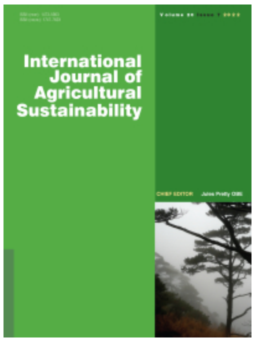

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Overcoming agricultural sustainability challenges in water-limited environments through soil health and water conservation: insights from the Ogallala Aquifer Region, USA

Abdelaziz Nilahyane[a,b], Rajan Ghimire [b], Bharat Sharma Acharya[c], Meagan E. Schipanski[d], Charles P. West[e] and Augustine K. Obour[f]

[a]African Sustainable Agriculture Research Institute (ASARI), Mohammed VI Polytechnic University (UM6P), Laâyoune, Morocco; [b]Agricultural Science Center, New Mexico State University, Clovis, NM, USA; [c]Oklahoma Department of Mines, State of Oklahoma, Oklahoma City, OK, USA; [d]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA; [e]Department of Plant and Soil Science, Texas Tech University, Lubbock, TX, USA; [f]Agricultural Research Center-Hays, Kansas State University, Hays, KS, USA

ABSTRACT

A rapid decline in water availability for crop production has driven substantial changes in cropping systems in the arid and semi-arid regions, including transitions from irrigated to dryland cropping. Management decisions play a critical role in the sustainability of agricultural systems facing transitions. Specifically, adopting practices that increase crop water use efficiency, improve soil health, and conserve water in the soil profile could improve agricultural sustainability. This review discusses published literature on the challenges associated with crop production and highlights management strategies to sustain soil health, enhance agricultural production, and farm profitability in the Ogallala Aquifer region to elucidate pathways to agricultural sustainability in water-limited environments around the world. We searched for published papers discussing soil health and water conservation practices, including conservation tillage, crop residue management, crop diversification, cover cropping, and livestock integration in cropping systems. These studies demonstrate adopting conservation systems can increase soil organic carbon (SOC) storage, water infiltration, soil microbial activities, water use efficiency, and decrease N fertilizer inputs compared to conventional systems. Integrating more than one soil and water conservation practice can complement to enhance soil health and sustainability of dryland or limited-irrigation agriculture in the Ogallala Aquifer region and similar agroecosystems across the world.

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1. Introduction

Agricultural sustainability remains a key component of rural development and long-term stewardship of the land and human resources. While the sustainable agriculture and food systems concept was realized after World War II, it gained momentum only after the Brundtland Report in 1987, which emphasized interrelationships between people, resources, environment, and development (Velten et al., 2015). Sustainable agriculture involves maintaining ecosystem productivity and an adequate food supply for all people, preserving environmental quality, and conserving nonrenewable resources and biological diversity (Weil, 1990).

In recent years, soil health has emerged as a critical component of sustainable agriculture. Healthy soils support agricultural sustainability in many ways;

CONTACT Rajan Ghimire rghimire@nmsu.edu Agricultural Science Center, New Mexico State University, 2346 State Road 288, Clovis, NM, USA

increase soil carbon storage, mitigate climate change impacts, increase nutrient and water use efficiency, and reduce nutrient leaching (Doran & Zeiss, 2000; Lal, 2016). Maintaining soil health is more critical in water-limited environments, such as arid and semi-arid regions, than the other regions because healthy soils can store and/or infiltrate more water, and soil water sustains crop production and farm profitability. Therefore, developing agricultural strategies that can capture precipitation and store it efficiently in the soil, improve soil water conservation, and enhance the water use efficiency of subsequent crops is needed to improve soil health and overcome sustainability challenges of agriculture in water-limited environments. An in-depth analysis of simultaneous soil health and water conservation benefits of alternative management systems can guide pathways to rapidly improve agricultural sustainability in arid and semi-arid regions (Kassam et al., 2012; Maharjan et al., 2020).

As one of the world's largest aquifers, the Ogallala Aquifer has been a primary source of irrigation water in the Great Plains for many decades. The Ogallala Aquifer region has a mean annual rainfall of 520 mm yr^{-1} with strong north–south air temperature and potential evapotranspiration (ET) gradients; the ET often exceeds the mean annual rainfall in the western and southern parts of the aquifer region (Crosbie et al., 2013). While significant spatial heterogeneity in saturated thickness across the aquifer exists, intensive water pumping for irrigated crop production has led to a decline in water levels (Haacker et al., 2016). Therefore, in many areas, irrigation management has shifted from full irrigation to deficit irrigation systems (Haacker et al., 2019). The shift in water availability has also shifted cropping systems that continuous corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), or corn-soybean (*Glycine max* (L.) Merr.) rotations are possible in areas with greater water availability while more drought-tolerant crops such as forage and grain sorghum (*Sorghum bicolor* (L.) Moench) have become more prevalent in water-limited areas (Bhattarai et al., 2020). Some farmers have even considered alternative crops that maintain production levels under dryland conditions, including beans, safflower (*Carthamus tinctorius* L.), sesame (*Sesamum indicum* L.), sunflower (*Helianthus annus* L.), and millets (Johnston et al., 2002; Trostle, 2001). However, changes in soil health and their relationship with the long-term sustainability of cropping systems undergoing transitions from irrigated to dryland or deficit irrigation are largely unknown.

The main goal of this review is to elucidate the challenges of sustainable crop production in water-limited environments highlighting examples from the Ogallala Aquifer region. We also aim to discuss management strategies in the region to overcome challenges of soil health management and water conservation while transitioning from irrigated to limited irrigation and dryland production systems. This review includes published studies predominantly from the Ogallala Aquifer region varying in tillage, cover cropping, crop residue management, crop rotation, and livestock integration in cropping systems. However, water-limited environments are spread across the world, e.g. the San Joaquin Valley of California, the Murray-Darling basin and Australian wheat belt, the Indo-Gangetic basin of South Asia. Although we do not fully know the future of agriculture in these areas, growing evidence suggests current business-as-usual management practices can not sustain agricultural production in the region. Climate change and variability will likely further stress the water supply in already water-limited environments (Gowda et al., 2019), urging the need to identify relevant soil health and water conservation practices for improving agricultural sustainability in the areas. Therefore, we used cases of the Ogallala Aquifer region as a proxy for water-limited environments across the world, and crop yield, water use, and soil health responses as indicators of agricultural sustainability (Figure 1). The studies published between 2000 and 2021 in the subject accessed through Google Scholar or Scopus of Elsevier are included in the analysis.

2. Overview of agriculture in the Ogallala Aquifer region and sustainability challenges

Agriculture in the Great Plains, USA, relies on the Ogallala Aquifer, the largest of the High Plains Aquifer system and one of the largest aquifers in the world (Haacker et al., 2019). The Ogallala Aquifer includes approximately 3750 km^3 of water and underlies 450,000 km^2 in parts of Oklahoma, Texas, Kansas, Nebraska, Colorado, Wyoming, New Mexico, and South Dakota (Lauer et al., 2018). Agriculture is the largest consumer of water from the Ogallala Aquifer. Large-scale irrigation in the Ogallala region started in the early 1960s, owing to advances in pumping technology and the invention of the centre-pivot irrigation system (Hornbeck & Keskin, 2014). Continuous

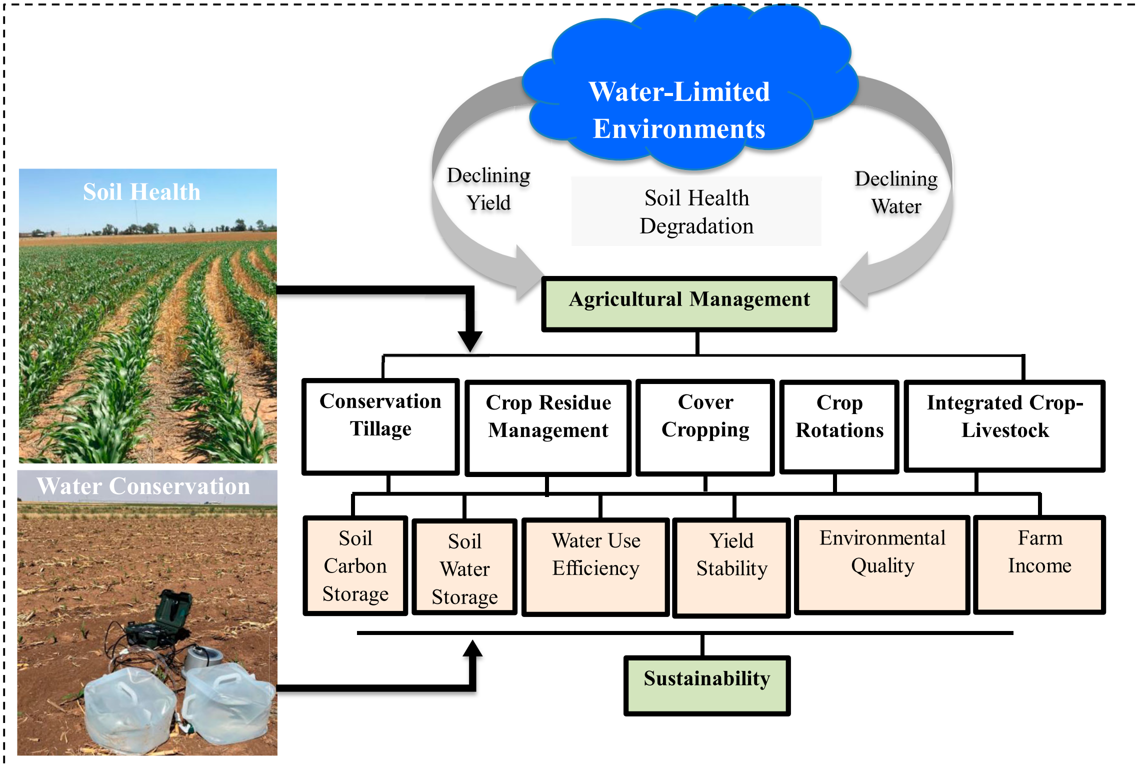

Figure 1. Agricultural management strategies to overcome sustainability challenges in water-limited environments through improved soil health and water management.

corn is the predominant cropping system in the area. Cotton or corn-soybean rotations are also planted in areas with enough water for irrigated crop production. However, with excessive pumping, groundwater levels in many parts of the aquifer have decreased from pre-development levels, and water quality has also diminished, threatening agricultural sustainability in the region, primarily attributable to over-pumping and partly to droughts and population growth (Dennehy et al., 2002). For example, aquifer storage has declined by 410 km^3 since 1935, and the southern and central High Plains have recorded more than a 10% decline per decade (Figure 2) (Haacker et al., 2016). Assuming that the rates of decline continue, projections indicate that nearly 24% of the currently irrigated area in the Ogallala Aquifer region will fail to support irrigation by 2100 (Deines et al., 2020).

Recent innovations in irrigation practices and policies in the Ogallala Aquifer region have improved irrigation efficiency through better scheduling programmes prescribing water delivery at the most yield-sensitive times in the crop growth cycle and promoting conservation irrigation systems. Despite these improvements, water levels in the aquifer declined drastically in the last few decades, prompting producers facing greater water scarcity in their farms to adopt deficit-irrigation strategies. The tradeoffs in shifting to limited irrigation include reduced crop yield (Irmak, 2015; Kisekka et al., 2016; Klocke et al., 2011; Schlegel et al., 2012) and declines in soil health (Cano et al., 2018). For example, a shift from fully irrigated to deficit-irrigated corn in southwest Kansas decreased grain yield from 11.9–6.1 Mg ha^{-1} at 25% of full irrigation (Klocke et al., 2011), demonstrating a significant income loss to producers and adding more challenges to the sustainability of agriculture in the region.

The yield loss is even greater when irrigated cropping systems are transitioned to complete dryland production systems. Farmers managing dryland crops use extended fallow periods between cash crops such as winter wheat (*Triticum aestivum* L.) and sorghum to conserve soil water and concentrate

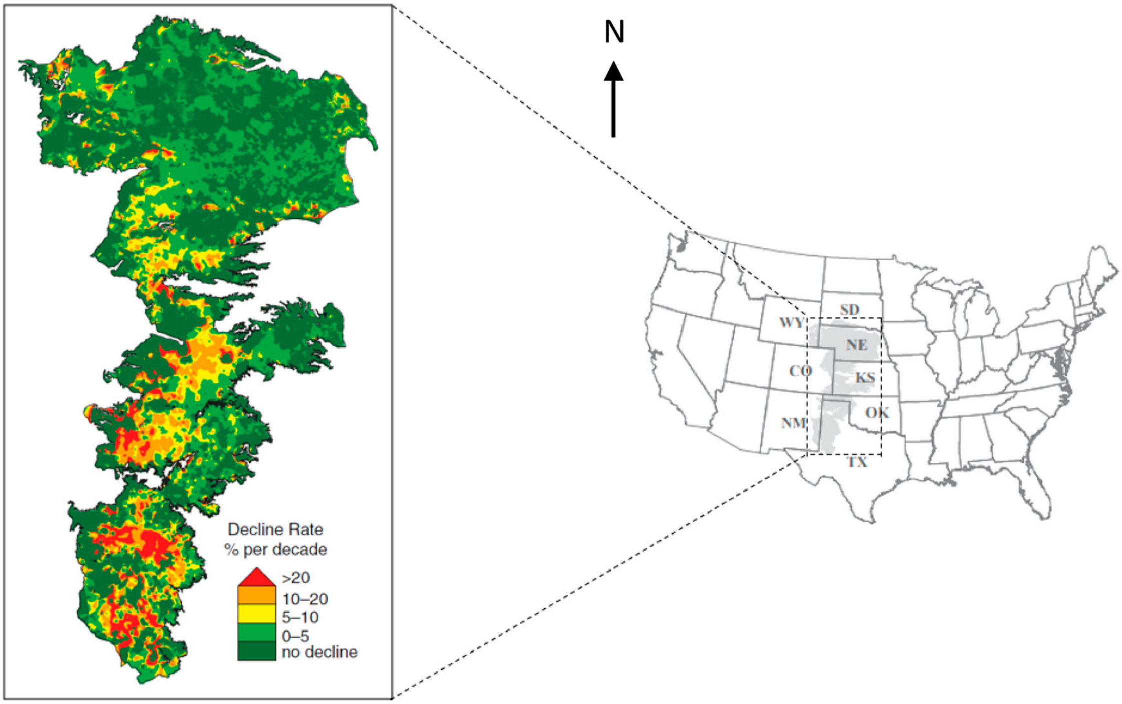

Figure 2. The decline in groundwater levels as a percentage per decade in the Ogallala Aquifer from 1992 to 2012 (Haacker et al., 2016).

the limited water available for irrigation in high-value crop production. Typical crop-fallow systems in the Ogallala regions produce one crop in two years in the winter wheat-fallow rotation or two crops in three years in the winter wheat-sorghum-fallow rotation (Hansen et al., 2012). For example, the predominant winter wheat-fallow, winter wheat- sorghum-fallow, and winter wheat-corn-fallow rotations leave more than ten months of fallow between two crops (Hansen et al., 2012; Nielsen et al., 2017; Schlegel et al., 2018b). Repeated tillage for weed management during extended fallow periods can increase evaporation and surface soil erosion and reduce precipitation-storage efficiency and soil organic matter, thereby reducing soil health, crop productivity (Ghimire et al., 2018), and ultimately agricultural sustainability.

Non-irrigated lands in the Ogallala Aquifer region are also highly vulnerable to topsoil and organic matter losses driven by wind and water erosion (Blanco-Canqui et al., 2013). Prolonged soil exposure over extended fallow periods aggravates soil erosion (Shaver et al., 2003). Surface soil in fallow lands is exposed to wind and water erosion because low water availability greatly restricts plant productivity, root anchoring, and ground cover. Wind annually causes up to 18 Mg ha^{-1} of soil erosion in the Great Plains (Hansen et al., 2012). Erosion can also be induced by heavy rainstorms in late spring to late summer on land with sparse vegetative cover (Blanco-Canqui et al., 2013). Intensive tillage and overgrazing physically break crop residues (Six et al., 2000), deplete SOC, break soil aggregates, and further promote soil erosion, reducing soil water and nutrient-holding capacities of the soil (Lal, 2004).

Soil degradation is another challenge limiting agronomic productivity and sustainability in the Ogallala Aquifer region, caused largely by excessive tillage and crop residue removal (Cano et al., 2018). Soil degradation has led to SOC loss and disruption of soil aggregates (Peterson et al., 2020). Compaction due to wheel traffic and tillage-pan development destroys soil structure and reduces pore space, water infiltration, and gas exchange in soil (Zhang & Peng, 2021). The cultivated area (Figure 3) has declined considerably in the southern Ogallala Aquifer regions in the past few decades, specifically due to poor land management during the transition from irrigated to dryland. In conjunction with land management practices, the hydrologic dynamics of

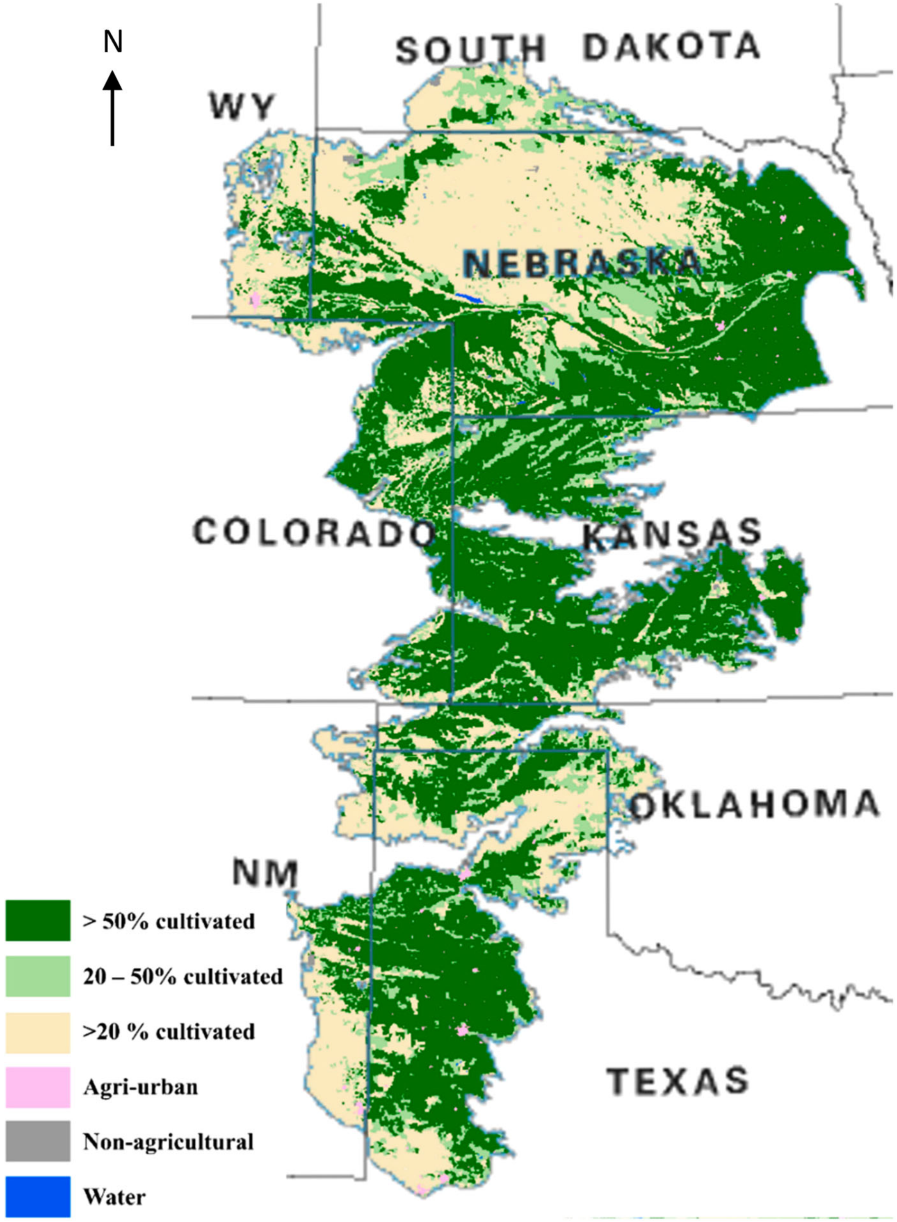

Figure 3. Cropland cover % during 2020 in the Ogallala Aquifer region (Cropland data layer, US Department of Agriculture, National Agricultural Statistical Service (USDA-NASS).

the Ogallala aquifer can aggravate the salinization of the water source for irrigation (Chaudhuri & Ale, 2014). Low SOC has diminished microbial diversity and activities such as nutrient cycling and availability (Acosta-Martinez et al., 2007). Therefore, groundwater declines and SOC loss negatively impacted the effective storage and release of water and nutrients.

Climate change is an emerging threat to soil and water resources and the sustainability of agriculture in the Ogallala Aquifer region. There is widespread agreement that climate change will result in significant summer droughts due to a reduction in annual precipitation and pronounced high temperature and precipitation patterns, adding more stress to agricultural production in the region (Stocker, 2014).

Climate projections show the likelihood of aridity increases in the southwestern USA and humidity increases in the northeastern part of the country (Basso et al., 2013). In addition, the IPCC report projects a temperature increase of 2–5°C and a decrease in precipitation by the end of this century in the southern parts of the Ogallala aquifer region (Crosbie et al., 2013). Prolonged dry periods and high temperatures aggravate photosynthate losses via night-time respiration and a decline in crop yield (Lin et al., 2017).

3. Approaches to overcome sustainability challenges

Achieving sustainable crop production with declining water availability demands a deeper understanding of how alternative soil and water management strategies can overcome obstacles to sustainable and profitable crop production and a clean and healthy environment in the Ogallala Aquifer region (Cano et al., 2018; Deines et al., 2020). Alternative production practices and management strategies, including conservation tillage, rotational cropping, cover cropping, and crop-livestock integration, demonstrate the potential to improve the sustainability of agriculture in the region. The following section summarizes the studies addressing the predominant management practices to overcome the agricultural sustainability challenges in the Ogallala Aquifer region, specifically soil health, soil water storage and water use efficiency, and crop yield and yield stability.

3.1. Tillage and residue management

The Conservation Technology Information Center (CTIC) defines conservation tillage as a tillage system that reduces soil disturbance and leaves more than 30% of the soil surface covered by crop residue after planting to prevent soil erosion. Conservation tillage practices involve reducing both the intensity and frequency of soil disturbance. Relative to more intensive tillage practices, conservation tillage systems improve agricultural sustainability by providing ecosystem services, including improved soil properties, increased SOC sequestration, reduced greenhouse gas emission, reduced soil erosion, and ultimately increased crop yield and profitability (Jin et al., 2017; Li et al., 2018). Farmers commonly use the fallow periods between crops to conserve soil water. Studies demonstrated that reduced tillage during fallow could increase soil-water storage efficiency and water conservation compared to conventional tillage by reducing soil disturbance and accumulating crop residue at the soil surface as mulch (Peterson et al., 1996; Saseendran et al., 2009). In the Great Plains, cropland under no-tillage varied from 25% of the total cropland surface in the northern parts to around 5% in the southern regions (Hansen et al., 2012; Pittelkow et al., 2015). No-tillage can increase soil water infiltration and aggregate stability, ultimately, water conservation than conventional tillage. For example, Farahani et al. (1998) reported that no-tillage fields hold water for three to four months longer than conventional tillage fields due to greater ground cover and improved soil structure. Other studies have reported the benefits of conservation tillage in reducing soil disturbance and production costs and improving soil aggregation, SOC, and soil biological activity (Busari et al., 2015; He et al., 2011). However, some studies showed no differences in total porosity, saturated hydraulic conductivity, and water retention characteristics between no-till and conventional tillage management (Blanco-Canqui et al., 2017). No-tillage could increase crop yield under dryland farming (Hansen et al., 2012). Through a meta-analysis, Pittelkow et al. (2015) showed that no-till yields matched conventional-tillage yields in dryland areas, mostly for oilseeds, cotton, and legumes. Negative impacts on yield have also been observed but are generally lesser under crop rotation and residue retention (Pittelkow et al., 2015). Grain sorghum yield increased by 23% in the Great Plains region of the USA with no-tillage compared to reduced tillage (Schlegel et al., 2013). Recently, Schlegel et al. (2018a) reported a 120% yield increase in sorghum and a 31% increase in wheat under no-tillage compared to conventional tillage and concluded that no-tillage is the better option for dryland sorghum. Overall, conservation tillage shows similar or positive effects on improving crop yield under water-limiting conditions.

Effects of minimum soil disturbance on soil and water conservation under the conservation tillage system are often complemented by increased residue cover on the soil surface. While crop residue removal by grazing or baling can reduce nutrient cycling, soil biological activity, water infiltration, aggregate stability, and soil water storage, retaining residues on the surface can improve soil health and increase soil water storage. Positive impacts of residue retention on soil water conservation occur from reduced evaporation and low sediment loss due to soil erosion. Klocke et al. (2008) reported growing season water savings of 86 mm to 99 mm from residue cover compared to residue removal under corn in southwest Kansas. In a recent study in Colorado, Schneekloth et al. (2020) observed corn grain yield increase of 1.1 Mg ha^{-1} yr^{-1}, increased soil water content at planting, and reduced penetrometer resistance following residue retention compared to residue removal under limited irrigation. Further, they noted that residue removal increased irrigation requirement by an additional 60 mm yr^{-1} to obtain the same grain yield as with residue retention. This beneficial effect of surface residue retention was consistent across tilled and no-till systems. Crop residue retention on the soil surface is generally recommended in dryland cropping systems to enhance yields by increasing soil water conservation (Wortman et al., 2013); no-tillage could complement crop residue effects under such conditions. The greater yield in cropping systems with residue retention is attributed to improved soil-water infiltration and water retention properties, crop water use efficiency (reduced evaporation and greater transpiration) (Baumhardt et al., 2013), and reduced surface evaporation (Klocke et al., 2008)

3.2. Cover cropping

Cover crops are crops grown between cash crops to protect soil from erosion and improve precipitation storage, soil nutrients, and organic matter (Abdalla et al., 2019). Cover crops can be grazed and/or terminated mechanically or chemically (Dabney et al., 2010). An in-depth study on cover crop species selection, planting and termination dates, soil moisture monitoring, and economics of the overall cropping system could maximize the benefits of cover cropping and support sustainable crop production (Ghimire et al., 2018; Wortman et al., 2013). There are many benefits of cover crops, including yield increase of subsequent crops (Miller et al., 2011), reductions in wind and water erosion (Unger & Vigil, 1998), decrease in soil-borne crop pathogens (Sainju et al., 2005), and weed suppression (Davis et al., 2005; Mesbah et al., 2019). In a recent study, Baxter et al. (2021) showed no detrimental effect of no-till cover crops on soil water compared to winter fallow, while summer teff production was reduced under delayed termination of cover crops relative to early termination. A meta-analysis on cover crop impact on soil water storage, succeeding crop yield, and water use efficiency showed no effect of cover crop on succeeding crop yield, decreased evapotranspiration by 6.2%, but increased water use efficiency by 5% compared to no cover crop (Wang et al., 2021). Nitrogen-fixing cover crops increase crop yields more than low or no nitrogen-fixing crops. Miller et al. (2011) showed an increase in winter wheat yield by 5.2% in Montana following winter pea (*Pisum sativum* L.). Similarly, Northup and Rao (2015) reported a 14% increase in winter wheat yield following lablab bean (*Lablab purpureus* (L.) Sweet) in central Oklahoma. Legume cover crops can fix atmospheric nitrogen and be used as green manure for the subsequent crop (Finney et al., 2016; White et al., 2016). Legumes mature early and use less soil water than nonlegume cover, increasing soil water availablility to succeeding crops and enhancing their yields. Lyon et al. (2007) showed 60 mm more water with early harvesting of triticale (×*Triticosecale* Wittmack) cover crop than late harvesting and the following winter wheat production in Nebraska. Cover crops interact with the tillage method in dryland farming to affect soil water use and storage. For example, in the Texas Panhandle, no-till wheat as a cover crop increased the irrigation water use efficiency of cotton by 11% over six years compared to the conventional tillage system (DeLaune et al., 2020). Wheat yield loss is minimized under early cover-crop termination, which allows for a sufficient fallow phase before planting the main grain crop (Schlegel & Havlin, 1997). However, in a recent study near Clovis, New Mexico, cover crops showed minimal effect on winter wheat yield and water use efficiency under supplemental irrigation for the main crop (Mesbah et al., 2019).

Cover crops have the potential to increase potentially mineralizable C, permanganate oxidizable C, SOC, total N, and microbial activities, with relative impacts varying depending on cover crop type, mixture, termination date, soil texture, soil nutrient status, and tillage systems (Table 1). Cover crops can increase soil aggregate stability, porosity, infiltration, and water-holding capacity under dryland farming relative to fallow (Lotter et al., 2003). Long-term cover cropping studies show the potential to increase SOC; meta-analyses reported that cover crops could increase SOC storage by 12% or 0.32 ± 0.08 Mg ha^{-1} yr^{-1} compared to no cover cropping controls (McClelland et al., 2021; Poeplau & Don, 2015). However, C sequestration rates may vary with cover crop biomass and type (legume, grass, brassica), planting

Table 1. Response of selected cover crop studies in the Ogallala Aquifer region, US.

Location	Soil type	Cover crop[†]	Focal area	Study duration (year)	Key findings	Soil health – water conservation relationship	Reference
Lubbock, Texas	Clay loam	Wheat, rye, rape-kale, hairy vetch, burr medic	Crop productivity, forage nutritional value, and soil water of cover crop and subsequent teff hay crop	2	Rye produced the greatest accumulated forage Delayed termination of cover crop reduced summer teff productivity Tillage reduced water content in all except rye and wheat at a 20-cm depth relative to no-till.	Soil moisture increase	Baxter et al.,2021
Lamesa, Texas	Fine sandy loam	Rye and mixed-species (hairy vetch, Austrian winter pea, rye, and radish)	Impact on early and late season water for subsequent cotton crop	3	Soil water increased more with no-till following cover crop termination and decreased less during cotton growth than conventional till Cover crop likely to reduce evaporative loss and increase water infiltration Cover crop termination at least a month before cotton planting replenish 14% water deficiency	Soil moisture increase	Burke et al., 2021
Clovis, New Mexico	Clay loam	Pea, oat, canola, pea + oat, pea + canola, pea + oat + canola, and pea + oat + canola + hairy vetch + radish + barley	Soil health indicators and wheat yield	2	Oat and their mixture with other cover crops increased soil inorganic N, potentially mineralizable C, permanganate oxidizable C, SOC, and total N compared to pea and canola, soil moisture content was higher under POC and SSM than fallow at the termination date	Soil health improvement	Ghimire et al., 2019
Texas		Rye, hairy vetch, radish, winter pea	Soil C storage, cotton lint yield, and economic returns in cotton monoculture farming	17	No-till rye cover crop had twice SOC compared to conventional tillage (winter fallow) after 17 yrs Cotton lint yield was lower under no-till and rye compared with conventional tillage	Soil health improvement	Lewis et al., 2018
Clovis, New Mexico	Clay loam	Pea, oat, canola, pea + oat, pea + canola, pea + oat + canola, and pea + oat + canola + hairy vetch + radish + barley	Weed suppression	3	Cover crops, mainly oats, and their mixture suppressed weeds and maintained ground cover during summer	Soil moisture increase	Mesbah et al., 2019
Clovis, New Mexico	Clay loam	Pea, oat, canola, pea + oat, pea + canola, pea + oat + canola, and pea + oat + canola + hairy vetch + radish + barley	Soil CO_2-C emissions,	2	High seasonal and interannual variation in CO2-C emission due to fluctuations in temperature and water content	Soil health improvement	Nilahyane et al., 2020

Clovis, New Mexico	Clay loam	Pea, oat, canola, pea + oat, pea + canola, pea + oat + canola, and pea + oat + canola + hairy vetch + radish + barley	Microbial community	2	Cover crops increase microbial community size, fungal abundance, and enzyme activities associated with C and nutrient cycling. Among cover crops, oat and its mixture with legumes and brassicas improved soil health and nutrient cycling in a hot and dry climate.	Soil health improvement	Thapa et al., 2021
Garden City, KS	Silty loam	Hairy vetch, hairy vetch + triticale, winter pea, winter pea + triticale, Winter triticale (winter)	Plant available water, wheat yield, grain quality, and profitability	5	Minimal negative impact on wheat yield growing a cover crop in place of fallow if wheat yield potential was 3500 kg ha^{-1} or greater. However, growing a cover crop reduced the net returns by 50–100%.	Soil moisture increase	Holman et al., 2018
Farm fields in KS, CO, NE	Silty clay loam and clay loam	Barley + oat + rapeseed + pea + sunflower + flax + safflower	Soil health indicators, forage production, and wheat yield	2	Cover crops increased soil aggregate stability compared to summer fallow. Grazing cover crops did not reduce soil health	Soil health improvement	Kelly et al., 2021

†Consult the reference paper for scientific names of the cover crops.

season (spring vs. winter planting), weather (wet vs. dry year), soil type, tillage, and cover crop management (early vs. late termination; long-term vs. short term establishment) (McClelland et al., 2021). Cover cropping with no-till/conservation tillage may increase SOC at the near-surface depths (Blanco-Canqui et al., 2013; Lewis et al., 2018) owing to low residue decomposition rates (Olson et al., 2014), as well as at deeper depth when deep-rooted cover crops are used.

Soil water limitations often constrain cover cropping in the semi-arid central and southern Great Plains. Transpiration by an actively growing cover crop can reduce water availability for the subsequent crop (Rusinamhodzi et al., 2011; Unger & Vigil, 1998). Studies in northern (Aiken et al., 2013; Miller et al., 2006) and central (Nielsen & Vigil, 2005; Schlegel & Havlin, 1997) Great Plains reported a reduction in soil water content and succeeding crop yields following cover crops. For example, decreased winter wheat yields in dry years were reported by replacing fallow with cover crops in Colorado (Nielsen & Vigil, 2005) and Kansas (Holman et al., 2018; Kelly et al., 2021). Lyon et al. (2004) showed a decrease in soil water content by at least 32% during the winter wheat phase over three years due to spring cover crops.

Analyzing all these studies showed that cover crops could increase, decrease, or have no effect on subsequent crop yield depending on precipitation or availability of supplemental irrigation, ET rate, cover crop types, and tillage. Adopting cover crops in lands transitioning to dryland production is possible if farmers optimize crop management practices, including planting and termination dates, species mixtures, etc., and subsequent crop water management.

3.3. Crop rotation, intensification, and diversification

For optimum growth and successful crop establishment, dryland crops rely on precipitation and soil water storage at planting. Seeding rates and planting and harvesting dates can be adjusted to match the limited water supply, and crop species or cultivars with lower water usage or shorter maturity ratings can be selected. Changing crop planting time, such as delayed planting in short and long-season corn hybrids, can reduce seasonal irrigation needs by up to 31% due to lower temperature stress and ET and retain profitable yields (Marek et al., 2020). In drylands, diversifying high-water-demanding crops with low-water-demanding crops in the rotation can sustain soil water, improve water use efficiency, and enhance crop yields compared to monocropping.

Diversifying crop rotations is also an option to conserve soil moisture and improve soil health indicators. It also reduces disease and pest infestation and ultimately increases crop yield compared to continuous monocropping and crop-fallow practices (Sainju et al., 2009). Farmers commonly rely on synthetic fertilizers and pesticides to control weeds, insects, and disease infestations in monocropping systems. However, high costs of synthetic chemicals decrease margins and lower farm profits. Chemicals used in crops also increase resistance to pesticides, ground and surface water contamination, and heavy metal toxicities, which call for alternative management practices (Rosenzweig et al., 2018b). Crops with high water demand exhausts the soil water profiles and decreases the water productivity of the subsequent crops. The sequence of high- and low-water-demand crops could be a choice for a successful crop rotation system in dryland systems of the Ogallala Aquifer region and similar other regions worldwide.

Intensive cropping systems with diverse crops reduce fallow frequencies, maximize residue return to the soil, increase soil C and nutrients, and ultimately enhance crop yields (Hansen et al., 2012; Thapa et al., 2022; Yang et al., 2020). Cropping intensification and diversification also decrease pest and disease incidences. For instance, through cropping system intensification, Rosenzweig et al. (2018a) reported a 35% increase in soil microbial biomass and a two-fold increase in fungal biomass relative to the wheat-fallow system. In addition, intensified crop rotation increased SOC by 17% in 0-10 cm and 12% in 0-20 cm soil depth compared to a wheat-fallow system. Total and potentially mineralizable nitrogen levels were 12% and 30% greater in the intensified crop rotation systems than the wheat-fallow, respectively (Rosenzweig et al., 2018b). Continuous cropping can increase the size and activity of microbial communities, which enhance crop nutrient uptake, strengthen plant growth, and improve nutrient use efficiency. Reducing the fallow periods can reduce weed pressure and decrease herbicide dependency. Weeds are strong crop competitors for light, nutrients, and water. Increasing soil cover with intensive cropping systems reduces weed competition and limits soil water storage depletion (Mesbah et al., 2019). In the dryland cropping areas of Nebraska and Colorado, crop intensification by continuous cropping showed the potential to reduce nitrogen fertilizer inputs by 22%, total herbicide application by 50%, and increase annual grain production by 60% compared to the traditional wheat-fallow cropping system (Rosenzweig et al., 2018b). More importantly, continuous cropping increased net operating income by 80% over the wheat-fallow system (Rosenzweig et al., 2018b). Intensifying crop rotations from wheat-fallow to wheat-sorghum-fallow or wheat-corn-fallow or wheat-corn-forage crop system also increased annualized crops yields, residue retention, SOC, and overall system profitability across the Ogallala Aquifer region (Bowman et al., 1999; DeVuyst & Halvorson, 2004; Lyon et al., 2007; Nielsen et al., 2017; Norwood et al., 1990; Sherrod et al., 2003). The profitability of dryland cropping systems was improved significantly when fallow was replaced with annual forages instead of grain crops (Holman et al., 2018; Lyon et al., 2004; Nielsen et al., 2017).

Diversifying crops in farming systems increases crop productivity due to complementary input use, water conservation, and interaction between species (Hooper et al., 2005). Continuous wheat increased cumulative infiltration compared to a wheat-fallow system under no-tillage management in western Kansas (Blanco-Canqui et al., 2010). Crop diversity promotes the ecological intensification of dryland agriculture, reduces the need for inorganic fertilizer and pesticide inputs (García-Palacios et al., 2019), and provides multiple beneficial agro-ecosystem services, including soil carbon sequestration, nutrient cycling, pest suppression, and pollination (Isbell et al., 2017). Overall, crop diversification through rotation and intercropping, along with conservation tillage, can improve the sustainability of agriculture by offsetting the negative impacts of monoculture and improving soil health, enhancing water conservation, and increasing crop yield and profitability (Brouder & Gomez-Macpherson, 2014).

3.4. Livestock integration in cropping systems

Interest in crop-livestock integration stems from concerns over soil degradation, farm profitability, and regulation of concentrated feeding operations. Managing feedstock to supply good nutrition throughout the year during the transition from irrigated to dryland production is crucial for successful livestock integration in such systems. As such, farmers need to include diverse forage species in their cropping systems and manage the grazing intensity of livestock, which also offers further opportunities for crop diversification (Zilverberg et al., 2015). Livestock integration in the cropping system can reduce irrigation water use due to shifting to forage crops using less water. For instance, crop-livestock integrated systems in Lubbock, Texas, demonstrated reduced irrigation water use by 25%, reduced N fertilizer input by 36%, and improved soil health parameters over the long term, compared with continuous cropping of cotton without a forage component (Table 2). Acosta-Martínez et al. (2010) reported increased soil microbial community and enzyme activities of C, N, P, and S cycling under an integrated system compared to continuous cotton. Other benefits associated with livestock integration, such as enhanced aggregate stability of soil particles and water infiltration, are also reported (Franzluebbers, 2007; Liebig et al., 2012). Considering the benefits of cover crops in dryland, livestock producers can rely on forage cover crops to provide supplemental feed for livestock, especially during periods of the year when perennial pastures are dormant to provide adequate forage (Liebig et al., 2015).

Table 2. Summary of select integrated crop-livestock system studies in the southern Ogallala Aquifer regions.

Types of Monoculture and Integrated Systems[†]	Advantages/Key Findings	Soil Health/ Water Conservation Relationship	Reference
Cotton monoculture, integrated crop-livestock system with old world bluestem paddock and two paddocks of a rotation (wheat-fallow-rye]-cotton)	More SOC, aggregate stability, and soil enzyme under perennial pasture than under continuous cotton More protozoa and fungi under integrated cotton than in cotton monoculture	Soil health improvement	Acosta-Martinez et al., 2004
Cotton monoculture, integrated crop-livestock system with old world bluestem paddock and two paddocks of a rotation (wheat-fallow-rye]-cotton)	Microbial biomass C was higher in the rotation independent of the crops compared to continuous cotton after 7 yrs Total C was higher in both the rotation and pasture of the integrated system compared to continuous cotton after 10 yrs More enzyme activities of C-, N-, P- and S-cycling under an integrated system	Soil health improvement	Acosta-Martínez et al., 2010
Cotton monoculture with terminated wheat and integrated crop and livestock sys- paddock rotation with grazed wheat and rye and the perennial 'WW-B. Dahl' old world bluestem	The integrated system had 23% less irrigational water use, 40% less N fertilizer input, 90% increase in profitability	Soil moisture increase	Allen et al., 2005
Cotton monoculture, integrated cotton-forage-beef cattle system	Water-saving of 25%, reduced soil erosion, 40% reduction in N fertilizer input, improved soil microbial activities, increased C storage and water infiltration compared to cotton monoculture	Soil moisture increase	Allen et al., 2007
Cotton monoculture with terminated wheat and integrated crop- livestock system paddock rotation with grazed wheat and rye and the perennial 'WW-B. Dahl' old world bluestem	Integrated system had 25% less irrigational water use, 36% less N fertilizer input, and fewer other chemical inputs	Soil moisture increase	Allen et al., 2012
Two integrated crop-livestock systems: Low irrigation system with native perennial grass Foxtail millet and cotton, and moderate irrigation systems with old world bluestem and bermudagrass	Non irrigated, seeded native grass mixtures decreased total water use	Soil moisture increase	Zilverberg et al., 2015
Two integrated crop-livestock systems: Low irrigation system with native perennial grass foxtail millet and cotton, and moderate irrigation systems with old world bluestem and bermudagrass	Non irrigated system more efficient in water use Integrated system reduced total irrigation water compared with crop monocultures	Soil moisture increase	Zilverberg et al., 2014

[†]Consult the reference paper for scientific names of the cover crops.

Because plant species differ in nutritive value, selecting appropriate species is essential for the correct diet composition of livestock. Diverse forage utilization strategies offer flexibility in designing integrated crop-livestock systems based on a local context. Grazing crop residues is a low-cost feeding option in crop-livestock integrated systems and can benefit soil because 50% of crop residue mass is typically grazed. The remaining crop residue remains on the ground, mixed with the surface soil by the livestock hoof action (Franzluebbers, 2007). Other options include supplemental feeding of hay harvested from nearby rangeland and non-irrigated pivot corners and supplementation with co-products from annual crop production, such as cottonseed meal and hulls and distillers' grains from corn and grain sorghum ethanol plants. These options favour circularity in regional-scale nutrient returns to the soil that produced those crops.

4. Conclusion and future directions for improving the sustainability of agriculture facing the transition to dryland

While there are significant challenges associated with dryland transitions in water-limited environments, alternative conservation strategies show promise to foster soil health, water conservation, and sustainable crop production. Several studies from the Ogallala Aquifer region demonstrated that conservation tillage management generally reduces soil disturbance, slows water loss from the surface soil, and improves soil physical properties and biological activities. Similarly, cover cropping increases SOC, aggregate stability, cumulative water infiltration, microbial activities, and crop yield depending on cover crop type, cover crop mixture, termination date, soil texture, and tillage systems. Crop rotation and integrated crop-livestock systems also increased irrigation water use efficiency, total C and enzymatic activities, and decreased N fertilizer inputs compared to crop monocultures. Overall, no-till, cover-crop management, crop diversification, and livestock integration improve soil quality and water storage for long-term sustainability agriculture in Ogallala Aquifer regions. More comprehensive research is warranted on how these alternative strategies interact to change soil physical, mechanical, hydraulic, and biological properties, water storage and quality, and profitability in dryland farming.

Overcoming sustainability challenges in water-limited environments requires improved knowledge of the magnitude and direction of changes in various soil health and water conservation parameters with the adoption of conservation farming practices. However, understanding the complex nexus of soil health, water dynamics, and crop yield is a major limitation to successfully adopting these practices in the real world. Because soil health and water conservation parameters respond slowly to alternative management practices in water-limited environments, measures to minimize economic risk at the farm-to-field scale and implementing policy to incentivize the adoption of improved management practices should be emphasized. Future research should focus on combining multiple management alternatives to maximize soil health and water conservation benefits. Studies included in this review show that combining more than one management practice is possible and can benefit crop production in drylands. However, these management practices need more research as the adoption of these practices by farmers is still facing many challenges. Research is underway toward developing and using drought-tolerant cultivars, changes in planting dates (early or late), and adjustment of seeding rates and planting methods (e.g. skip-row configuration). The findings of these ongoing studies may provide important insight for improving the sustainability of agriculture in the Ogallala Aquifer region and similar other agroecosystems across the world.

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ORCID

Rajan Ghimire http://orcid.org/0000-0002-6962-6066

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