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Review

Soil Health Assessment and Management Framework for Water-Limited Environments: Examples from the Great Plains of the USA

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Abstract: Healthy soils provide the foundation for sustainable agriculture. However, soil health degradation has been a significant challenge for agricultural sustainability and environmental quality in water-limited environments, such as arid and semi-arid regions. Soils in these regions is often characterized by low soil organic matter (SOM), poor fertility, and low overall productivity, thus limiting the ability to build SOM. Soil health assessment frameworks developed for more productive, humid, temperate environments typically emphasize building SOM as a key to soil health and have identified the best management practices that are often difficult to implement in regions with water limitations. This study reviewed existing soil health assessment frameworks to assess their potential relevance for water-limited environments and highlights the need to develop a framework that links soil health with key ecosystem functions in dry climates. It also discusses management strategies for improving soil health, including tillage and residue management, organic amendments, and cropping system diversification and intensification. The assessment of indicators sensitive to water management practices could provide valuable information in designing soil health assessment frameworks for arid and semi-arid regions. The responses of soil health indicators are generally greater when multiple complementary soil health management practices are integrated, leading to the resilience and sustainability of agriculture in water-limited environments.

Keywords: conservation agriculture; cover crops; semi-arid region; soil carbon; soil functions

1. Introduction

Farm productivity and economic profitability have been linked to effective soil health management [1–3]. Since the widespread adoption of the concept of healthy soil a few decades ago, there has been a consensus that soil health indicates the capacity of soils to function within an ecosystem and land-use boundaries, such as sustaining productivity, maintaining environmental quality, and promoting plant and animal health [4]. Soil health depends on complex biophysical and biochemical interactions in time and space, leading to the creation of a suitable environment for plant growth. It emphasizes soil as a living, dynamic system that provides multiple ecosystem services such as carbon (C) sequestration, nutrient cycling and storage, soil water retention and availability, erosion control, and crop productivity [5,6].

Soil health management in water-limited environments could benefit from an improved understanding of the linkages between soil health indicators and water conservation. However, such information is lacking, in part due to the relatively low adoption of soil health management practices, such as cover crops, improved crop rotations, conservation tillage, etc., in water-limited environments compared to more mesic or humid environments, or due to challenges in implementing soil health-promoting practices in semi-arid row crop systems because of the short-term losses in profitability. In addition, soil organic matter (SOM) has been the central component of soil health assessment due to its perceived impacts on soil's physical, chemical, and biological properties. While numerous studies have shown the critical role of SOM content in soil biological activity and diversity, nutrient cycling, cation exchange capacity (CEC), soil bulk density, aggregate stability and structure, and water storage and infiltration [7–10], the response of SOM to management changes in water-limited environments is typically very slow. Measurable changes in SOM accumulation can take decades in arid and semi-arid regions because precipitation limits plant biomass production and soil C inputs [11–13]. Producers and landowners in dry areas are looking for indicators that are more responsive to management changes while being inexpensive, reproducible, accessible through commercial laboratories or at-home testing, and able to provide management guidance [8].

Measuring responsive parameters such as microbial communities (specifically, fungal communities), enzyme activities, and labile SOM components could be valuable for water-limited regions. Saprophytic fungi and arbuscular mycorrhizal fungi (AMF) have survived and functioned better than most bacterial groups in semi-arid areas [12,14]. These fungal groups can also respond faster to sudden increases in soil moisture than bacterial communities in semi-arid regions. Similarly, labile soil organic C (SOC) and nitrogen (N) components can respond to management changes within 2–4 years [11,15,16]. The SOM components that serve as early indicators of soil health improvements include mineralizable C (soil respiration) and N, permanganate oxidizable C (POXC), particulate organic matter (POM), microbial biomass C (MBC) and N (MBN), dissolved organic C and N, and available soil nutrients [17,18]. Soil physical indicators such as aggregate stability, infiltration rates, and saturated conductivity (Ksat) can also respond rapidly to management changes [19]. Specifically, soil aggregate stability could be a valuable physical indicator of soil health in arid and semi-arid regions due to its rapid response to management changes, its relationship with many soil functions, and its sensitivity to changes in management [20]. Well-aggregated soils increase infiltration rates, thus improving water capture and storage compared to poorly aggregated soils. Studies demonstrated a rapid increase in soil aggregate fractions with cover cropping in the limited irrigation and dryland conditions of the central and southern Great Plains [7,21]. Small proportional changes in surface soil C (<20% increase) were positively associated with much larger changes in soil aggregation (>200% increase) and microbial biomass (>300% increase) in intensified, continuous dryland cropping systems relative to traditional wheat (*Triticum aestivum* L.)-fallow rotations [22]. Similarly, the higher soil water infiltration in continuous wheat was attributed to the greater aggregate stability compared to that in the wheat-sorghum (*Sorghum bicolor* L. Moench)-fallow rotation in semi-arid Texas High Plains [23].

No specific set or number of indicators or threshold scores define healthy soil. Soil health varies within soil types, climates, environmental conditions, and agricultural management practices [24]. The selection of the appropriate indicators will help producers and landowners identify the right management strategies to improve soil health. In arid and semi-arid regions, these indicators should be low-cost, sensitive to management changes, and responsive to soil water dynamics. This review discusses approaches for soil health assessment, examines the linkages between different soil health indicators and soil functions in water-limited environments, and ultimately discusses alternative management practices with the potential to improve soil health and agricultural sustainability.

2. Approaches for Soil Health Assessment

Soil health assessment indicates how well soil contributes to ecosystem services and can predict the ability of soils to provide those services if an adopted management scenario continues. Soil health is often evaluated by measuring various indicators within three main categories: physical, chemical, and biological properties of soil, which provide insight into key soil functions. Soil physical indicators primarily reflect limitations to seedling emergence, root growth, and soil water infiltration or the movement and storage of water in the soil profile. Examples of physical soil health indicators include the topsoil depth, bulk density, porosity, aggregate stability, infiltration rate, texture, crusting, and compaction [19]. Soil chemical indicators often relate to soil nutrient availability and the ability of soils to support plant nutrient uptake. Soil pH, electrical conductivity (EC), SOM, cation-exchange capacity, nutrient concentrations, and elements that may be potential contaminants (heavy metals, radioactive compounds, etc.) are important chemical indicators, while soil biological communities (macro- and microorganisms) of different sizes, diversity, and activities serve as the biological indicators of soil health [15–18]. Soil microbial communities are central to multiple ecosystem services, and they both drive and are constrained by many physical and chemical soil processes.

The relevance of different soil functional indicators changes from site to site. The relative importance of indicators related to soil water functions, such as water movement and retention, would be greater for arid and semi-arid regions. In contrast, nutrient provisioning and availability may be prioritized in areas with plenty of water. The indicators selected for assessing soil health must be: (a) responsive to changes in climate and soil management practices so that growers can use them as a basis for prioritizing management practices, (b) easy to sample, measure, and interpret for growers, (c) cheap and relatively accessible to many growers and applicable to field conditions, and (d) able to represent critical agronomic and soil ecological processes [6,20]. Soil health indicators developed for more productive, humid regions may not be responsive to management changes in water-limited environments due to the differences in the soil type, climate, crops and cropping intensity, and agricultural management practices.

Current soil health assessment frameworks do not account for regional differences in climate, soil conditions, and management. Different government agencies, non-government organizations, and universities have developed metrics for soil health assessment that may have broader relevance. For instance, Cornell University's comprehensive soil health assessment (CASH) identified 39 potential indicators [20] and narrowed them down to 12–13 parameters to make the evaluation simple, cost-effective, and universal. These indicators are aggregate stability, penetration resistance, available water capacity, bulk density, soil pH, phosphorus (P), potassium (K), nitrate-N, organic matter content, soil proteins, soil respiration, and soil pathogen population. The Soil Health Institute (SHI) has also endorsed 18 primary indicators as "Tier 1" and 12 secondary indicators as "Tier 2" [25]. The "Tier 1" list mostly included physical and chemical components rather than biological ones. The United States Department of Agriculture's Natural Resources Conservation Service (USDA-NRCS) proposed a similar set of physical (aggregate stability, available water capacity, bulk density, infiltration, slaking, soil crust, soil structure, and macropores), chemical (reactive carbon, soil EC, soil nitrate, and soil pH), and biological (earthworm count, POM, potentially mineralizable N, soil enzymes, soil respiration, and total organic C) indicators [26]. In these various soil health assessment matrices, soil properties identified as major indicators are a group of soil properties that have defined thresholds (i.e., rankings of poor to good) or have been benchmarked nationally [19]. The Soil Management Assessment Framework (SMAF) [27] and the Haney Soil Health Test (HSHT) [28] have also proposed a suite of indicators for monitoring soil health, but they are not as comprehensive as the CASH, SHI, or USDA-NRCS frameworks for soil health assessment. The Haney test does not even provide region-specific soil health information. More recently, the Soil Health Assessment Protocol and Evaluation (SHAPE) tool has been proposed to help overcome the geographical limitations of SMAF and CASH by leveraging a nationally distributed dataset and incorporating more edaphic and climatic factors [29]. Similarly, Zvomuya et al. [30] emphasized certain indicators such as soil salinity (EC), cation exchange capacity, and calcium carbonate content for arid and semi-arid regions. However, these regionally relevant parameters are not emphasized in the major soil health assessment frameworks.

In all soil health assessment frameworks, high emphasis is given to indicator selection. While indicator selection is critical, soil health assessment goes beyond identifying indicators. Typical steps in the development of the assessment framework involve quantifying the response of selected soil indicators, providing an appropriate score for each indicator based on the criteria set for defining the weight of each parameter, creating assessment metrics, and, finally, assigning soil health scores (Figure 1). There are multiple ways to integrate data into a final soil health score. Some approaches for integrating the measured indicators and developing the soil health index include: (i) weighted additive scores for individual indicators and (ii) the use of statistical tools such as multiple regression, principal component analysis, or factor analysis [21,31,32]. Expert opinion can also be used for scoring soil health [33]. However, these steps are not regionally tailored to address soil health issues specific to a particular region or specific soil functions and have a regionally tailored assessment matrix. Therefore, developing a regionally tailored scoring matrix that emphasizes water-sensitive indicators could provide a more representative soil health assessment framework for water-limited environments. More research on region-specific minimum data development and alternative scoring functions based on the relative response of indicators is needed for effective soil health assessment in regions varying in soils, climate, and agricultural systems.

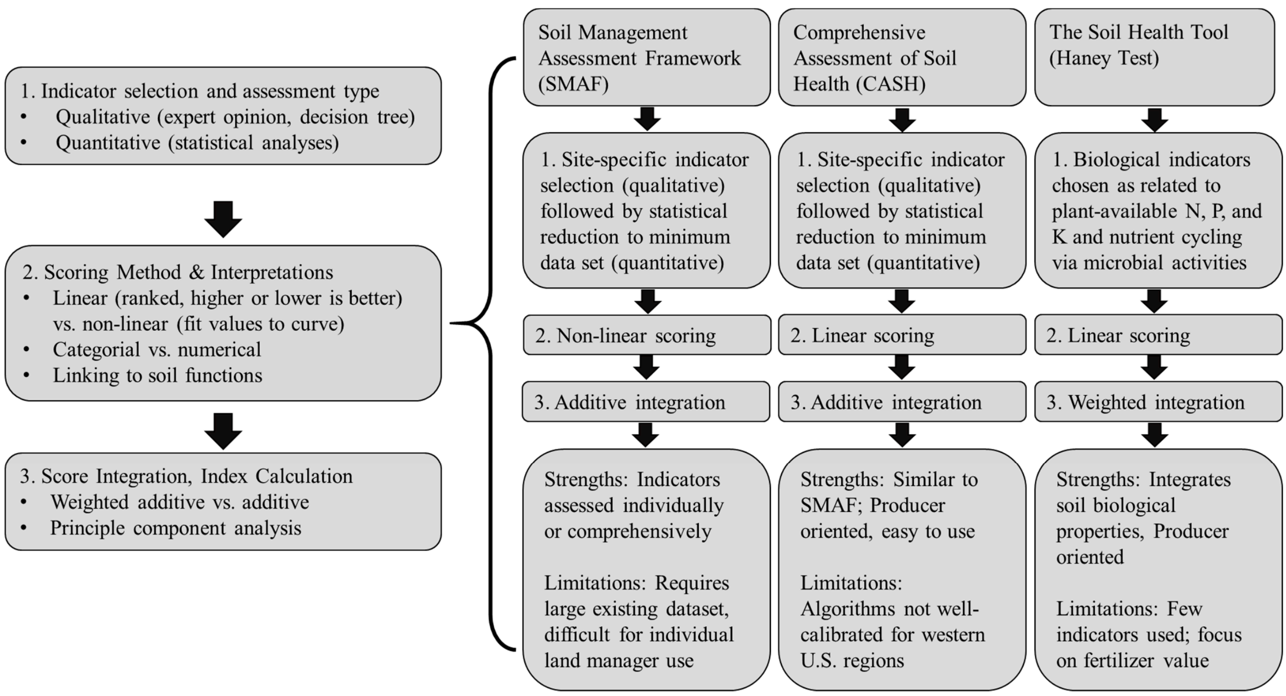

Figure 1. Sequential steps in soil health assessment, with examples shown for commonly used soil health index tools in the U.S. under various frameworks.

There has been a widespread interest among researchers, policymakers, and agricultural stakeholders in soil health assessment and management. The Soil Health Institute's North American Soil Health assessment project evaluated 31 different soil health indicators on soil samples collected from 125 long-term agricultural research sites across North America. This project aimed to give farmers, ranchers, and others science-based measurements for evaluating the health of their soils. This project can provide information on region-specific as well as universal indicators for assessing soil health by engaging farmers and agricultural stakeholders in identifying and prioritizing soil health indicators, developing assessment metrics, and interpreting soil health results. Given that soil has enormous heterogeneity, soil management is site-specific, and its ecosystem services vary with the soil and climatic condition. In addition, soil health management is linked with agricultural sustainability and environmental quality. Most indicators are developed based on research conducted in experimental farms with replicated plots or a small field section and are not validated on working farms, where direct replication is generally not possible. This means that the conditions under which they are developed vs. used may not be comparable (e.g., [27]), which adds to the complexity of employing them for on-farm soil health assessment. The broader validation of soil health indicators through on-farm testing and the engagement of stakeholders in the process (Figure 2) will establish the soil health assessment framework with broader acceptance.

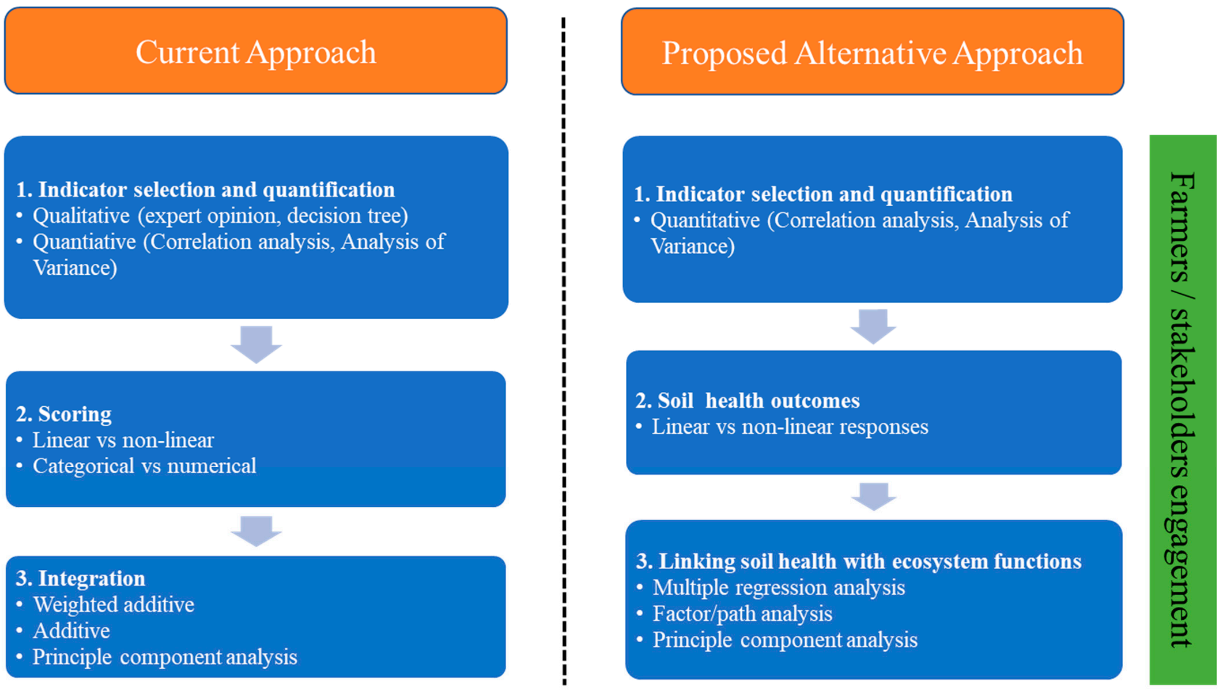

Figure 2. Current and proposed framework for soil health assessment in water-limited environments.

Current soil health assessment does not consider inputs from stakeholders. Accounting for region-specific differences in the response of various indicators, engaging stakeholders in soil health assessment, and linking soil health assessment with key ecosystem services could benefit farmers and landowners in arid and semi-arid regions. Different indicators should be used depending on the soil health goals or targeted soil use. Engaging stakeholders in selecting the most representative indicators, on-farm trials, and goal-based indicator identification could enhance the adoption of soil health practices. The adoption rate of soil health practices is often higher when farmers experience changes in their observations.

3. Linking Soil Health with Essential Water Functions

Developing an effective and reliable soil health assessment framework for water-limited environments requires an improved understanding of the linkages between soil health indicators and essential water functions. The ability of soils to infiltrate and retain precipitation or irrigation water is a function of soil physical properties such as aggregation, porosity, compaction, and soil texture, as well as site factors such as slope, residue cover, and surface roughness. Soil aggregate formation is strongly influenced by soil biology, particularly soil fungi [34], rooting activity, and soil macrofauna [35]. Soil chemical properties such as pH, EC, SOM content, and nutrients determine the diversity and abundance of microbial communities. Fungal communities respond rapidly to management changes; they respond even in sandy soils (55% sand content) before detectable changes in SOM were observed in the Great Plains semi-arid region [36]. Various physical, chemical, and biological soil properties influence soil functions that have implications for soil water conservation (Table 1). However, their direct and indirect relationships with essential water functions have not been studied well in arid and semi-arid regions. Measuring the response of soil properties, including more sensitive biological communities or processes, along with water storage and movement, is likely essential for comprehensive soil health assessment in water-limited environments.

Table 1. Soil health indicators, their functions, and their implications for soil water conservation.

Indicator/Method	Soil Function	Implications for Water Conservation and Related Soil Functions
Physical		
Bulk density	Porosity	Higher water infiltration with less compaction
Soil texture	Porosity	A direct baseline measure of soil water storage capacity
Soil aggregates (%)	Soil structure	Soil structure, higher water storage in well-aggregated soil
Wet aggregate stability	Soil structure	Capacity of soil to resist crusting and water erosion and to facilitate infiltration
Water infiltration	Soil water dynamics	Soil water capture, water use efficiency, and heat transfer
Soil water retention	Soil water dynamics	Soil water storage and plant available water
Soil depth	Soil water dynamics	Soil water storage and availability for crops
Chemical		
Soil pH	Soil acidity/alkalinity	Nutrient availability, creating a suitable environment for plant and microbial growth
Electrical conductivity	Salinity	Nutrient availability, plant and microbial growth, soil structure, and water-holding capacity
Soil organic C	Microbial substrate availability, nutrient provision, buffering	Direct measure of SOM status (58% of SOM) and baseline potential of water storage
Plant available nutrients	Nutrient provision	Nutrient availability for crop and microbial growth
Biological		
Microbial biomass C	Microbial community size	Soil processes such as decomposition, N fixation, C sequestration, nutrient availability
FAME profiling Fungal: AMF, saprophytic; Bacteria: G+, G−, Actinobacteria	Microbial community size and diversity of microbial groups	Mediate key soil processes such as decomposition, nutrient cycling, and water uptake, especially depending on the microbial groups (e.g., higher fungal populations can provide greater decomposition, cementing agents for aggregate stability, and a higher diversity of enzymes in soils to decompose a wide variety of substrates). AMF can provide an additional benefit to drought resilience.
Three-day CO_2 mineralization	Microbial activity	Indicate decomposition vs. sequestration of carbon, SOM storage, nutrient/water cycling
Particulate Organic Matter (POM)	Fresh residue C	Early indication of C sequestration and water conservation
Permanganate oxidizable carbon (POXC)	Diversity of C sources	This C pool can represent simple C sources available for microbial decomposition, substrates from root exudates, and microbial biomass C.
N mineralization	Crop N supply	Integrative indicator of labile N and microbial activity for increasing N availability
Enzyme activity assays: *β-glucosidase*, *β-glucosaminidase*, *acid/alkaline phosphatase*, *arylsulfatase*	Nutrient cycling	Indicator of potential enhancement in SOM and nutrient cycling and availability with a direct linkage to water changes in soil
Soil macrofauna	Residue/nutrient turnover	Soil aggregation and water dynamics, decomposition and nutrient cycling, pest control

The soil health literature often cites the general claim that increasing SOM by 1% enhances the water-holding capacity by >250,000 L ha^{-1} (25 mm) [37]. While there is generally a positive correlation between SOM and water-holding capacity [38], this relationship is influenced by multiple factors [39,40]. In addition, SOM changes may be relatively small and take decades to detect in arid and semi-arid environments. Therefore, increasing SOM enough to have a meaningful impact on soil water holding capacity is challenging in environments where an increase in SOM by 1% often represents a doubling of baseline SOM stocks. Since building SOM in water-limited environments can be quite difficult and it can take many years to generate detectable changes, there are approaches that could provide some insights into compositional changes in SOM that may affect soil water dynamics. The evaluation of SOM components such as mineralizable C (soil respiration) and N, POXC, POM, MBC, MBN, dissolved organic C and N, and available soil nutrients could serve as an early indicator of soil health improvements [17,18]. Similarly, isotopic methodologies can be explored to better characterize compositional changes in SOM dynamics and how not only soil management but also more frequent droughts and climate variability in semi-arid regions interfere with soil health and productivity.

The selection of indicators in soil health assessment should reflect soil water functions and beyond, e.g., soil erosion, biodiversity conservation, dust prevention, SOC sequestration, etc., to become more effective for water-limited environments. Risks associated with the implementation of soil health management systems in water-limited environments vary with the evapotranspiration gradient, with considerably higher risks in the hot, dry areas than in temperate drylands, where the majority of dryland cropping systems still include summer fallow [41]. However, there is a significant knowledge gap in soil health management in water-limited environments due to the lack of research-based information in understanding the relationship between various soil health indicators and essential soil water functions. The more rapid response of parameters such as microbial communities (specifically, fungal communities), enzyme activities, and labile SOM components could provide valuable insight into soil health management in water-limited environments. Similarly, soil aggregate stability could be a valuable physical indicator of soil health in arid and semi-arid regions. However, quantifying the relationship of these soil properties with soil water functions is critical for a reliable estimate of soil health in water-limited regions.

4. Implementing Soil Health Management to Improve Water Functions

Linkages between soil health and water functions in dry environments can be established by an improved understanding of the interaction between soil management, soil health indicators, and water functions related to these dynamic soil properties (Figure 3). Management selection in arid and semi-arid regions is affected by low rainfall, high climatic variability (specifically, heat and drought), and low inherent soil fertility statuses. Options for soil health improvement are limited, and the relative response of selected soil health management systems is small. Understanding the complex interactions between climatic factors, inherent and dynamic soil properties, and associated soil functions can help in designing the best management practices. Therefore, management selection should emphasize practices adapted to arid and semi-arid regions. Alternative soil management practices, their soil health response, and their linkages to soil water functions are discussed in the following sections.

4.1. Minimizing Soil Disturbance

Soil disturbance disrupts soil's physical structure, impacting soil's biological communities and associated microbially mediated processes. Tillage is the major disturbance activity in cultivated soils, which is typically practiced for seedbed preparation, weed control, crop residue mixing and incorporation, and fertilizer and amendment application. Producers in semi-arid row crop environments may also employ tillage to increase soil aeration and disrupt soil surface crusts formed after rainfall events. However, these benefits are short-term; a poor soil structure can cause several soil issues. Intensive tillage exposes soil to direct raindrop impact at the surface, thereby increasing the susceptibility of aggregates to disruption [42]. It reduces water and air-filled pore spaces between aggregates, thus restricting infiltration, increasing surface crusting, and leading to wind and water erosion. In addition, it disrupts roots and fungal hyphal networks, reducing the enmeshing action of soil particles in those hyphal networks, and decreases aggregate stability [34]. Increased soil temperature and soil aeration from tillage are expected to increase soil microbial activity, thereby increasing SOM mineralization, in which SOC is converted to carbon dioxide (CO_2)

and lost to the atmosphere [43]. Additionally, while tillage can stimulate microbial activity, it typically has negative impacts on soil macrofauna communities, so all of the functions they provide are diminished, especially those related to soil structure [44]. Earthworms are probably the most important soil engineers, at least where there is adequate moisture, and they are also the most susceptible organisms to tillage [35]. Therefore, intensive tillage often leads to poor soil health and inefficient water capture and use because of the poor soil structure and low SOM content.

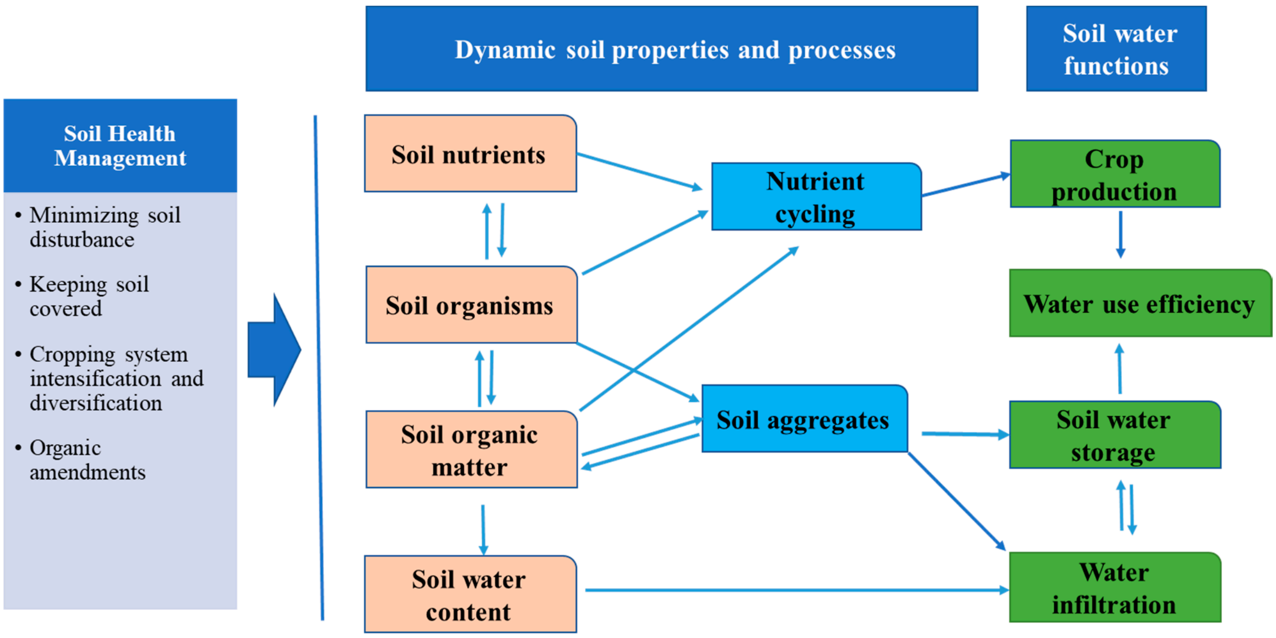

Figure 3. Interactions among soil management, soil health status, and soil functions in a water-limited environment.

Reducing tillage frequency and intensity can increase fungal growth, aggregate formation and stability, SOM accumulation, and soil health improvements by reversing the negative effects of intensive tillage. A study in eastern Montana and western North Dakota showed that conventional tillage increased the CO_2 flux by 62–118% as compared to no-tillage [45], while a study in eastern New Mexico reported a 26% greater wet aggregate stability and 9–15% greater permanganate oxidizable C under a 0–20 cm depth of no-tillage and strip-tillage compared to conventional tillage [46]. Research from Akron, Colorado, revealed that no-tillage and reduced-tillage resulted in 21% more SOC at the 0–30 cm depth than conventional tillage and moldboard plow [47]. Although minimizing soil disturbance through conservation tillage has also been linked to increased water infiltration, erosion resistance, soil aeration, and soil C stabilization [42,48], a quantitative relationship between soil aggregation, SOC storage, and soil water functions has not been established in these studies. Similarly, reduced- and no-till systems have been shown to support soil macrofauna communities in irrigated systems of eastern Colorado, along with associated improvements in soil aggregation and water infiltration [9,44]. Comprehensive research on the linkages between soil health improvements with reduced- and no-tillage management and soil water functions, including infiltration and water storage, will help design the best soil management practices for arid and semi-arid environments.

4.2. Keeping the Soil Covered

Maintaining soil cover with living or dead crop residues provides another mechanism for enhancing soil health and water functions in water-limited regions. Residue cover protects soil from wind and water erosion, while crop residue removal can reduce SOM by reducing C inputs and increasing susceptibility to soil loss. Soil cover increases precipitation storage efficiency and reduces the soil evaporation rates, making more soil moisture available for plant use [49]. Crop residue accumulation after 12 years of no-tillage management in three sites in eastern Colorado increased water sorptivity via improving soil aggregation, bulk density, and porosity and favored greater water infiltration and precipitation use efficiency [50]. Moreover, the surface cover reduces soil compaction by dissipating the raindrop energy, suppresses weed growth by limiting the amount of sunlight available to weed seedlings, and provides a protective habitat for soil organisms, positively affecting soil health. Carbon and other essential elements in the plant residues become a source of nutrition for soil flora and fauna, including bacteria and fungi, which mediate 90% of the soil ecosystem functions [51]. In semi-arid western Kansas, fields with spring triticale (×*Triticosecale* Wittm.) and spring lentil (*Lens culinaris* Medik.) residues had greater soil aggregates than bare soil, with spring lentils reducing the wind erodible fraction by 160% [52]. Dryland studies in Nebraska have demonstrated that wheat stubble increased the non-growing season soil water storage by 2–2.5 inches compared to bare soil [53]. After four crop seasons, SOC and total N, light fraction organic matter-C, and N were greater in soils with straw retention than in those with straw removal in semi-arid Canada [54]. Govaerts et al. [55] also reported that the SOC and total N were 1.15 and 1.17 times greater with straw retained than with straw removed, respectively, in semi-arid Mexico.

Keeping the soil covered by cover crops provides vegetative cover, controls soil erosion, enhances soil aggregation, adds organic matter, and increases soil biological activity [15,52], which could significantly improve soil water functions. Besides providing ground cover, cover cropping can maximize cropping intensity and diversity, thereby contributing to increased microbial substrate diversity, the proliferation of diverse soil organisms, and improved nutrient cycling. Dryland cropping systems with a history of winter cover crops (rye (*Secale cereale* L.)) improved soil microbial biomass and enzyme activities compared to cropping systems without winter cover crops [12]. Replacing fallow with hairy vetch (*Vicia villosa* Roth), rye, and mustard (*Brassica juncea* L.) as winter cover crops increased the mean weight diameter of dry soil aggregates and the wet aggregate stability in sweet corn (*Zea mays* L.)-fallow rotation in central and southern New Mexico [56]. However, growing cover crops in arid and semi-arid regions can deplete soil water storage, affecting the subsequent crop yield. A study on soil water storage with cover cropping in irrigated corn demonstrated a depletion in soil water at cover crop termination but greater soil water storage at the main crop harvest, suggesting overall positive effects of cover cropping on soil water storage [57]. While this study suggests that a careful selection of cover crop species and planting and termination timing could benefit cropping systems, it also discusses a complex relationship between soil health and water dynamics.

4.3. Cropping Systems Intensification and Diversification

Farmers have been attempting the intensification and diversification of cropping across arid and semi-arid regions. However, their response to soil health and water dynamics is inconsistent across the regions. For example, cover crops could be a promising option for increasing the complexity of rotations and extending the duration of photosynthetic capture in annual crop rotations, thus increasing organic C inputs to the soil. Increasing crop diversity with cover cropping can also diversify microbial substrates and support long-term improvements in soil health. Legume species in cover crop mixtures can fix atmospheric N in their root nodules and increase the soil N content, while grass cover crops have a dense fibrous root system and produce more root biomass, contributing to greater root-derived C in the soil [58]. The greater root biomass and length density of grass cover crops increase root channels and improve soil aggregation through enmeshing action. The rhizosphere of living brassica species, i.e., canola (*Brassica napus* L.) roots, releases a fumigant-like compound (2-phenylethyl isothiocyantae) that helps suppress pest populations and soil-borne diseases [59]. Diversified cropping systems improve the retention and cycling of nutrients and maintain soil biodiversity [60]. Research from semi-arid western Kansas comparing winter triticale, winter lentil, spring lentil, spring pea

(*Pisum sativum* L.), and spring triticale cover crops revealed an up to 12.2–17.4% increase in SOC (0–10 cm depth) with spring pea than with continuous winter wheat and fallow [52]. Mixtures of legumes, grasses, and oilseed cover crops produced greater belowground biomass, root C and N, and soil biodiversity than either species alone [61,62]. In eastern New Mexico, diverse cover crops that included cereals, legumes, and brassicas had 31% and 41% greater microbial community sizes and fungal fatty acid methyl ester (FAME) markers, respectively, at a 0–15 cm depth compared to fallow [15]. A six-species mixture of legumes, grasses, and brassicas in the same study plots increased the combined enzyme activity of acid phosphatase, β-glucosidase, and β-glucosaminidase by 44% and that of potentially mineralizable C (PMC) by 39% at termination time compared to fallow [11,15].

Crop rotations, which include growing a variety of crop species, can benefit the soil food web, improve nutrient cycling, and reduce soil-borne diseases and pests [15,19,21]. Crop rotation and intensification using a variety of crops, including low-water users, taproots, fibrous roots, high-C crops, legumes, and non-legumes, increase soil cover, contributing to key functions such as rainfall infiltration, SOM formation, and stabilization [21]. Several on-farm and research station experiments across the Central Great Plains have demonstrated that crop diversification and reducing the frequency of summer fallow periods through cropping intensification can improve the chemical, biological, and physical metrics of soil health, supporting improved profitability [22]. Cotton (*Gossypium hirsutum* L.), when rotated with peanut (*Arachis hypogaea* L.), sorghum, rye, or wheat, increased enzyme activities in comparison to continuous cotton in semi-arid soils from west Texas [63]. Another study from Akron, Colorado, reported greater soil fungal markers in rotations that reduced fallow and increased crop diversity from a typical winter wheat-fallow to a corn-proso millet (*Panicum miliaceum* L.)-winter wheat or corn-fallow-winter wheat for 15 years [64]. These shifts in the microbial community composition led to an increase in C and P cycling enzyme activities in both diversified rotations. Both SOC and total N were higher for sorghum-wheat-soybean (*Glycine max* L.) than for continuous sorghum from 0–55 cm in central Texas [65]. Intensive cropping (wheat-soybean double-crop and sorghum-wheat-soybean) increased SOC by 15–21% and total N by 19% at depths of 0–55 cm compared to continuous soybean, regardless of the tillage regime [66].

Improved knowledge of the relationship between soil health and soil water dynamics could help develop a soil health framework for water-limited regions because the potential longer-term benefits of cropping system intensification regarding soil health may have variable effects on soil water functions. For example, changes in the soil water content, infiltration, and water conservation in intensified rotations can have short-term trade-offs with crop productivity in water-limited regions [67,68]. A study in eastern NM revealed that, although the cropping system scale water balance was positive for the cover crop-corn rotation, the cover crops depleted 47–91 mm of soil water during their growth [57]. If rainfall or irrigation water is not available during the early growth of the main crop, the cash crop yield might be significantly reduced. Soil health indicators that capture system-level responses may not represent the seasonal and inter-annual dynamics of soil water storage and depletion. Therefore, careful planning and selecting the right crop or cover crops in the rotation are essential for agricultural sustainability and soil health in water-limited regions.

4.4. Role of Organic Amendments in Soil Health and Water Dynamics

Because increasing C inputs in arid and semi-arid areas are limited by water availability, organic amendments, such as manure and compost, could be a low-cost alternative for rapidly improving soil health and sustaining crop production in water-limited environments, especially in areas close to feedlots, dairies, or similar operations. Dairy enterprises are concentrated in eastern New Mexico, where about 329,000 milking cows produce more than 1.2 million metric tons of dry manure annually [69,70]. Similarly, beef cattle produce an additional 1.2 million metric tons of dry manure annually in eastern Colorado [71]. Since eastern New Mexico and Colorado have surplus manure from dairy and beef cattle, this represents a potentially convenient and inexpensive option for improving soil health, farm productivity, and profitability. Composted manure can increase nutrient availability, SOM storage, soil biological activity, aggregation, water-holding capacity, and aeration, ultimately supporting crop production and promoting the rural economy [72,73]. Moreover, heat generated during composting reduces weed seeds and pathogens [73]. Manure and composts often release nutrients slowly and can increase nutrient-use efficiency compared to chemical fertilizers. Recent studies in the central and southern Great Plains regions show that selected soil health indicators, including aggregation, enzyme activity, and particulate organic matter, respond positively to compost applications [74–76]. However, eastern New Mexico/West Texas farmers typically apply composted dairy manure based on crops' N needs, which may adversely affect soil health by creating an imbalance in other soil nutrients and an accumulation of salts [77,78]. The global warming potential of N in the form of increased N_2O emissions following compost application could also be a concern. However, associated increases in SOC can help offset the global warming potential of N in compost in semi-arid soils [79,80].

While improved soil microbial and biochemical functioning with poultry litter application has been reported [81], organic fecal materials such as manure derived from livestock contain organically bound N, P, K, calcium (Ca), and micronutrients, which might not be readily available for crops [81]. A high rate of manure and compost can also lead to salt accumulation [74]. The high salt concentration in soils decreases the microbial population and soil water potential, creating a water deficit condition and subsequently reducing the water use efficiency of crops. Additionally, a high accumulation of P and K in the soil increases the runoff and leaching of these nutrients, increasing environmental risks such as eutrophication. Therefore, salt accumulation should be carefully considered in nutrient management plans that integrate organic fecal materials in cropping systems. In addition, the challenges semi-arid and arid regions may experience are the hot temperatures associated with the faster decomposition of the compost and the lower long-lasting effects of the organic compost substrates in the soil. Organic amendment application should be integrated with other soil health practices that provide ground cover and lower soil temperature, thereby reducing the rate of organic matter decomposition and loss [43,74].

5. Challenges and Opportunities in Soil Health Assessment and Management in Water-Limited Regions

The soil health assessment and management framework for arid and semi-arid regions should be cost-effective, feasible, and linked to soil water conservation. Although there is no consensus on soil health indicators for water-limited environments, the importance of adopting alternative management to improve soil health is well-established. There are many challenges in identifying a minimum set of indicators for soil health assessment and using certain soil management practices in water-limited regions (Figure 4). Limited data on soil health responses to alternative management practices and their relationship with soil water functions are available, and the available data show highly variable responses to management alternatives. For example, cover crops may deplete soil water and nutrients and negatively impact the subsequent cash crop yield if careful planning and management for planting, species selection, and termination are not adopted. The early termination of cover crops in hot and dry regions could maintain soil moisture for the following cash crop but may not accumulate as much biomass carbon as needed to increase SOM. Inter-seeding cover crops into main crops should be carried out carefully to avoid competition between cover crops and the cash crop for water and nutrients. While inter-seeding before the main crop canopy closure or prior to harvest, when the crop canopy begins to re-open, would minimize the competition for water and nutrients, overcoming challenges in adopting soil health practices, such as selecting cover crop species that are drought- and shade-tolerant and relatively easy to establish would increase the possibility of improving soil health in water-limited areas.

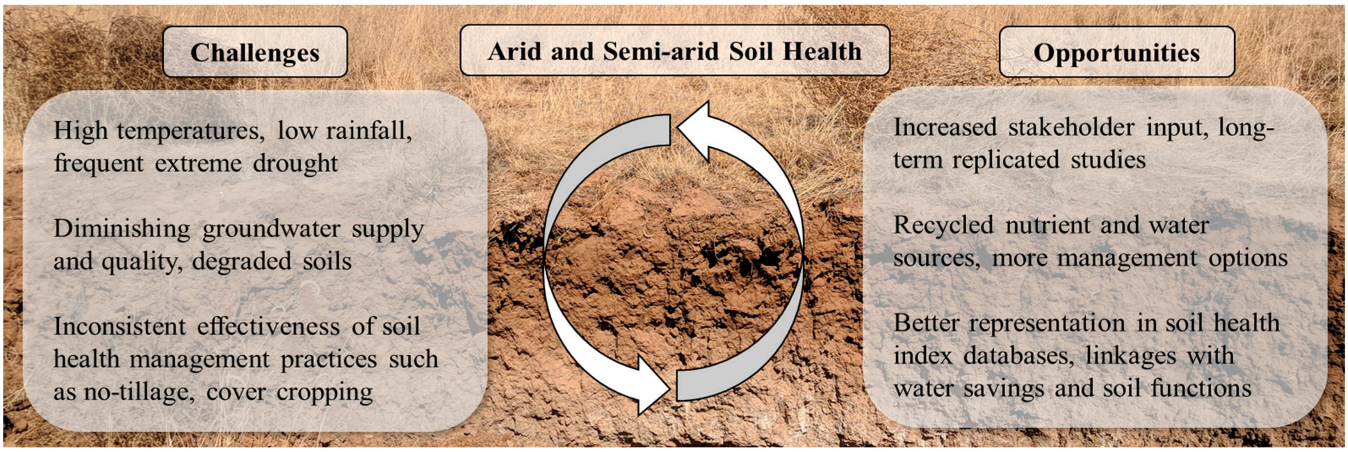

Figure 4. Challenges and opportunities of soil health assessment and management in arid and semi-arid (water-limited) environments of the western United States.

Multiple soil health management practices are often practiced together to enhance soil health benefits. Although the relative response of management strategies is variable, adopting multiple practices often provides synergistic, additive effects on soil health. A recent study that examined crop water use in a semi-arid cotton system after decades of implementing no-till practices with a rye or mixed species cover showed that, even though water use by cover crops depleted soil water prior to termination, which persisted in the early stages of cotton growth, the addition of cover crops resulted in greater water infiltration and storage throughout the growing season compared to conventionally tilled continuous cotton [82]. Similarly, cover crops and irrigation enhanced soil enzyme activities and promoted soil microbial community development [15,83]. Fields covered with cover crops and conservation tillage practices had 5 to 6 °C lower soil temperature and 3.5 to 4.9 °C lower soil surface air temperature and stored more soil water than conventional tillage without cover cropping in eastern New Mexico [84]. Similarly, rye, as a no-tilled cover crop, increased SOC, reduced penetration resistance, and increased infiltration by 34% compared to conventional tillage without cover crops in a 0–10 cm depth of cotton cropping systems in Lubbock, Texas [85]. A recent study across 96 dryland no-till fields in eastern Colorado and western Nebraska found 17% more SOC at 0–10 cm, twice as much aggregate stability, and three times greater fungal biomass in continuous rotations (no summer fallow) than in wheat-fallow [22]. Another study comparing diverse long-term cropping systems across the Great Plains revealed greater microbial biomass and mineralizable N under reduced-till diversified crop rotations than under conventional crop-fallow systems [56]. Planting winter and summer annual crops (corn, proso millet, and sunflower (*Helianthus annuus* L.) in sequence with winter wheat and fallow improved pest management in Akron, Colorado [86]. Another study in eastern New Mexico showed that cover crops significantly reduced the soil volumetric water content at cover crop termination and up to 30 days after sorghum planting [57]. However, the total soil water extraction at sorghum harvest was 8–89% higher under fallow than under cover crops, leading to an 18–23% greater forage sorghum yield after cover crops than after fallow. Therefore, cropping systems representing maximum biomass production and eventually returning to the soil are crucial for enhancing SOC, nutrient cycling, and aggregate stability, thereby improving soil health.

Climate change has added complexity to soil management and agricultural sustainability in dry environments. Increased temperature and a decreased amount and increased variability in the amount, intensity, and frequency of precipitation added challenges to agricultural production in water-limited environments of the Great Plains [8]. As the water supply is projected to decrease in the region, the importance of management practices that improve soil health is even greater in helping producers adapt to a changing climate.

Therefore, the development of a soil health assessment and management framework that is cost-effective, feasible, and promotes water conservation must be identified through multi-state collaborative research and implemented in the entire dry regions for thriving agriculture in the context of climate change. However, immense opportunities to improve soil health due to increasing research and growing interest in sustainable cropping practices in arid and semi-arid regions cannot be overlooked (Figure 4). New and innovative farming practices are rapidly evolving, a new source of water is identified, and recycling technology is being developed, demonstrating more opportunities to improve soil health. A robust soil health assessment and management framework based on stakeholder engagement is needed to mitigate challenges and maximize benefits from soil and water conservation practices in water-limited environments.

6. Conclusions

Our review evaluates existing soil health assessment frameworks and highlights the need to develop region-specific, stakeholder-driven approaches for a more reliable estimate of soil health in water-limited environments. Soil health assessment for water-limited environments likely cannot rely on the same primary indicators as more humid regions, or, at a minimum, the weighting of the different indicators will differ by the climate context. This lack of attention to soil health indicators and practices relevant to improved water dynamics constrains the adoption of soil health management practices in arid and semi-arid regions of the USA. For example, improving soil's physical and biological functions are likely more relevant in water-limited regions than emphasizing increasing the total SOM to increase the soil water holding capacity. It is also important to explore new approaches that can address changes in the SOM chemical composition, as it is common for these soils to have low SOM content, and it is unlikely that changes in the SOM quantity may be observed within a decade or longer and that it could take drastic management changes. Therefore, more responsive soil health indicators such as fungal biomass, labile organic matter fractions, and soil aggregates may indicate changes in key soil functions in arid and semi-arid regions. Developing a minimum dataset based on regional multi-location research is needed. In addition, designing cropping systems based on soil health goals and adopting no-tillage or reduced-tillage, cover cropping, diverse crop rotations, residue management, and organic amendments such as manure or compost could improve soil health and agricultural sustainability in dry regions. Since soil health management in arid and semi-arid environments is often challenged by soil water availability for biomass production, water management should be a primary consideration. Challenges and opportunities unique to water-limited regions lie in the proper management of crop residues, cover crop planting and termination timing, seeding rate or species selection, tillage practices, and organic amendments such as manure and compost, which affect the soil water and nutrient dynamics. Combinations of multiple soil health management practices may rapidly improve soil water functions and enhance the resilience and sustainability of agriculture in water-limited environments.

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