.1130/G36449.

Muhammad, N., Kader, M. A., Al-Solaimani, S. G., Abd El-Wahed, M. H., Abohassan, R. A., & Charles, M. E. (2025). A review of impacts of hydrogels on soil water conservation in dryland agriculture. *Farming System*, 100166.

Nackley, L., Van Lehman, L., Van Lehman, O., Owen, J. S., & Scagel, C. (2024). Investigating the Benefits of Tectonite Dust as an Amendment for Bark Substrates and Dryland Crops. *Plants*, *13*(1), 126. https://doi.org/10.3390/plants13010126

Naorem, A., Jayaraman, S., Dalal, R. C., Patra, A., Rao, C. S., & Lal, R. (2022). Soil Inorganic Carbon as a Potential Sink in Carbon Storage in Dryland Soils—A Review. *Agriculture*, *12*(8), 1256. https://doi.org/10.3390/agriculture12081256

Nasseri, A. Effects of irrigated and dryland conditions on energy indices in wheat production: a meta-analysis based on the principal components analysis. *Environ Dev Sustain* **27**, 13727–13753 (2025). https://doi.org/10.1007/s10668-024-04495-8

Naz, I., Ijaz, S. S., Y. Habteselassie, M., Ansar, M., & Khan, K. S. (2022). Impact of conservation tillage on organic matter dynamics in loess dryland soil, punjab, pakistan. *The Journal of Animal and Plant Sciences*, *32*(5), 1274–1286. https://doi.org/10.36899/JAPS.2022.5.0534

Nilahyane, A., Ghimire, R., Sharma Acharya, B., Schipanski, M. E., West, C. P., & Obour, A. K. (2023). Overcoming agricultural sustainability challenges in water-limited environments through soil health and water conservation: insights from the Ogallala Aquifer Region, USA. *International Journal of Agricultural Sustainability*, *21*(1), 2211484.

O'Leary, G. J., Aggarwal, P. K., Calderini, D. F., Connor, D. J., Craufurd, P., Eigenbrode, S. D., Han, X., & Hatfield, J. L. (2018). Challenges and Responses to Ongoing and Projected Climate Change for Dryland Cereal Production Systems throughout the World. *Agronomy*, *8*(4), 34. https://doi.org/10.3390/agronomy8040034

Osborne, B. B., Bestelmeyer, B. T., Currier, C. M., Homyak, P. M., Throop, H. L., Young, K., & Reed, S. C. (2022). The consequences of climate change for dryland biogeochemistry. *New Phytologist*, *236*(1), 15-20.

Palaniappan, S. P., Balasubramanian, R., Ramesh, T., Chandrasekaran, A., Mani, K. G., Velayutham, M., & Lal, R. (2009). Sustainable Management of Dryland Alfisols (Red Soils) in South India. *Journal of Crop Improvement*, *23*(3), 275–299. https://doi.org/10.1080/15427520902809888

Pannell, D. J., & Ewing, M. A. (2006). Managing secondary dryland salinity: options and challenges. *Agricultural water management*, *80*(1-3), 41-56.

Parr, J. F., & Papendick, R. I. (1997). Soil quality: relationships and strategies for sustainable dryland farming systems. *Annals of Arid Zone*, *36*(3).

Pfeiffer, M., J. Padarion, M.P. Vega 2023. Soil inorganic carbon distribution, stocks and environmental thresholds along a major climate gradient. Geoderma volume 433, May 2023, 116449. https://org/10.1016/geoderma23.116449.7

Qi, H., Lei, J., He, J., Lei, X., Jin, J., Zhou, L., & Wang, J. (2025). Exogenous Carbon Type Determines the Structure and Stability of Soil Organic Carbon in Dryland Farmlands Under a Continental Semi-Arid Climate. *Agronomy*, *15*(6), 1425. https://doi.org/10.3390/agronomy15061425

Ramírez, P.B., Calderón, F., Singh, S. *et al.* Legume-based rotation enhance long-term soil carbon storage in eastern Oregon dryland wheat systems. *Sci Rep* **15**, 13842 (2025). https://doi.org/10.1038/s41598-025-98916-x

Rehman, S. ur, Ijaz, S. S., Raza, M. A., Mohi Ud Din, A., Khan, K. S., Fatima, S., Raza, T., Mehmood, S., Saeed, A., & Ansar, M. (2023). Soil organic carbon sequestration and modeling under conservation tillage and cropping systems in a rainfed agriculture. *European Journal of Agronomy*, *147*, 126840. https://doi.org/10.1016/j.eja.2023.126840

Ren, X., Zou, W., Jiao, J., Stewart, R., & Jian, J. (2023). Soil properties affect crop yield changes under conservation agriculture: A systematic analysis. *European Journal of Soil Science*, *74*(5), e13413.

Ritchie, J. T., & Basso, B. (2008). Water use efficiency is not constant when crop water supply is adequate or fixed: The role of agronomic management. *European Journal of Agronomy*, *28*(3), 273-281.

Robertson, A. D., Zhang, Y., Sherrod, L. A., Rosenzweig, S. T., Ma, L., Ahuja, L., & Schipanski, M. E. (2018). Climate change impacts on yields and soil carbon in row crop dryland agriculture. *Journal of Environmental Quality*, *47*(4), 684-694.

Ryan, J. (2020). Soil fertility, crop nutrition, and cropping systems: Research for Mediterranean dryland agriculture. *Agronomy Journal*, *112*(5), 3350-3360.

Sainju, U. M. (2021). *The benefits of the no-till system on soil health and crop yields in dryland cropping systems*. Retrieved August 20, 2025, from https://www.publish.csiro.au/sr/SR21188

Sainju, U. M. (2024). Dryland soil carbon and nitrogen stocks in response to cropping systems and nitrogen fertilization. *Environments*, *11*(4), 70.

Serraj, R., & Siddique, K. H. (2012). Conservation agriculture in dry areas. *Field Crops Research*, *132*, 1-6. https://doi.org/10.1016/j.fcr.2012.03.002.

Sharififar, A., Misany, B., Arrouayas, D., Boulonne, L., Chevallier, T., Van Deventere, Field, D., et al. 2025. Soil inorganic carbon , the other and equally important soil carbon pool: Distribution, controlling factors, and the impact of climate change. Adv. In Agron. 178 (In press).

Simon, L. M., Obour, A. K., Holman, J. D., & Roozeboom, K. L. (2022). Long-term cover crop management effects on soil properties in dryland cropping systems. *Agriculture, Ecosystems & Environment*, *328*, 107852.

Singh, K., Mishra, S. K., Singh, M., Singh, K., & Brar, A. S. (2022). Water footprint assessment of surface and subsurface drip fertigated cotton-wheat cropping system–A case study under semi-arid environments of Indian Punjab. *Journal of Cleaner Production*, *365*, 132735.

Singh, R., Srivastava, P., Bhadouria, R., Yadav, A., Singh, H., & Raghubanshi, A. S. (2020). Combined application of biochar and farmyard manure reduces wheat crop eco-physiological performance in a tropical dryland agro-ecosystem. *Energy, Ecology and Environment*, *5*(3), 171–183. https://doi.org/10.1007/s40974-020-00159-1

Smith, W. K., Dannenberg, M. P., Yan, D., Herrmann, S., Barnes, M. L., Barron-Gafford, G. A., ... & Yang, J. (2019). Remote sensing of dryland ecosystem structure and function: Progress, challenges, and opportunities. *Remote Sensing of Environment*, *233*, 111401.

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., Balaguravaiah, G., M., V. S. B., G., R. C., Prasadbabu, M. B. B., & T., Y. R. (2012). Soil carbon sequestration and agronomic productivity of an Alfisol for a groundnut-based system in a semiarid environment in southern India. *European Journal of Agronomy*, *43*, 40–48. https://doi.org/10.1016/j.eja.2012.05.001

Srinivasarao, Ch., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., Sharma, S. K., Sharma, R. A., Jain, M. P., & Chary, G. R. (2012). Sustaining agronomic productivity and quality of a Vertisolic soil (Vertisol) under soybean–safflower cropping system in semi-arid central India. *Canadian Journal of Soil Science*, *92*(5), 771–785. https://doi.org/10.4141/cjss2011-098

Stewart, B. A., & Koohafkan, P. (2004). Dryland agriculture: long neglected but of worldwide importance. *Challenges and strategies of dryland agriculture*, *32*, 11-23.

Stewart, B. A., & Koohafkan, P. (2004). Dryland agriculture: long neglected but of worldwide importance. *Challenges and strategies of dryland agriculture*, *32*, 11-23. https://doi.org/10.2135/cssaspecpub32.c2.

Strauss, J., Swanepoel, P., Laker, M., & Smith, H. (2021). Conservation Agriculture in rainfed annual crop production in South Africa. *South African Journal of Plant and Soil*, *38*(3), 217–230. https://doi.org/10.1080/02571862.2021.1891472

Stringer, L. C., Reed, M. S., Fleskens, L., Thomas, R. J., Le, Q. B., & Lala-Pritchard, T. (2017). A New Dryland Development Paradigm Grounded in Empirical Analysis of Dryland Systems Science. *Land Degradation & Development*, *28*(7), 1952–1961. https://doi.org/10.1002/ldr.2716

Sultan, S., Khan, K. S., Akmal, M., Ahmed, Z. I., Hussain, Q., & Khosa, S. A. (2019). Carbon mineralization in subtropical dryland soil amended with different biochar sources. *Arabian Journal of Geosciences*, *12*(15), 451. https://doi.org/10.1007/s12517-019-4618-3

Svejcar, L. N., & Kildisheva, O. A. (2017). The age of restoration: Challenges presented by dryland systems. *Plant Ecology*, *218*(1), 1–6. https://doi.org/10.1007/s11258-016-0694-6

UNCCD (2024). COP 16 Riyadh. Three-Quarters of Earth's Land Became Permanently Drier in Last Three Decades. Riyadh, Saudi Arabia. https://www.un.org/sustainabledevelopment/blog/2024/12/press-release-three-quarters-of-earths-land-became-permanently-drier-in-last-three-decades-un/.

Unger, P. W., Schwartz, R. C., Baumhardt, R. L., & Xue, Q. (2023). Soil water conservation for dryland farming. In *Soil and Drought* (pp. 11-38). CRC Press.

van der Pol, L. K., Robertson, A., Schipanski, M., Calderon, F. J., Wallenstein, M. D., & Cotrufo, M. F. (2022). Addressing the soil carbon dilemma: Legumes in intensified rotations regenerate soil carbon while maintaining yields in semi-arid dryland wheat farms. *Agriculture, Ecosystems & Environment*, *330*, 107906. https://doi.org/10.1016/j.agee.2022.107906

Venkateswarlu, B., & Shanker, A. K. (2012). Dryland Agriculture: Bringing Resilience to Crop Production Under Changing Climate. In B. Venkateswarlu, A. K. Shanker, C. Shanker, & M. Maheswari (Eds.), *Crop Stress and its Management: Perspectives and Strategies* (pp. 19–44). Springer Netherlands. https://doi.org/10.1007/978-94-007-2220-0_2

Wachter, J. M., Painter, K. M., Carpenter-Boggs, L. A., Huggins, D. R., & Reganold, J. P. (2019). Productivity, economic performance, and soil quality of conventional, mixed, and organic dryland farming systems in eastern Washington State. *Agriculture, Ecosystems & Environment*, *286*, 106665. https://doi.org/10.1016/j.agee.2019.106665

Wang, G., Zhao, B., & Zhao, M. (2024). Investigation into the Performance Characteristics of the Organic Dry Farming Transition and the Corresponding Impact on Carbon Emissions Reduction. *Agriculture*, *14*(3), 459. https://doi.org/10.3390/agriculture14030459

Wang, H., Liu, Y., Wang, Y., Yao, Y., & Wang, C. (2023). Land cover change in global drylands: A review. *Science of The Total Environment*, *863*, 160943.

Wang, H., Wang, S., Yu, Q., Zhang, Y., Wang, R., Li, J., & Wang, X. (2020). No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. *Journal of Environmental Management*, *261*, 110261. https://doi.org/10.1016/j.jenvman.2020.110261

Wang, L., Jiao, W., MacBean, N., Rulli, M. C., Manzoni, S., Vico, G., & D'Odorico, P. (2022). Dryland productivity under a changing climate. *Nature Climate Change*, *12*(11), 981-994.

Wang, Y. (2020). WATER USE EFFICIENCY IN DRYLAND FARMING OF SOYBEANS IN THE SANJIANG PLAIN, CHIN. *Fresenius Environmental Bulletin*, *29*(9), 7219-7227.

Ward, C. (2016). *Improved agricultural water management for Africa's drylands*. World Bank Publications.

Wienhold, B. J., Luchiari, A., & Zhang, R. (2000). Challenges confronting soil management for dryland agriculture. *Annals of Arid Zone*, *39*(3).

Williams, A., Birt, H.W.G., Raghavendra, A. *et al.* Cropping System Diversification Influences Soil Microbial Diversity in Subtropical Dryland Farming Systems. *Microb Ecol* **85**, 1473–1484 (2023). https://doi.org/10.1007/s00248-022-02074-w

Williams, A., Kay, P., Stirling, G., Weng, X., & Bell, L. (2022). Impacts of reducing fallow periods on indicators of soil function in subtropical dryland farming systems. *Agriculture, Ecosystems & Environment*, *324*, 107727. https://doi.org/10.1016/j.agee.2021.107727

Winslow, M. D., Vogt, J. V., Thomas, R. J., Sommer, S., Martius, C., & Akhtar-Schuster, M. (2011). Science for improving the monitoring and assessment of dryland degradation. *Land Degradation & Development*, *22*(2), 145-149.

Wocheslánder, R., Harper, R. J., Sochacki, S. R., Ward, P. R., & Revell, C. (2016). Tagasaste (*Cytisus proliferus* Link.) reforestation as an option for carbon mitigation in dryland farming systems. *Ecological Engineering*, *97*, 610–618. https://doi.org/10.1016/j.ecoleng.2016.10.039

World Atlas of Desertification (2025). Aridity Projections. https://wad.jrc.ec.europa.eu/aridityprojections

Wu, Y., Jia, Z., Li, W., Gao, S., Zhang, X., Niu, X., & Huang, Y. (2024). Gravel Mulching Significantly Improves Crop Yield and Water Productivity in Arid and Semi-Arid Regions of Northwest China: Evidence from a Meta-Analysis. *Agronomy*, *14*(8), 1717.

Wuest, S. B., Schillinger, W. F., & Machado, S. (2023). Variation in soil organic carbon over time in no-till versus minimum tillage dryland wheat-fallow. *Soil and Tillage Research*, *229*, 105677.

Xie, H., Wang, W., He, P., Ding, W., Xu, X., Tan, X., & Liu, X. (2025). Rotation reshapes sustainable potato production in dryland by reducing environmental footprints synergistically enhancing soil health. *Resources, Environment and Sustainability*, 100247.

Xue, J.-F., Yuan, Y.-Q., Zhang, H.-L., Ren, A.-X., Lin, W., Sun, M., Gao, Z.-Q., & Sun, D.-S. (2018). Carbon footprint of dryland winter wheat under film mulching during summer-fallow season and sowing method on the Loess Plateau. *Ecological Indicators*, *95*, 12–20. https://doi.org/10.1016/j.ecolind.2018.07.024

Yaebiyo, G., Tadesse, T., Birhane, E., Hadgu, K. M., Kiros, S., & Meresa, T. M. (2024). Integrated adoption of controlled grazing and multipurpose fodder trees for enhancing tree cover in dryland farming systems. *Agricultural Systems*, *218*, 103967. https://doi.org/10.1016/j.agsy.2024.103967

Yang, W., Yue, S., Chang, F., Sun, H., Wang, Y., Niu, Z., ... & Deng, X. (2022). Reducing greenhouse gas emissions and increasing yield through manure substitution and supplemental irrigation in dryland of northwest China. *Agriculture, Ecosystems & Environment*, *332*, 107937.

Yang, X., Menefee, D., Cui, S., Rajan, N., & Fletcher, A. (2021). Assessing the impacts of projected climate changes on maize (Zea mays) productivity using crop models and climate scenario simulation. *Crop and Pasture Science*, *72*(12), 969–984. https://doi.org/10.1071/CP21279

Zarea, M. J. (2011). Conservation Tillage and Sustainable Agriculture in Semi-arid Dryland Farming. In E. Lichtfouse (Ed.), *Biodiversity, Biofuels, Agroforestry and Conservation Agriculture* (pp. 195–238). Springer Netherlands. https://doi.org/10.1007/978-90-481-9513-8_7

Zhang, L., Wei, H., Zhang, M., Yang, Y., Huang, Y., Chai, N., ... & Zhang, F. (2024). Adopting plastic film mulching system in the food-energy-water-carbon nexus to the sustainable dryland agriculture. *Agricultural Water Management*, *306*, 109183.

Zhang, Y., Huang, K., Zhang, J., Zhao, R., Ojima, D. S., Gao, J., & Zhu, Y. (2024). Dryland Social-Ecological Systems in Americas. In *Dryland Social-Ecological Systems in Changing Environments* (pp. 325-357). Singapore: Springer Nature Singapore.

Zhang, Y., Tan, C., Wang, R., Li, J., & Wang, X. (2021). Conservation tillage rotation enhanced soil structure and soil nutrients in long-term dryland agriculture. *European Journal of Agronomy*, *131*, 126379. https://doi.org/10.1016/j.eja.2021.126379

Zheng, J., Han, J., Liu, Z., Xia, W., Zhang, X., Li, L., ... & Pan, G. (2017). Biochar compound fertilizer increases nitrogen productivity and economic benefits but decreases carbon emission of maize production. *Agriculture, Ecosystems & Environment*, *241*, 70-78.

Zheng, Z., Liu, B., Fang, X., Fa, K., & Liu, Z. (2022). Dryland farm soil may fix atmospheric carbon through autotrophic microbial pathways. *CATENA*, *214*, 106299. https://doi.org/10.1016/j.catena.2022.106299

Zhuo, Z., Chen, Q., Zhang, X., Chen, S., Gou, Y., Sun, Z., ... & Shi, Z. (2022). Soil organic carbon storage, distribution, and influencing factors at different depths in the dryland farming regions of Northeast and North China. *Catena*, *210*, 105934.