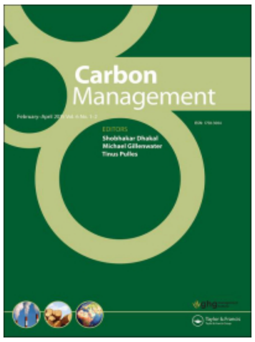

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More carbon per drop to enhance soil carbon sequestration in water-limited environments

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ABSTRACT
By storing carbon (C), soil provide natural solutions to climate change. However, implementing C sequestration practices on a large scale is complex because sequestration rates vary with climatic conditions, soil types and agricultural management. Researchers face challenges identifying effective C sequestration practices in arid and semi-arid regions because precipitation limits plant biomass production. We discuss the “more carbon per drop” approach to enhance C sequestration in a water-limited environment. This approach emphasizes increasing soil organic carbon (SOC) sequestration and reducing greenhouse gas emissions by enhancing water use efficiency and soil water storage. Agricultural strategies that increase the amount and diversity of C inputs, improve nutrient availability for crops, and minimize soil disturbance can simultaneously sequester soil C and enhance soil water storage. Strategies for enhancing SOC sequestration while increasing soil water storage could benefit farmers in arid and semi-arid regions because they can maintain a net-zero or net-negative C footprint. Therefore, implementing policies that promote SOC sequestration and soil water storage could provide natural climate solutions to the vast areas of the world facing water limitations.

KEY POLICY HIGHLIGHTS
- SOC sequestration in a water-limited environment is challenging; *more carbon per drop* simultaneously increases SOC and soil water storage
- The social, economic, and cultural challenges of changing management practices for C sequestration could be addressed through a diverse set of incentives
- Incentivizing conventional SOC sequestration practices while investing in research and development of new frontier technologies could provide a win–win solution

KEYWORDS
dry regions; carbon sequestration; climate change; water use efficiency

Introduction

Greater attention has been given to enhanced soil carbon (C) storage since the launch of the 4p1000 initiative at COP21 by the UNFCCC under the framework of the Paris Climate Agreement for limiting global warming below the 2 °C threshold [1]. Achieving the goal of the Paris Climate Agreement requires the large-scale implementation of soil organic carbon (SOC) sequestration and greenhouse gas (GHG) mitigation practices across crops and land uses [2, 3]. It is estimated that enhancing SOC sequestration by adopting improved agricultural and land management practices alone can remove 0.79 to 1.54 Gt C $year^{-1}$ from the atmosphere [4]. However, there is no consensus on negative emissions technologies and their potential to mitigate the current net global increase in anthropogenic CO_2 emissions of 4.9 Gt C $year^{-1}$ [5]. Specifically, SOC sequestration is largely unknown in the arid and semi-arid agroecosystems that cover more than 40% of the land area in the world. Effective C sequestration in water-limited environments is challenging because biomass production in these areas is constrained by high temperature, low moisture, and coarse-textured sandy soils [6].

Increased SOC sequestration on agricultural lands could enhance crop productivity while providing other agroecosystem benefits through their positive effects on soil water storage, nutrient cycling and erosion control [7, 8]. Adoption of SOC

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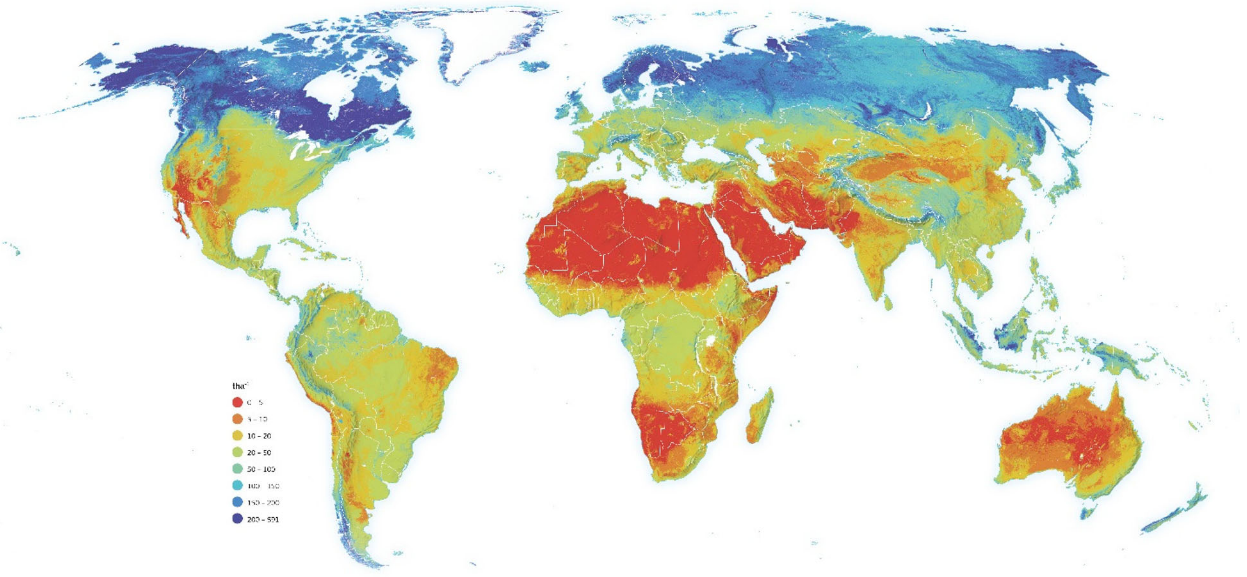

Figure 1. **Global soil organic carbon stock predicted for 0–1 m depth (Mg ha^{-1}) at 250 m resolution derived from soil organic carbon content, bulk density, and coarse fragments. Map retrieved from https://wad.jrc.ec.europa.eu/organiccarbon.**

sequestration practices also mitigates GHG emissions. Therefore, estimates of climate mitigation potential through C sequestration in agricultural soils remain incomplete without considering a detailed inventory of the GHG footprint of the complete production cycle, including field machinery use, farm input production and transport, emissions from the field, and during post-processing of agricultural products. Nitrous oxide (N_2O) and methane (CH_4) have 310 and 34 times higher global warming potential, respectively, than CO_2 on a 100-year time scale [3]. Therefore, minimizing N_2O and CH_4 emissions through improved soil management could substantially reduce global warming and climate change. Accounting for all sources and sinks of C and GHG emissions while monitoring water needed for each step will help develop SOC sequestration technologies for water-limited environments.

The term "water-limited environments" is used to describe arid and semi-arid regions with <500 mm annual precipitation where the ratio of total annual precipitation to potential evapotranspiration is <1 [6]. Working lands in water-limited environments cover >32% of the Earth's surface and 44% of the cultivated area globally and support food production for 20.2% of the global population [9]. Water-limited regions stretch across vast areas of the western United States and Mexico, western South America, southwestern and central Asia, northwestern India and Pakistan, Western Australia, and northern and southwestern Africa [6, 10]. Despite well-documented evidence of SOC sequestration through alternative agricultural strategies such as cover cropping, crop rotation and perennial cropping, using soil amendments, improved fertility management, and reduced- and no-tillage management in humid and sub-humid regions [11–13], the potential of arid and semi-arid areas to enhance SOC has not been studied extensively. Integrated modeling of observations, based on 150,000 soil profile descriptions and satellite-based parameters around the world, showed that soils in arid and semi-arid regions had lower SOC (<50 Mg ha^{-1}) than their storage potential (Figure 1). Innovation in agricultural technologies that increase SOC sequestration, mitigate GHG emissions, and increase soil water storage can provide a win–win solution to feed the growing population and mitigate climate change.

This paper provides an overview of cropland SOC sequestration practices in water-limited environments. In these environments, opportunities for SOC sequestration are limited by (a) a low biomass production and C input due to soil water limitation; (b) the absence of quantifiable, verifiable and monetizable benefits to sequestering SOC; (c) a lack of economic incentives to drive the changes in agriculture; and (d) scarcity of water necessary to enhance and realize benefits from adopting SOC sequestration practices. This paper discusses agricultural strategies to enhance SOC sequestration while improving soil water storage and productivity. A meaningful increase in SOC sequestration at the farm or regional scale must occur without simultaneous SOC reductions at other locations or increasing GHG emissions from the entire production system. Therefore, the systems approach, which accounts for SOC sequestration and GHG footprints of each farming component and their water use will provide clues on how to implement carbon managment strategies in water limited regions and establish optimum incentives for broader adoption of these practices .

Conceptualizing *more carbon per drop*

The phrase *more carbon per drop* is coined to describe agricultural strategies that increase SOC sequestration and mitigate GHG emissions per unit of water used for crop production. Since precipitation is the primary limiting factor for plant growth and production in arid and semi-arid drylands, soils are often low in fertility, and native vegetation is sparse. Rainfed agriculture in these areas produces low yield, contributing to low biomass input for the microbial transformation of biomass into stable C compounds. The SOC stocks in the top 30 cm of soil are generally less than 50 Mg ha^{-1} in water-limited agroecosystems [14]. Studies show that low SOC storage is often associated with a low soil water storage capacity [15–17]. High variability in climate, extended drought, and sparse but intense rainfall further increases uncertainty in SOC sequestration and stabilization in water-limited environments, affecting associated ecosystem services. However, adopting water conservation technologies in arid and semi-arid regions could increase soil carbon sequestration. Our approach, *more carbon per drop*, emphasizes identifying and promoting technologies that increase SOC and simultaneously improve soil water storage to develop climate-smart and resilient cropping systems in arid and semi-arid regions. This approach emphasizes improving water use efficiency so that more biomass C is recycled and ultimately stored in the soil. Summing above- and belowground plant biomass and soil organic matter, the C stock could be more than 200 Mg ha^{-1} in the vast area of arid and semi-arid regions, specifically in temperate agroecosystems [6]. Improving C storage through improved water use and conservation could further enhance the sequestration potential, thereby enhancing agricultural resilience in arid and semi-arid regions.

Land degradation is persistent in water-limited environments, resulting in more SOC loss through GHG emissions and soil erosion. Currently, 33% of the global soils have been degraded [9], including 25–35% of land area in arid and semi-arid regions [18]. Wind erosion, the main driving force of soil loss in arid and semi-arid areas, is the primary soil degradation process that results in a large amount of SOC loss from the soil surface [10]. These areas have lost much of their SOC due to agriculture or related land uses, decreased soil structural stability, increased erosion risks, and reduced water supply and nutrient availability [19]. Land degradation reduced SOC stocks by 33–90% in Chinese grasslands [20, 21]. However, the process of land degradation affecting SOC stocks is reversible. Implementing the *more carbon per drop* approach can revitalize the degraded land by restoring SOC because of the multiple ecosystem services associated with increasing SOC storage [7, 22]. Successful implementation of such strategies in water-limited environments could improve soil, water and environmental quality (Figure 2). The sustainable SOC sequestration technologies also improve soil chemical, biological, and physical properties, including soil pH, electrical conductivity, cation exchange capacity, nutrient mineralization, soil bulk density, soil structure and water-holding capacity [22–25]. Improved soil physical, chemical and biological properties enhance soil functions, including soil water retention and increased water availability to produce more biomass for sustainable C sequestration, making SOC a critical component of soil health and water conservation.

Water infiltration and availability is one of the most critical ecosystem functions associated with increasing SOC in arid and semi-arid regions. Although there is enormous variability in responses of different soils to sequester C and improve water storage, studies show a positive relationship between SOC sequestration and available water capacity (e.g. [22]). A study reported an increase in available water capacity with increased SOC content for sand ($r^2 = 0.79$), silt loam ($r^2 = 0.58$), and silty clay loam ($r^2 = 0.7$) soils [24]. Increasing SOC increased soil aggregation and aggregate stability, improving porosity and soil water retention [22]. Increased macro and mesopores also increase soil water infiltration and decrease runoff. A recent global metanalysis of the SOC–crop yield relationship showed that yield increases levelled off at approximately 2% SOC [26]. In arid and semi-arid agroecosystems, which often have <1% SOC because of low precipitation [27], increasing SOC up to 2% is an arduous task.

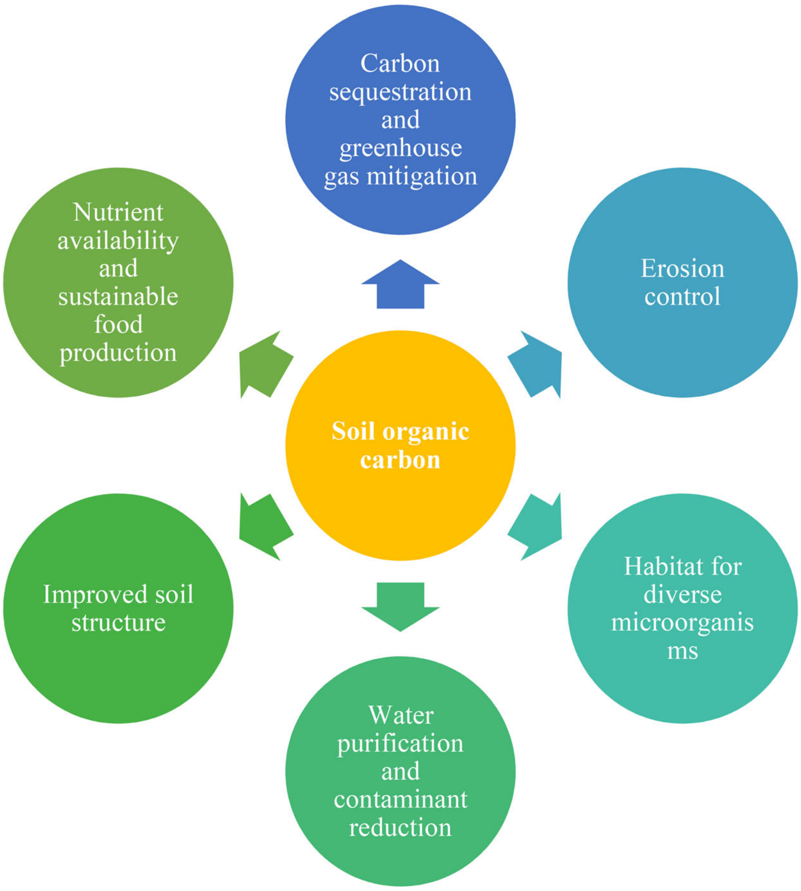

Figure 2. **Multiple ecosystem services related to increased soil organic carbon storage.**

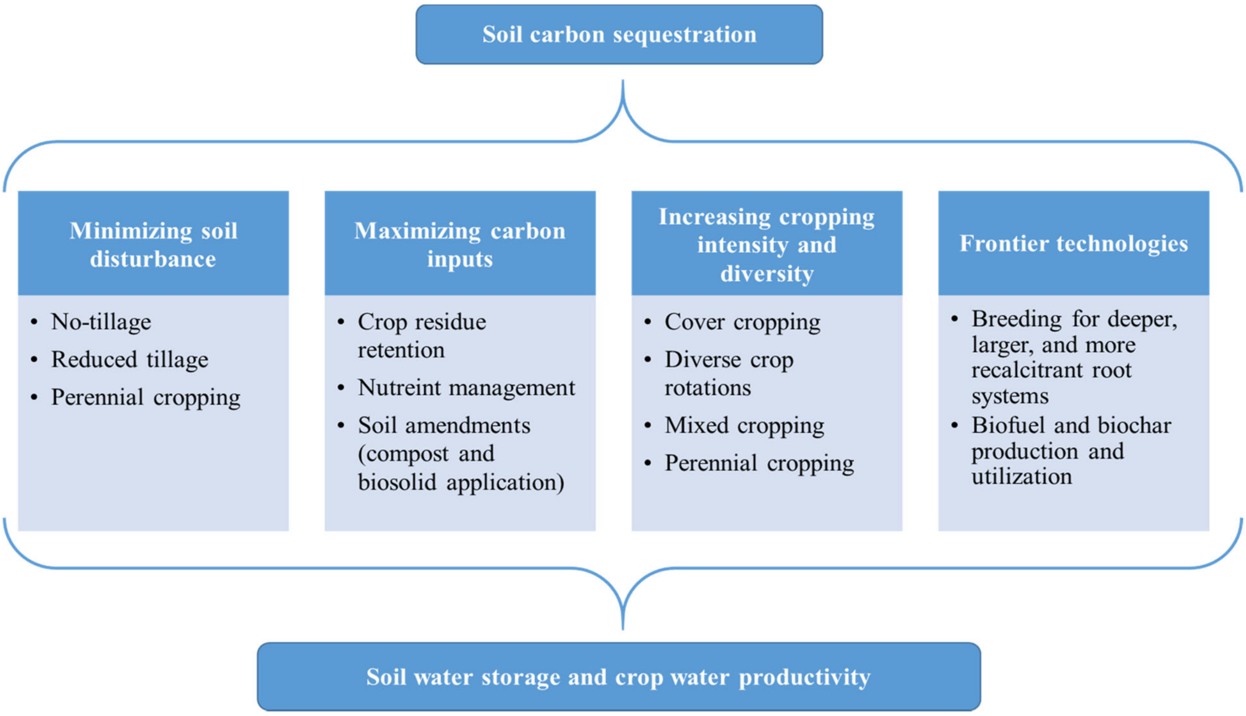

Figure 3. **Management strategies for increasing soil organic carbon sequestration can also increase soil water storage and crop water productivity in water-limited environments.**

However, increasing SOC sequestration while improving soil water storage functions could substantially improve food and nutritional security.

Improved farming practices such as cropping system intensification and diversification, cover cropping, crop rotation, mixed- or intercropping of deep- and shallow-rooted crops, efficient nutrient management practices using organic and inorganic fertilizer sources, conservation tillage and improved grazing management in rangelands can

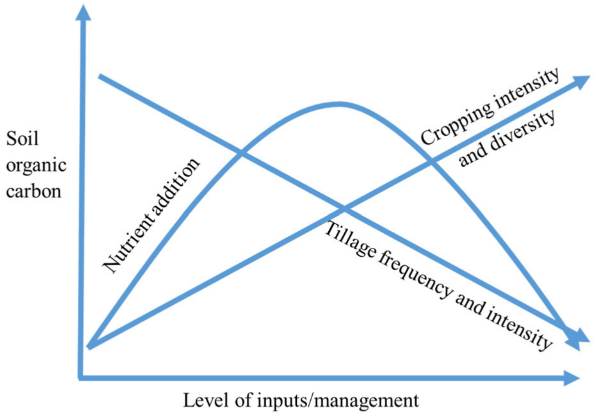

Figure 4. A schematic diagram showing soil organic carbon response to tillage, cropping, and nutrient management strategies (figure not to scale).

sequester 4.4 to 6.9 Pg CO_2e year^{-1} [28]. Adopting frontier technologies such as breeding for crop varieties with deeper, larger and more recalcitrant root systems could add 3 Pg CO_2e year^{-1} in soils or through the root tissues themselves [29–31]. In addition, cultivating biomass crops and combustion in power plants outfitted with C capture and storage technology will allow permanent storage of C in the ground. Adopting multiple practices together could have greater effects on SOC sequestration (Figure 3). The water storage potential of these management alternatives has not been explored under different soil and climatic conditions. Identifying best management practices and implementing them on a regional scale can provide natural climate solutions for dry areas.

Effects of alternative SOC sequestration practices are often complementary [10]. For example, reducing tillage and increasing cropping intensity and diversity increases SOC sequestration. Reduced soil disturbance under reduced- and no-tillage protects soil C from microbial breakdown. Increasing cropping intensity and diversity, on the other hand, increases C sources and diversity. Improved nutrient management, such as using the 4R nutrient stewardship (right source, rate, time and place), can increase nutrient use efficiency, leading to greater crop production and C storage. However, increasing nutrient application rates do not linearly affect SOC sequestration because under- or over-application of nutrients can negatively affect crop yields, biomass C inputs and net GHG emissions (Figure 4). A recent study by Sevenster *et al*. [32] demonstrated that declining SOC contributed less than 3% of the total GHG emissions while fertilizer use accounted for 37%, lime use 12%, and the combined burning and decomposition of residue 20% in Australian rainfed grain cropping systems in 2005. However, increased use of these inputs in grain production between 2005 and 2015 did not meaningfully change SOC but did increase total GHG emissions from this sector. SOC sequestration strategies, such as planting perennial crops, selecting water-efficient crops and varieties, breeding crops for deeper and denser root systems, and restoring degraded marginal lands by planting bioenergy crops, could increase C inputs per unit of water in dry regions [23].

Irrigation availability in arid and semi-arid croplands is another factor that contributes considerably to SOC storage. The availability of irrigation water has made the Great Plains region of the USA one of the most productive agroecosystems globally. The Ogallala Aquifer, among the largest aquifers in the world, is the primary source of groundwater in the Great Plains region. However, crop production potential has not been fully harnessed in recent years due to declining irrigation capacity. A study projected that an area of 22,000 km^2 (24% of currently irrigated lands) in the Ogallala Aquifer region of the USA may be unable to support irrigated agriculture by 2100, and 13% of this area may not be even suitable for dryland crop production due to soil degradation [33]. With this transition, a significant amount of soil and vegetation C will be lost to the atmosphere. A recent study demonstrated that a change from irrigated to dryland production could decrease SOC storage in 0–30 cm soil profile by 14% in 14 years [34], equivalent to an annual flux of additional 1.2 million metric tons of CO_2 year^{-1} from the Ogalalla Aquifer region alone. Implementing more efficient water application technologies, including sub-surface drip systems or low-energy precision applications, could increase crop production and SOC storage. Therefore, development of frontier technologies that increase SOC sequestration and improve water use efficiency while reducing the GHG footprint of agricultural systems is urgently needed. Using green water for biomass production and implementing bio-based C capture technologies could further enhance SOC sequestration and mitigate global warming. Pre-season irrigation or dormant season irrigation to refill the soil profile and encourage crops to root deeper to use that water has shown to increase irrigation efficiency [35]. Deep-rooted crops extract water and nutrients from the deeper soil profile, contributing to greater biological activity and more SOC accrual in the soil [36]. Integrating proven technologies and emerging approaches in water management and SOC sequestration helps achieve *more carbon per drop* in water-limited environments.

Implementing *more carbon per drop* in water-limited environments

Maximizing carbon inputs

Increasing C inputs is the first step to improve SOC sequestration in agroecosystems. Maintaining residue cover benefits soil by increasing C inputs, minimizing soil erosion by wind and water, maintaining a low soil temperature in hot, dry environments, and conserving moisture. Positive effects of crop residues on SOC sequestration and soil water storage are often reported in systems where no-tillage is combined with surface residue cover [37]. However, the crop residues required to enhance SOC sequestration vary with soil type, climatic conditions and management practices. Machado [38] predicated the need for 5.2–7.8 Mg ha^{-1} $year^{-1}$ crop residue to maintain SOC in dryland cropping systems of eastern Oregon, USA. In hot, dry conditions of the southern Great Plains, $>$5 Mg ha^{-1} cover crop residue addition is required to sustain SOC [39]. Neither study reported soil water storage potential and crop water productivity in these cropping systems. A global meta-analysis of 176 studies suggested returning crop residues after crop harvest increased SOC by 12.8% [40]. Since increasing SOC sequestration is directly related to improving soil moisture storage capacity, increasing residue input through better crop management could improve C cycling and water storage in dry regions. However, meta-data on crop residue management and soil water storage is not available. Identifying the crop residue effects and amount of residue needed to harness soil C sequestration and water storage benefits can increase agricultural resilience and mitigate climate change in water-limited agroecosystems.

Improved nutrient management is another approach to increase SOC sequestration and mitigate greenhouse gas emissions. Increased nutrient supply supports better crop production and biomass recycling, ultimately increasing SOC storage. Studies show higher SOC with integrated nutrient management practices through organic and inorganic sources [41]. Increasing SOC sequestration often requires a high rate of nutrient addition to replace nutrients removed during crop harvest [12]. Nutrients primarily needed for SOC sequestration in soils include N, P, S and micronutrients, as constituents of various C compounds [42, 43]. About 80 kg N, 20 kg P, and 14 kg S is required to form 1 Mg humus-C [42]. The SOC sequestration in a water-limited environment is typically constrained not by nutrient availability but rather by the balance of nutrients to sustain crop production and biomass C inputs [44]. The nutrients not utilized by crops due to moisture limitation are either accumulated in soil or lost to the environment (Figure 4). For example, over-application of nutrients in Australian drylands led to greater GHG emissions without any significant impacts on SOC sequestration [32]. Therefore, nutrient management strategies should be developed in such a way that the benefits of C sequestration are not negated by their environmental footprints, including GHG emissions and loss through leaching. The SOC sequestration in degraded soils requires large amounts of mineral fertilizers to support biomass production sufficient to maintain soil fertility. As fertilizer production leads to GHG emissions, maximizing C sequestration in degraded lands by maximizing nutrient inputs may not always be a climate-smart strategy. Any fertilizer applied should be synchronized to plant uptake to minimize adverse environmental impacts through GHG emissions or nutrient loss through wind and water erosion. Site-specific nutrient management strategies showed promise in increasing crop production while reducing GHG emissions from arid and semi-arid cropping systems [45]. More research on site-specific nutrient management effects on soil water dynamics may benefit agroecosystems by improving SOC sequestration and soil water retention.

Minimizing soil disturbance

More carbon per drop will be fully harnessed with extensive research on the co-benefits of conservation tillage for SOC sequestration and soil water storage. Conventional agriculture uses tillage to (1) prepare a smooth seedbed, (2) make soil loose which favors rooting of crops, (3) incorporate fertilizers and crop residue, (4) control weeds and diseases, and (5) make the soil warm in cooler regions. Conventional tillage typically involves moldboard plowing, disking and harrowing. Crop residues are incorporated into soils during conventional tillage, leaving less than 15% of crop residue on the soil surface [46]. Studies suggested depletion in SOC occurs with continuous tillage in arid

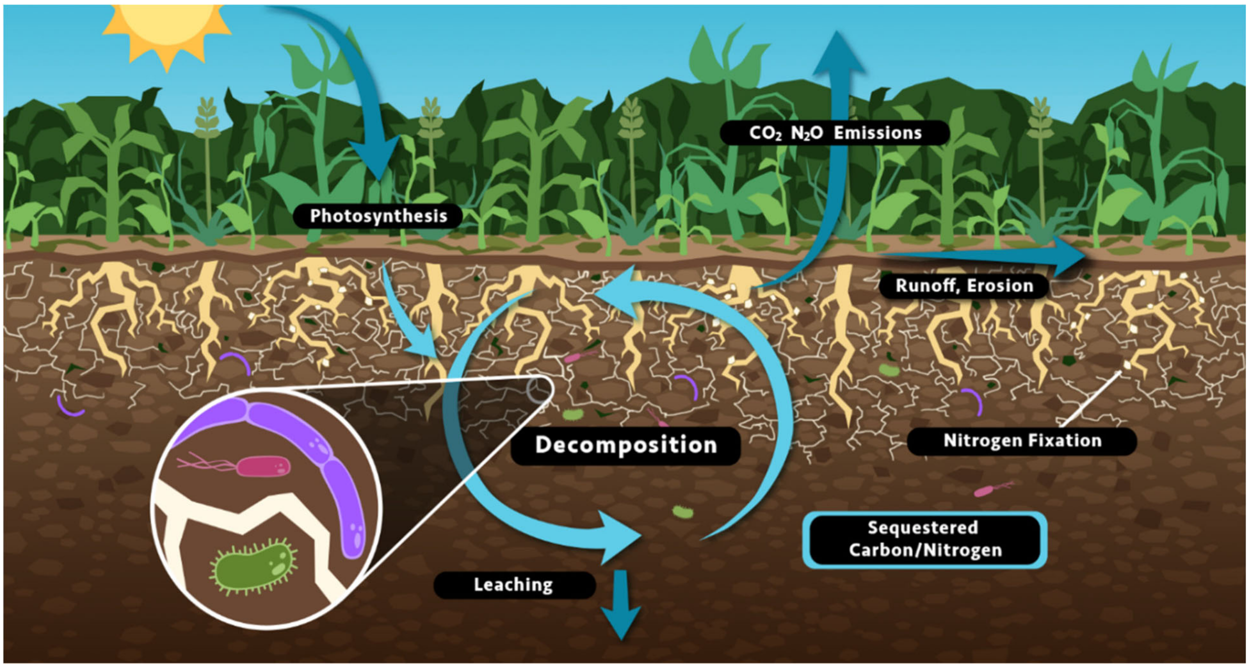

Figure 5. **Soil organic carbon and nutrient cycling in the agroecosystem are regulated by crop species, diversity, and soil management practices. Both C and N generated by plant activities may be sequestered in the soil profile or lost to the environment by leaching or surface runoff (Image concept: Rajan Ghimire; graphic work by Evan Evans of NMSU Innovative Media and Communications).**

and semi-arid soils [47–49]. Tillage plays a significant role in crop residue placement and decomposition in soil [11, 50], which ultimately influences the water storage characteristics of soils. Therefore, there has been increasing attention to alternative tillage management practices to improve soil health, SOC sequestration and crop production while minimizing water and nutrient loss, soil erosion and other adverse environmental effects.

Conservation tillage practices include no-tillage, strip tillage, reduced tillage, mulch tillage, etc., which leave more than 30% of the soil surface covered with crop residues [46]. Studies demonstrate increased soil water storage (e.g. [51]) and available water content (e.g. [52]) with conservation tillage systems in water-limited conditions. The latter study also reported an increase in SOC with conservation tillage, and the effect was limited to surface (top 30 cm) soil. Conservation tillage systems often accumulate high SOC near soil surfaces because reduced soil disturbance slows down the rate of crop residue decomposition [47]. Reducing soil disturbance also builds a suitable environment for soil microorganisms, improves aeration, promotes soil aggregation and structure, and serves as a nutrient bank for plant growth. Soils with reduced disturbance are also high in available substrates, wetter and cooler, and fluctuate less in moisture and temperature, supporting SOC accumulation [53, 54]. An increase in soil water storage and SOC sequestration in surface soil with conservation tillage systems has been reported from arid and semi-arid regions across the world, including the Great Plains and Pacific Northwest of the USA [16, 47, 55], western India [17] and most of Australia [37]. For example, a long-term conservationagriculture study in Pusa, India, showed no-tillage relative to conventional tillage increased economic water use efficiency by 42% and SOC sequestration by 3.5–31.8% [17]. Decreasing tillage operations reduced evaporation losses and thereby increased soil water storage because of improved water retention in the semi-arid US Great Plains [15]. A global meta-analysis revealed that conservation tillage increased SOC by 3.15 ± 2.42 Mg ha^{-1} (mean ± 95% confidence interval) in the surface 10 cm of soil but did not enhance SOC stock in the 0–40 cm profile [56]. Further research is needed on the effects of reduced or no soil disturbance on soil water conservation and SOC accumulation simultaneously.

Increasing cropping intensity and diversity

Increasing cropping intensity and diversity is critical for maximizing plant biomass production and diversifying microbial substrates. Continuous cropping or increased cropping intensity could put more organic matter into the soil, where soil microbes decompose it, and part of organic matter could be sequestered in the soil (Figure 5). Certain plants work with symbiotic microbes to fix nitrogen, which is added to the soil upon the decomposition of such plants, ultimately supporting crop

Table 1. **Cover crops for cropping system intensification and soil organic carbon sequestration in arid and semi-arid regions.**

Study location	Soil type	Study duration	Soil depth (cm)	Tillage	Crop rotation	Fallow	Cover crops	Sequestration rate (kg ha^{-1} year^{-1})	Ref.
Garden city, KS	Ulysses silt loam	5	0–7.5	NT	Winter wheat–fallow	9.9	11.2	260	[68]
Clovis, NM	Olton clay loam	5	0–15	NT	Winter wheat–sorghum–fallow	18.2	18.5	51	[64]
Woodslee, Canada	Clay loam	17	0–15	CT	Monoculture winter wheat	46.8	52.7	344	[69]
Shaanxi, China	Silt loam	5	0–20	CT	Summer fallow–winter wheat	18.9	20.4	300	[70]
Victoria, Australia	Vertosol	12	0–30	NT	Fallow–wheat–chickpea	23.0	25.4	202	[71]

production and soil C accumulation. Increasing cropping intensity through cover cropping, crop rotation, inter-cropping, mixed cropping and perennial cropping increases SOC and improves nutrient cycling and soil water storage [54, 57, 58]. It can also alleviate N loss, reduce wind and water erosion, and improve soil aggregation [54, 59, 60]. Continuous ground cover from various crops in rotation moderates soil temperature to mild winter and summer conditions and maintains a constant supply of microbial substrates needed for increasing SOC sequestration [53, 61]. A recent global meta-analysis revealed that intensification and diversification of cropping systems through cover cropping increased C sequestration by 0.56 Mg ha^{-1} year^{-1} [57]. Using diverse crops in rotation or as cover crops improves the quantity and quality of crop residue returned to the soil, ultimately increasing the persistence of C stored in the soil [62–64].

Increasing cropping intensity in water-limited environments is challenging because it could deplete the soil moisture needed for effective C sequestration. Although the effects of cropping intensification on SOC sequestration in water-limited environments vary with soil type, tillage practices and fertility management [65–67], the net effect is positive (Table 1). However, increased cropping intensity often results in increased water demand and water use efficiency. In Colorado, USA, a study suggested a decrease in soil moisture and subsequent crop yield with cover cropping compared to crop rotations without cover crops [72]. Studies in eastern New Mexico, USA, with supplemental irrigation demonstrated no difference in soil water storage, crop yield and water productivity of cropping systems with and without cover cropping [73]. In another study, under the irrigated condition, crop yield and water productivity were significantly greater with cover cropping than without cover crops [74].

SOC accumulation due to cover cropping or cropping system intensification is often realized when combined with no-tillage or reduced tillage management because reduced or no-tillage often increases soil water storage [16, 54]. Ecological intensification of cropping systems in Brazil resulted in both SOC sequestration and increased soil water storage [25]. Their study also demonstrated high soil cover, low soil water and nutrient losses, and increased grain yield with the adoption of no-tillage and more intensive cropping. Implementing more than one soil and water management strategy could help achieve *more carbon per drop* in arid and semi-arid regions in a few years.

Frontier carbon management practices

With growing interest in soil-based C sequestration practices as a natural climate solution, researchers have focused on developing innovative management practices with the potential to increase SOC sequestration considerably without increasing GHG emissions. Paustian *et al.* [23] suggested biochar applications , developing and growing perennial grain crops, and planting annual crops bred to produce deeper and more extensive root systems as frontier practices for increasing SOC . Biochar, a charcoal-like product of thermal degradation of biomass in the limited presence or absence of oxygen, can increase SOC sequestration, improve soil structure, increase nutrient cycling and sustain crop productivity [75]. In recent years, converting crop residues, manure, compost and other agricultural wastes into biochar and reusing them as a soil amendment has been increasingly practiced for SOC sequestration and stabilization [76, 77]. The biochemically recalcitrant and predominantly aromatic C present in pyrolyzed material can permanently increase SOC [78]. Biochar additions can also interact with the native SOC and either stimulate or reduce the rate of decomposition of the native SOC, depending on soil moisture, nutrients and pH content [23]. In water-limited environments, biochar has greater potential to increase SOC because of the slow decomposition of biochar

C under water-limited conditions. The most significant contribution of biochar as a negative emissions technology is due to its N_2O reduction potential. A recent meta-analysis reported biochar application could reduce N_2O emissions by 9–12% [79]. An earlier global assessment suggested an almost 50% reduction in N_2O emissions compared to non-biochar-amended soils [80].

Perennial cropping increases SOC sequestration by minimizing disturbance and increasing root and aboveground biomass inputs. Perennial crops have deeper and denser root systems than annual row crops, producing 3–10 times more belowground biomass [81]. In addition, the roots of perennial crops typically have a higher C:N ratio than their annual counterparts [82], reducing decomposition rates. Studies also show that root-derived C is retained longer and forms more stable soil aggregates than shoot-derived C [83]. In water-limited environments, the roots of perennial crops extend to a greater soil depth, resulting in greater total root biomass production [84]. A study from southern Alberta, Canada, reported 14.9% and 11% greater SOC under perennial wheatgrass (*Agropyron trichophorum* L.) than under fallow–-wheat and wheat–wheat rotations, respectively, at 0–7.5 cm depth [85]. Breeding perennial crops suitable for arid and semi-arid regions could enhance SOC sequestration in these regions. Researchers are also looking for options to increase root biomass density in annual crops [23]. Increasing biomass inputs through breeding annual or perennial crops for deeper and denser root systems could substantially enhance SOC sequestration without affecting GHG emissions. More research on innovative and transformative technologies that can capture and sequester a substantial amount of carbon while improving soil health and water storage capacity lays the foundation for the next generation of climate-smart farming technologies in water-limited environments.

Economic and policy implications

There is a robust scientific basis for managing agricultural soils to increase SOC sequestration and implement natural climate solutions. Incentivizing the adoption of well-developed, conventional SOC sequestering practices while investing in research and development of new frontier technologies could occur in the next two to three decades [23]. Benefits from such practices may accrue directly to the landowner as improved yields and profitability and indirectly to society through improved water and air quality. For example, greater SOC can improve water holding capacity and enhance soil moisture availability, adding to the yield and quality of crops [86, 87]. Increasing SOC and offsetting C emissions also help mitigate climate change. Such benefits can be measured by considering the damages mitigated or avoided by reduced changes in climate. The damage mitigation value have been estimated to range from \$70 s to > \$200 per metric tonne of C equivalent [88]. The range could be higher for water-limited environments because dry conditions trigger more air pollution and associated human health hazards. Nevertheless, because of the growing recognition of the value of SOC sequestration and offsetting CO_2 emissions, C markets are emerging, and assistance to landowners to adopt practices that increase SOC sequestration has received greater attention. This additional benefit may be sufficient for some landowners to include "carbon" in their overall product portfolio. However, committing to management changes for C sequestration might also limit a farmer's ability to manage other factors.

Motivating farmers and landowners to adopt sustainable SOC sequestration practices on a large scale will likely transform agricultural production and its value chain and provide a practical and natural solution to climate change. However, SOC sequestration from agricultural land-use changes and alternative management practices should emphasize determining how much of the estimated "technical" potential is economically feasible, how cost-effective are the different alternatives for possible incentive payments, and what is the net value of incentives required in water-limited environments. The social, economic and cultural challenges of changing management practices for C sequestration could be addressed through a diverse set of incentives and measures. They must consider region-specific barriers that may hinder the implementation of SOC sequestration practices, such as security of tenure, lack of financial resources, or the aging profile of farm families. Developing and implementing policies to promote *more carbon per drop* could provide a win–win solution for farmers and society in water-limited environments.

Conclusion

Climate change continues to be a significant threat to agricultural sustainability. This paper discussed a *more carbon per drop* approach to improve agricultural sustainability and resilience in arid and semi-arid agroecosystems, which emphasizes improved water management for increasing SOC sequestration. Promoting management practices that improve soil water storage and increase SOC sequestration, and developing frontier water conservation technologies, can put farmers and landowners in arid and semi-arid regions at the forefront of climate change solutions. Current agricultural policies lack attention necessary to support arid and semi-arid agriculture innovations that maximize environmental services, including soil water conservation and SOC sequestration. Therefore, developing policies to promote SOC sequestration and incentive programs for developing frontier agricultural practices could lead to broader adoption of these technologies and provide a win–win solution for agriculture and the environment.

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Data sharing statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study. This paper provides the authors' perspective and review of the literature on carbon sequestration in arid and semi-arid regions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

1. Minasny B, Malon BP, McBratney AB, et al. Soil carbon 4 per mille. Geoderma. 2017;292:59–86. doi:10.1016/j.geoderma.2017.01.002.
2. Amelung W, Bossio D, de Vries W, et al. Towards a global-scale soil climate mitigation strategy. Nat Commun. 2020;11(1):5427. doi:10.1038/s41467-020-18887-7.
3. Smith P, Davis SJ, Creutzig F, et al. Biophysical and economic limits to negative CO_2 emissions. Nat Clim Change. 2016;6(1):42–50. doi:10.1038/nclimate2870.
4. Fuss S, Lamb WF, Callaghan MW, et al. Negative emissions – part 2: costs, potentials and side effects. Environ Res Lett. 2018;13(6):063002. doi:10.1088/1748-9326/aabf9f.
5. Friedlingstein P, O'Sullivan M, Jones MW, et al. Global Carbon Budget 2020. Earth Syst Sci Data. 2020;12(4):3269–3340. doi:10.5194/essd-12-3269-2020.
6. Hanan NP, Milne E, Aynekulu E, et al. A role for drylands in a carbon neutral world? Front Environ Sci. 2021;9:539. doi:10.3389/fenvs.2021.786087.
7. Adhikari K, Hartemink AE. Linking soils to ecosystem services – a global review. Geoderma. 2016;262:101–111. doi:10.1016/j.geoderma.2015.08.009.
8. Lal R. Eco-intensification through soil carbon sequestration: harnessing ecosystem services and advancing sustainable development goals. J Soil Water Conserv. 2019;74(3):55A–61A. doi:10.2489/jswc.74.3.55A.
9. United Nations. United Nations decade for desert and fight against desertification; 2020 [cited 2020 Dec 12]. https://www.un.org/en/events/desertification_decade/whynow.shtml.
10. Lal R. Carbon sequestration in dryland ecosystems. Environ Manage. 2004;33(4):528–544. doi:10.1007/s00267-003-9110-9.
11. Franzluebbers AJ. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till Res. 2002;66(2):95–106. doi:10.1016/S0167-1987(02)00018-1.
12. Lal R. Restoring soil quality to mitigate soil degradation. Sustainability. 2015;7(5):5875–5895. doi:10.3390/su7055875.
13. Sainju UM, Singh BP, Whitehead WF. Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. Agron J. 2005;97(5):1279–1290. doi:10.2134/agronj2004.0213.
14. Bardgett RD, Bullock JM, Lavorel S, et al. Combatting global grassland degradation. Nat Rev Earth Environ. 2021;2(10):720–735. doi:10.1038/s43017-021-00207-2.
15. Aase JK, Pikul JL. Crop and soil response to long-term no-tillage practices in the Northern Great Plains. Agron J. 1995;87(4):652–656. doi:10.2134/agronj1995.00021962008700040008x.
16. Hansen NC, Allen BL, Baumhardt RL, et al. Research achievements and adoption of no-till, dryland cropping in the semi-arid US Great Plains. Field Crop Res. 2012;132:196–203. doi:10.1016/j.fcr.2012.02.021.
17. Parihar CM, Yadav MR, Jat SL, et al. Long-term conservation agriculture and intensified cropping systems: effects on growth, yield, water, and energy-use efficiency of maize in Northwestern India. Pedosphere. 2018;28(6):952–963. doi:10.1016/S1002-0160(17)60468-5.
18. Davies J, Poulsen L, Schulte-Herbrüggen B, et al. Conserving dryland biodiversity. 2012. Nairobi, Kenya: International Union for the Conservation of Nature (IUCN), p. xii + 84.
19. Gomiero T. Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustainability. 2016;8(3):281. doi:10.3390/su8030281.

20. Dong SK, Wen L, Li YY, et al. Soil-quality effects of land degradation and restoration on the Qinghai–Tibetan Plateau. Soil Sci Soc Am J. 2012; 76(6):2256–2264. doi:10.2136/sssaj2012.0092.
21. Wu R, Tiessen H. Effect of land use on soil degradation in alpine grassland soil, China. Soil Sci Soc Am J. 2002;66(5):1648–1655. doi:10.2136/sssaj2002.1648.
22. Haynes RJ, Naidu R. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr Cycl Agroecosyst. 1998;51(2):123–137. doi:10.1023/A:1009738307837.
23. Paustian K, Larson E, Kent J, et al. Soil C sequestration as a biological negative emission strategy. Front Clim. 2019;1:8. doi:10.3389/fclim.2019.00008.
24. Rawls WJ, Pachepsky YA, Ritchie JC, et al. Effect of soil organic carbon on soil water retention. Geoderma. 2003;116(1-2):61–76. doi:10.1016/S0016-7061(03)00094-6.
25. Silva LCM, Avanzi JC, Peixoto DS, et al. Ecological intensification of cropping systems enhances soil functions, mitigates soil erosion, and promotes crop resilience to dry spells in the Brazilian cerrado. Int Soil Water Conserv Res. 2021;9(4):591–604. doi:10.1016/j.iswcr.2021.06.006.
26. Oldfield EE, Bradford MA, Wood SA. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil. 2019;5(1):15–32. doi:10.5194/soil-5-15-2019.
27. Martens DA, Emmerich W, McLain JET, et al. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. Soil till Res. 2005;83(1):95–119. doi:10.1016/j.still.2005.02.011.
28. Griscom BW, Adams J, Ellis PW, et al. Natural climate solutions. Proc Natl Acad Sci USA. 2017;114(44): 11645–11650. doi:10.1073/pnas.1710465114.
29. Jansson C, Faiola C, Wingler A, et al. Crops for carbon farming. Front Plant Sci. 2021;12:938.
30. Kell DB. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. Ann Bot. 2011;108(3):407–418. doi:10.1093/aob/mcr175.
31. Paustian K, Lehmann J, Ogle S, et al. Climate-smart soils. Nature. 2016;532(7597):49–57. doi:10.1038/nature17174.
32. Sevenster M, Bell L, Anderson B, et al. Australian Grains Baseline and Mitigation Assessment. Main Report. CSIRO, Australia, 2022. doi:10.25919/j7tc-kz48.
33. Deines JM, Schipanski ME, Golden B, et al. Transitions from irrigated to dryland agriculture in the Ogallala Aquifer: land use suitability and regional economic impacts. Agric Water Manage. 2020;233:106061. doi:10.1016/j.agwat.2020.106061.
34. Ghimire R, Khanal BR. Soil organic matter dynamics in semiarid agroecosystems transitioning to dryland. PeerJ. 2020;8:e10199. doi:10.7717/peerj.10199.
35. Stone LR, Gwin RE, Gallagher PJ, et al. Dormant-season irrigation: grain yield, water use, and water loss. Agron J. 1987;79(4):632–636. doi:10.2134/agronj1987.00021962007900040010x.
36. Pierret A, Maeght JL, Clement C, et al. Understanding deep roots and their functions in ecosystems: an advocacy for more unconventional research. Ann Bot. 2016;118(4):621–635. doi:10.1093/aob/mcw130.
37. Page KL, Dang YP, Dalal RC, et al. Changes in soil water storage with no-tillage and crop residue retention on a Vertisol: impact on productivity and profitability over a 50 year period. Soil till Res. 2019;194: 104319. doi:10.1016/j.still.2019.104319.
38. Machado S. Soil organic carbon dynamics in the Pendleton long-term experiments: implications for biofuel production in Pacific Northwest. Agron J. 2011;103(1):253–260. doi:10.2134/agronj2010.0205s.
39. Ghimire B, Ghimire R, VanLeeuwen D, et al. Cover crop residue amount and quality effects on soil organic carbon mineralization. Sustainability. 2017; 9(12):2316. doi:10.3390/su9122316.
40. Liu C, Lu M, Cui J, et al. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob Chang Biol. 2014;20(5):1366–1381. doi:10.1111/gcb.12517.
41. Hazra KK, Nath CP, Singh U, et al. Diversification of maize-wheat cropping system with legumes and integrated nutrient management increases soil aggregation and carbon sequestration. Geoderma. 2019;353: 308–319. doi:10.1016/j.geoderma.2019.06.039.
42. Kirkby CA, Kirkegaard JA, Richardson AE, et al. Stable soil organic matter: a comparison of C:N:P:S ratios in Australian and other world soils. Geoderma. 2011; 163(3-4):197–208. doi:10.1016/j.geoderma.2011.04.010.
43. Kirkby CA, Richardson AE, Wade LJ, et al. Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol Biochem. 2013;60:77–86. doi:10.1016/j.soilbio.2013.01.011.
44. Gong XY, Chen Q, Lin S, et al. Tradeoffs between nitrogen- and water-use efficiency in dominant species of the semiarid steppe of Inner Mongolia. Plant Soil. 2011;340(1-2):227–238. doi:10.1007/s11104-010-0525-9.
45. Khosla R, Inman D, Westfall DG, et al. A synthesis of multi-disciplinary research in precision agriculture: site-specific management zones in the semi-arid Western Great Plains of the USA. Precision Agric. 2008;9(1-2):85–100. doi:10.1007/s11119-008-9057-1.
46. CTIC. 2011. National Crop Residue Management Survey data, Conservation Technology Information Center (CTIC). [cited 2021Dec 23] Available from: https://www.ctic.org/CRM.
47. Brown TT, Huggins DR. Soil carbon sequestration in the dryland cropping region of the Pacific Northwest. J Soil and Water Conserv. 2012;67(5):406–415. doi:10.2489/jswc.67.5.406.
48. Ghimire R, Thapa VR, Cano A, et al. Soil organic matter and microbial community responses to semiarid croplands and grasslands management. Appl Soil Ecol. 2019;141:30–37. doi:10.1016/j.apsoil.2019.05.002.
49. Norton JB, Mukhwana EJ, Norton U. Loss and recovery of soil organic carbon and nitrogen in a semiarid agroecosystem. Soil Sci Soc Am J. 2012;76(2): 505–514. doi:10.2136/sssaj2011.0284.
50. Wright AL, Dou F, Hons FM. Soil organic C and N distribution for wheat cropping systems after 20 years

of conservation tillage in Central Texas. Agric Ecosyst Environ. 2007;121(4):376–382. doi:10.1016/j.agee.2006.11.011.

51. Lampurlanés J, Plaza-Bonilla D, Álvaro-Fuentes J, et al. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res. 2016;189:59–67. doi:10.1016/j.fcr.2016.02.010.
52. Jemai I, Aissa NB, Guirat SB, et al. Impact of three and seven years of no-tillage on the soil water storage, in the plant root zone, under a dry subhumid Tunisian climate. Soil Tillage Res. 2013;126:26–33. doi:10.1016/j.still.2012.07.008.
53. Ghimire R, Norton JB, Stahl PD, et al. Soil microbial substrate properties and microbial community responses under irrigated organic and reduced-tillage crop and forage production systems. PLoS One. 2014;9(8):e103901. doi:10.1371/journal.pone.0103901.
54. Rosenzweig ST, Fonte SJ, Schipanski ME. Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems. Agric Ecosyst Environ. 2018;258:14–22. doi:10.1016/j.agee.2018.01.016.
55. Thapa VR, Ghimire R, Duval BD, et al. Conservation systems for positive net ecosystem carbon balance in semiarid drylands. Agrosyst Geosci Environ. 2019;2(1):1–8. doi:10.2134/age2019.03.0022.
56. Luo Z, Wang E, Sun OJ. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric Ecosyst Environ. 2010;139(1-2):224–231. doi:10.1016/j.agee.2010.08.006.
57. Jian J, Du X, Reiter MS, et al. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol Biochem. 2020;143:107735. doi:10.1016/j.soilbio.2020.107735.
58. Ledo A, Smith P, Zerihun A, et al. Changes in soil organic carbon under perennial crops. Glob Chang Biol. 2020;26(7):4158–4168. doi:10.1111/gcb.15120.
59. Liebig MA, Tanaka DL, Wienhold BJ. Tillage and cropping effects on soil quality indicators in the Northern Great Plains. Soil till Res. 2004;78(2):131–141. doi:10.1016/j.still.2004.02.002.
60. Nicoloso RS, Rice CW. Intensification of no-till agricultural systems: an opportunity for carbon sequestration. Soil Sci Soc Am J. 2021;85(5):1395–1409. doi:10.1002/saj2.20260.
61. Blanco-Canqui H, Mikha MM, Presley DR, et al. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci Soc Am J. 2011;75(4):1471–1482. doi:10.2136/sssaj2010.0430.
62. Frasier I, Noellemeyer E, Figuerola E, et al. High-quality residues from cover crops favor changes in microbial community and enhance C and N sequestration. Global Ecol Conserv. 2016;6:242–256. doi:10.1016/j.gecco.2016.03.009.
63. King AE, Hofmockel KS. Diversified cropping systems support greater microbial cycling and retention of carbon and nitrogen. Agric Ecosyst Environ. 2017;240:66–76. doi:10.1016/j.agee.2017.01.040.
64. Thapa VR, Ghimire R, VanLeeuwen D, et al. Response of soil organic matter to cover cropping in water-limited environments. Geoderma. 2022;406:115497. doi:10.1016/j.geoderma.2021.115497.
65. Feller C, Albrecht A, Blanchart E, et al. Soil organic carbon sequestration in tropical areas. General considerations and analysis of some edaphic determinants for lesser Antilles soils. Nutr Cycl Agroecosys. 2001;61(1/2):19–31. doi:10.1023/A:1013359319380.
66. Peterson GA, Westfall DG. Managing precipitation use in sustainable dryland agroecosystems. Ann Appl Biol. 2004;144(2):127–138. doi:10.1111/j.1744-7348.2004.tb00326.x.
67. Shaver TM, Peterson GA, Sherrod LA. Cropping intensification in dryland systems improves soil physical properties: regression relations. Geoderma. 2003;116(1-2):149–164. doi:10.1016/S0016-7061(03)00099-5.
68. Blanco-Canqui H, Holman JD, Schlegel AJ, et al. Replacing fallow with cover crops in a semi-arid soil: effects on soil properties. Soil Sci Soc Am J. 2013;77(3):1026–1034. doi:10.2136/sssaj2013.01.0006.
69. Agomoh IV, Drury CF, Phillips LA, et al. Increasing crop diversity in wheat rotations increases yields but decreases soil health. Soil Sci Soc Am J. 2020;84(1):170–181. doi:10.1002/saj2.20000.
70. Zhang D, Yao P, Zhao N, et al. Building up the soil carbon pool via the cultivation of green manure crops in the Loess Plateau of China. Geoderma. 2019;337:425–433. doi:10.1016/j.geoderma.2018.09.053.
71. Robertson F, Armstrong R, Partington D, et al. Effect of cropping practices on soil organic carbon: evidence from long-term field experiments in Victoria, Australia. Soil Res. 2015;53(6):636–646. doi:10.1071/SR14227.
72. Nielsen DC, Vigil MF. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron J. 2005;97(3):684–689. doi:10.2134/agronj2004.0071.
73. Mesbah A, Nilahyane A, Ghimire B, et al. Efficacy of cover crops on weed suppression, wheat yield, and water conservation in winter wheat–sorghum–fallow. Crop Sci. 2019;59(4):1745–1752. doi:10.2135/cropsci2018.12.0753.
74. Paye WS, Ghimire R, Acharya P, et al. Cover crop water use and corn silage production in -semi-arid irrigated conditions. Agric Water Manag. 2022;260:107275. doi:10.1016/j.agwat.2021.107275.
75. Bruun EW, Hauggaard-Nielsen H, Ibrahim N, et al. Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass Bioenergy. 2011;35(3):1182–1189. doi:10.1016/j.biombioe.2010.12.008.
76. Lee JW, Hawkins B, Day DM, et al. Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. Energy Environ Sci. 2010;3(11):1695–1705. doi:10.1039/c004561f.
77. Spokas KA, Cantrell KB, Novak JM, et al. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. J Environ Qual. 2012;41(4):973–989. doi:10.2134/jeq2011.0069.
78. Keith A, Singh B, Singh BP. Interactive priming of biochar and labile organic matter mineralization in a

smectite-rich soil. Environ Sci Technol. 2011;45(22): 9611–9618. doi:10.1021/es202186j.

79. Verhoeven E, Pereira E, Decock C, et al. Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. J Environ Qual. 2017;46(2): 237–246. doi:10.2134/jeq2016.10.0396.
80. Cayuela ML, van Zwieten L, Singh BP, et al. Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric Ecosys Environ. 2014; 191:5–16. doi:10.1016/j.agee.2013.10.009.
81. DuPont ST, Beniston J, Glover JD, et al. Root traits and soil properties in harvested perennial grassland, annual wheat, and never-tilled annual wheat. Plant Soil. 2014;381(1-2):405–420. doi:10.1007/s11104-014-2145-2.
82. Dietzel R, Jarchow ME, Liebman M. Above-and belowground growth, biomass, and nitrogen use in maize and reconstructed prairie cropping systems. Crop Sci. 2015;55(2):910–923. doi:10.2135/cropsci2014.08.0572.
83. Gale WJ, Cambardella CA, Bailey TB. Root-derived carbon and the formation and stabilization of aggregates. Soil Sci Soc Am J. 2000;64(1):201–207. doi:10.2136/sssaj2000.641201x.
84. Skinner RH, Comas LH. Root distribution of temperate forage species subjected to water and nitrogen stress. Crop Sci. 2010;50(5):2178–2185. doi:10.2135/cropsci2009.08.0461.
85. Bremer E, Janzen HH, McKenzie RH. Short-term impact of fallow frequency and perennial grass on soil organic carbon in a Brown Chernozem in Southern Alberta. Can J Soil Sci. 2002;82(4):481–488. doi:10.4141/S02-007.
86. Libohova Z, Seybold C, Wysocki D, et al. Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey Characterization Database. J Soil Water Conserv. 2018;73(4):411–421. doi:10.2489/jswc.73.4.411.
87. Olness A, Archer D. Effect of organic carbon on available water in soil. Soil Sci. 2005;170(2):90–101.
88. Clay D, Bly A, Briese L, et al. Voluntary versus state-based compliance markets in the United States. 2021. doi:10.1002/essoar.10507653.2.