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SPECIAL SECTION: NEAR-TERM PROBLEMS IN MEETING WORLD FOOD DEMANDS AT REGIONAL LEVELS

Cover crops to improve soil health in the North American Great Plains

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Abstract

Rotating cereal crops (e.g., wheat [*Triticum aestivum* L.] with a 10- to 21-mo summer fallow period [fallow]) is a common farming practice in dryland (rainfed) agricultural regions. Fallow is associated with several challenges including low precipitation storage efficiency, depletion of soil organic carbon (SOC), loss of soil fertility, little crop residue retention and soil erosion, and few control options for herbicide-resistant (HR) weeds. The inability to effectively control HR weeds poses a major challenge to maintaining soil and water conservation practices such as no-tillage, as some producers are considering tillage to control weeds. Cover crop (CC) integration into wheat-based production systems to replace portions of the fallow period provides an opportunity to increase SOC, improve soil fertility, suppress weeds, and increase profitability of dryland crop production, especially when CCs are used as forage. This forum paper used the North American Great Plains as a model region to review information on (a) challenges of dryland agriculture; (b) integrating CCs in dryland agriculture; (c) benefits, challenges, and limitations of CCs in dryland crop production; (d) management options for CC integration in dryland grain systems; and (e) recommendations for future research efforts.

1 | INTRODUCTION

1.1 | Challenges of dryland agriculture in the U.S. Great Plains

The North American Great Plains encompasses arid and semiarid areas including Canada and the United States. The focus of this paper is on these areas within the United States that extends from Montana in the North to the Texas panhandle in the South and bordered by the Rocky Mountains in the West and areas of higher rainfall in the East (Figure 1; Unger & Baumhardt, 2001). As in other dryland regions, soil water availability is the single most limiting factor affecting crop production (Peterson et al., 2020). Irrigation is used where available, but most of the region relies only on precipitation as snow and rain for crop production. Precipitation in the region ranges from an average of <600 mm in the East to <300 mm

Abbreviations: CC, cover crop; HR, herbicide resistant; NT, no-tillage; SOC, soil organic carbon.

in the West (Figure 1; Nielsen, 2018). Precipitation amounts are highly variable with intermittent droughts being common throughout the growing season that increase the risk of crop failure (Hansen et al., 2012). Predicted future climatic changes will exacerbate the challenge of variable temporal and spatial precipitation distribution across the Great Plains. The East–West precipitation gradient dictates agricultural practices across the region and varies from row crop production in the East to mixed crop–livestock systems in the West (Carr et al., 2021). Declining water levels of the Ogallala and other aquifers have resulted in diminished well capacities for irrigated crop production in the central and southern Great Plains (Cano et al., 2018). In addition to depletion of the aquifer saturation thickness and well capacity, increased salinity has resulted in water quality too poor for irrigation purposes. Furthermore, increased water demand near population centers for human and industrial uses have reduced water availability for irrigation and created tension between end-users. Sedimentation and nutrient run-off have reduced reservoir capacity and water quality. These decreases in water quality and availability have expanded dryland agriculture in the central and southern Great Plains.

The Great Plains is an important grain-producing region, accounting for 62% of all wheat and 96% of grain sorghum [*Sorghum bicolor* (L.) Moench] production in the United States (USDA-NASS, 2019). Wheat–fallow (W–F) or wheat–summer crop (e.g., corn [*Zea mays* L.], cotton [*Gossypium* spp.] or grain sorghum)–fallow (W–S–F) are the dominant grain production systems in the Great Plains. The W–F system is still used extensively in the northern Great Plains (spring and winter wheat), despite growing interest in cool-season pulses (e.g., spring pea [*Pisum sativum* L.]) and oilseed {e.g., canola [*Brassica napus* L.], Ethiopian mustard (*B. carinata* A.Braun) and camelina [*Camelina sativa* (L). Crantz]} crops (Alberti et al., 2019; Carr et al., 2021; Mohammed et al., 2017; Obour et al., 2018). Winter wheat–fallow also dominates grain production systems in the driest regions of eastern Colorado and western Kansas, while W–S–F is common throughout the rest of the central and southern Great Plains (Hansen et al., 2012; Nielsen & Vigil, 2018; Peterson & Westfall, 2004). Fallow is practiced as a risk-avoidance strategy where stored water limits crop failure and stabilizes yields. However, the water storage efficiency of this system is very low and ranges from 17 to 45% (Peterson & Westfall, 2004). Depending on location and cropping scheme, the fallow period extends from 14 to 21 mo in W–F or 10 to 11 mo in W–S–F (Carr et al., 2021). In the past, tillage was used to manage weeds during fallow. However, tillage reduced soil residue cover, resulting in severe wind erosion, depletion of SOC, and a decline in soil fertility, as well as decreased aggregation, water infiltration rates, and inefficient water storage (Hansen et al., 2012; Peterson et al., 2020). This has created a lasting legacy of soil degradation across the Great Plains.

Core Ideas

- Available soil water is the most limiting factor affecting dryland crop production.
- Herbicide resistant weeds pose a major challenge to dryland no-tillage farming.
- Decades of conventional management have degraded soils with low SOC and fertility.
- Cover crops could intensify dryland crop production, improve soil, and suppress weeds.
- Cover crops must be used as a forage resource to be economical in water-limited environments.

The adoption of no-tillage (NT) practices has reduced soil erosion, slowed losses of SOC and depletion of soil fertility, and most importantly improved soil water infiltration and water storage (Hansen et al., 2012; Peterson et al., 2020). Improved water storage with NT allowed for intensifying cropping systems and reduced the area of W–F across the Great Plains (Lenssen et al., 2018; Rosenzweig et al., 2018; Sainju et al., 2020). Although many benefits have been derived from NT, the development of herbicide resistant (HR) weed populations and soil compaction, as well as stratification of pH, SOC, and nutrients in the soil profile, challenge the long-term sustainability of NT farming in the Great Plains. These factors can have a significant negative impact on crop yields and the profitability of dryland farming, especially considering current marginal profit levels and ever increasing input costs.

Widespread adoption of NT crop production in the Great Plains is attributed to efficacy and simplicity of weed management with glyphosate [(N-phosphonomethyl) glycine] (Hansen et al., 2012). However, the extensive NT fallow period promotes HR weed development. In tillage-based systems, weed control during fallow is accomplished with a combination of tillage and two to three applications of glyphosate tank-mixed with other herbicides (e.g., paraquat [1, 1′-Dimethyl-4, 4′-bipyridinium dichloride], dicamba [3,6-dichloro-2-methoxybenzoic acid], 2,4-D [2,4-Dichlorophenoxyacetic acid] etc.), while five to six herbicide applications are common in NT fallow fields (Lutcher, 2015).

Producer preferences for simplified herbicide programs, lack of diversity in herbicide modes of action, and failure in creating herbicides with new modes of action since the early 1980s have resulted in multiple HR kochia [*Kochia scoparia* (L.) Schrad.] and Palmer amaranth (*Amarathus palmeri* S. Watson) populations in the Great Plains (Kumar et al., 2020). Other problematic HR weeds include horseweed (*Conyza canadensis* L.) and Russian thistle [*Salsola tragus* (L.) Scop.] (Heap, 2020). The lack of effective herbicides to control

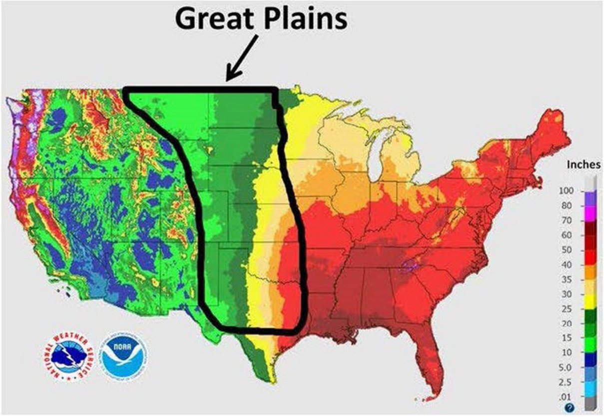

FIGURE 1 Map showing mean annual precipitation across the United States, with the Great Plains region outlined in a dark line. Source: Nielson, 2018

grass weed species including feral rye (*Secale cereale* L.), three-awn grass (*Aristida purpurea* Nutt.), and tumble windmill grass (*Chloris verticillata* Nutt.) poses an additional challenge to NT crop production in the region (Kettler et al., 2000; Obour et al., 2021). For example, competition from HR three-awn and tumble windmill grass reduced winter wheat yields in NT by 11% compared with tilled treatments (Obour et al., 2021).

Stratification of soil pH and phosphorus (P) has been reported in NT systems in the Great Plains (Obour et al., 2017; Schroder et al., 2011). For example, Obour et al. (2017) reported a decrease in soil surface pH from 6.4 with an unfertilized control to 5.7 with 67 kg N ha^{-1} applied annually for 50 yr to a NT cropping system in western Kansas. The authors also reported greater P concentration in the upper soil surface under NT compared with a tilled system. Similar decreases in surface soil pH have been reported in the northern Great Plains in systems under long-term NT (Reeves & Liebig, 2016). This is a recent problem for the calcareous soils of the Great Plains, a result from the application of ammonium-based fertilizers over a long period of time (Barak et al., 1997). Soil pH stratification affects soil microbial activity, N_2O emissions (Behkea et al., 2020), and nutrient availability and uptake by crops (Deubel et al., 2011). Similarly, greater P concentrations in the upper soil surface with NT can increase the risk of P losses due to surface runoff (Baker et al., 2017; Duncan et al., 2019).

The challenges, along with the increasing costs of managing HR weeds coupled with small profit margins, have tempted some dryland producers to revert to tillage (Obour et al., 2021). One driver for reverting to tillage is the economic cost of managing HR weeds in NT systems. The custom rate for tillage using an undercutter or wide sweep blade in Kansas averages US$28 ha^{-1} (KDA, 2020), compared with $33 ha^{-1} for a burndown herbicide application (Doug Dreiling, Midland Marketing, personal communication, 2020). Four herbicide applications typically are needed to control weeds during the fallow period under NT, costing approximately $132 ha^{-1}, while a single undercutter operation to control HR weeds plus two herbicide applications to control newly emerged weeds costs only $94 ha^{-1} ($28 ha^{-1} for tillage plus $66 ha^{-1} with two herbicide applications). Therefore, over the short term, it makes economic sense to consider tillage as a low cost option to manage HR weeds. However, long-term impacts of the reintroduction of tillage into NT systems on soil and plant health is unknown (Obour et al, 2021), but pose a major threat to the gains made after eliminating tillage. Growing CCs to replace portions of the fallow period may help maintain NT practices by providing integrated management options for HR weeds while enhancing soil quality in dryland production systems.

1.2 | Integrating cover crops in dryland no-tillage systems

Despite increased cropping intensification with NT, cropping systems in the Great Plains still typically include fallow phases. Therefore, CC planting opportunities exist to eliminate or partial replacement of the fallow period to diversify and maximize precipitation use efficiency and resilience of dryland crop productions in the U.S. Great Plains.

1.2.1 | Cover crops in the northern Great Plains

This subregion of the Great Plains includes the states of North and South Dakota, Montana, Wyoming, and northern Nebraska. Although precipitation is low and highly variable, relatively cooler air temperatures create more favorable growing conditions than further South, allowing for greater cropping system intensification (Carr et al., 2021). Nevertheless, alternating wheat (winter or spring) with summer fallow (W–F) remains a common practice in this subregion, despite negative effects on soil health and the environment.

The fallow period extends up to 21 mo between grain harvest in August and planting the next crop in April of the following year when spring wheat is grown, and 14 mo when winter wheat is harvested in July with the next winter wheat crop planted in the following year September or October (Carr et al., 2021; Hansen et al., 2012). Adoption of NT allowed cropping system intensification with shortened fallow periods using appropriate crop sequences that balance water and N requirements (Lenssen et al., 2014; Lenssen et al., 2020; Sainju et al., 2020). Still, these intensified cropping systems maintained a fallow period ahead of spring or winter wheat planting. The duration of fallow can be reduced by planting CCs in late summer after grain harvest and prior to planting a grain crop the following spring. However, establishment and productivity of late summer CCs in the northern Great Plains is limited by precipitation after planting and early fall frosts (Liebig et al., 2015). Dormant seeding late in the fall (November and December) may be employed to ensure early spring germination and establishment of CCs, a planting strategy used successfully for annual grain crops in the northern Great Plains (Coulman et al., 2013). Planting CCs in the spring allowed soil-water recharge following grain harvest the previous fall, resulting in increased biomass production from spring-planted CCs compared with late-summer planted CCs at Mandan, ND (Sanderson et al., 2018). The spring-planted CCs are terminated mid-summer and then followed with planting a grain crop in the fall or the following spring.

1.2.2 | Central and southern Great Plains

In this Great Plains ecoregion, winter wheat–grain sorghum or corn–fallow rotations are common, but W–F is still practiced in areas where annual precipitation is <500 mm (Nielsen et al., 2017). Intensified crop rotations with annual forages and grain crops have increased annualized crop yield, increased residue retention, reduced soil erosion, increased SOC and overall profitability (Holman et al., 2018; Nielsen et al, 2017; Rosenzweig et al., 2018). When irrigation water is available (Ogallala or High Plain's aquifer), continuous corn, a corn–soybean [*Glacine max* (L.) Merr.] rotation or continuous cotton are the dominant crop rotations. However, irrigation practices have shifted to deficit watering systems because of declining water levels in the Ogallala aquifer (Kisekka et al., 2016; Schlegel et al., 2012). In areas with diminished well capacities, producers have transitioned to dryland cropping or are growing forage and grain sorghum that are more drought tolerant compared with corn (Carr et al., 2021).

One common rotation in the southern and central Great Plains is W–S–F. This rotation has two fallow periods: one extending from winter wheat harvest in June or July until summer crop planting the following May or June (about 9–12 mo), and the second from summer crop harvest in October to winter wheat planting the following year in October (about 11 mo). Summer or late fall-planted CCs can replace the fallow period between wheat harvest and corn or sorghum planting the following year. Similarly, spring-planted CCs can replace the fallow period between sorghum (or corn) harvest and planting of the next winter wheat crop (Table 1). Both approaches may improve soil health, suppress weeds, and provide options to diversify crop production.

Water availability affects the ability to integrate CCs into the rotations with a yield loss. For example, in an irrigated system, spring-planted CCs had no effect on subsequent winter wheat yields in the southern Great Plains (Ghimire et al., 2019) and fall-planted CCs had no effect on cotton yields or economic returns in the Texas Rolling Plains (DeLaune et al., 2020).

1.2.3 | Cover crop selection

In general, cropping system and planting windows dictate the CC species that can be planted and the termination time for each subregion in the Great Plains (Table 1). Cool-season grass species including barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and spring triticale (× *Triticosecale* Wittm.) are commonly planted as single species or in mixtures with spring pea, radish (*Raphanus sativus* L.), rapeseed, safflower (*Carthamus tinctorius* L.), and sunflower (*Helianthus annuus* L.) in the spring or early summer across the region (Calderon et al., 2016; Ghimire et al., 2019; Holman et al., 2018; Kelly et al., 2021; Liebig et al., 2015; Thapa et al., 2021). Summer CCs are usually warm-season grasses and broadleaves including sorghum–sudangrass [*Sorghum* × *sudanense* (Piper) Stapf], pearl millet (*Pennisetum glaucum* L.), cowpea (*Vigna unguiculata* L), sunflower, and sun hemp (*Crotalaria juncea* L.) (Sanderson et al., 2018). Other winter annuals including cereal rye, winter triticale, winter wheat, Austrian winter pea, berseem clover (*Trifolium alexandrinum* L.), common vetch (*Vicia sativa* L.), flax (*Linum usitatissimum* L.), hairy vetch (*Vicia villosa* Roth), and lentil (*Lens culinaris* L.) are planted in late fall to provide cover in both the fall and spring seasons (Holman et al., 2018; Lewis et al., 2018).

Cover crop production in the semiarid Great Plains is highly variable, depending on precipitation, growing season, and CC species (Holman et al., 2018). Grass CC species and mixtures tend to produce more biomass than legume CCs in this region (Holman et al., 2021). For example, the most productive grass CCs in dryland environments in the central Great Plains are sorghum–sudangrass > triticale > wheat > oat > barley (Holman et al., 2020; Holman et al., 2021; Kelly et al., 2021; Simon et al., 2021). Broadleaf legume CCs are not competitive and generally produce little biomass when grown alone or in mixtures (Holman et al., 2018).

Although summer CCs can produce more biomass, there is a greater risk of establishment failure when CCs are planted after winter wheat harvest because of limited soil water availability and highly variable summer rainfall (Sanderson et al., 2018; Simon et al., 2021). For example, late summer planted CCs biomass was 96 kg ha^{-1} in 2009 compared with 1,430 kg ha^{-1} in 2008 when precipitation was timely following CC planting at Mandan, ND (Liebig et al., 2015). Spring-planted CCs have a greater chance of establishment success because of more available soil water to get CCs established compared to typical summer CC planting windows. Summer CCs can produce substantial biomass and provide ecosystem benefits, such as weed suppression and enhanced soil health, when

TABLE 1 Potential options in fitting cover crops in dryland cropping in the semiarid U.S. Great Plains

U.S. Great Plain ecoregion	Cropping system	Planting window	Terminationtiming	Cover crop species	Selected references
Northern Great Plains	Wheat–fallow or planting after annual grain crop (corn, pea, or canola) in a more intensified rotation	Summer (August through September)	Frost kill (summer cover crop)	Summer: Pea, proso millet; spring triticale, soybean, radish, red clover; turnip, and winter canola	Reese et al., 2014; Liebig et al., 2015; Sanderson et al., 2018, Khan & McVay, 2019
		Spring planting (May)	April termination with herbicides (for summer grain crops)	Spring: Barley, pea, proso millet, safflower, sorghum sudan, soybean, red clover, radish, turnip and triticale	
			July termination for spring cover crops		
Central Great Plains	Wheat–fallow	Spring planting (late February through April)	June through 1st week in July	Spring: Barley, berseem clover, flax, lentil, oat, pea, phacelia, rapeseed, triticale vetch, safflower, and sunflower.	Blanco-Canqui et al., 2013; Holman et al., 2018; Eash et al., 2021
		Fall planting (late August through September)		Winter: winter barley, winter oat, triticale, winter lentil, clovers, rapeseed, winter peas,winter canola	

(Continues)

TABLE 1 (Continued)

U.S. Great Plain ecoregion	Cropping system	Planting window	Terminationtiming	Cover crop species	Selected references
Central Great Plains	Winter wheat–summer crop–fallow or wheat wheat–summer crop–summer crop–fallow	Summer or fall planted (July through September)	Frost kill (summer cover crops)	Spring: Barley, berseem clover, buckwheat, flax, lentil, oat, pea, phacelia, rapeseed, radish, triticale vetch, safflower, and sunflower	Nielsen et al., 2015; Kelly et al., 2021; Holman et al., 2021; Simon et al., 2021
		Spring planting (late February through April)	June through 1st week in July for spring planted or overwintering cover crops	Summer and fall: sorghum sudan, millet, cowpea, radish, sunflower, sun hemp, triticale	
Southern Great Plains (with or without irrigation)	Winter wheat–summer–crop fallow; corn–corn or cotton–cotton	Winter (September–October)	Terminated in April (winter cover crop for next grain crop)	Winter: Austrian winter pea, cereal rye, crimson clover, hairy vetch, turnips, triticale, rapeseed, and winter wheat	DeLaune & Mubvumba, 2020. Ghimire et al., 2019; Lewis et al., 2018; Thapa et al., 2019
		Spring (late February through April)	June through 1st week in July for spring planted.	Spring: Barley, berseem clover, flax, lentil, oat, pea, phacelia, rapeseed, radish, triticale vetch, safflower, and sunflower	

there is adequate water to get the CC established. While fall-planted CCs do not typically produce as much biomass, they can stabilize the soil for longer periods by maintaining cover and growing roots during the fall and early spring. Planting multi-species CCs has been suggested as a strategy to improve biomass production and ecosystem benefits (Finney et al., 2016). However, planting multi-species CCs in dryland environments has not improved biomass production, residue cover, or weed suppression benefits when compared to a single productive species or simple CC mixtures (Carr et al., 2020; Holman et al., 2018; Liebig et al., 2015; Nielsen et al., 2015; Sanderson et al., 2018).

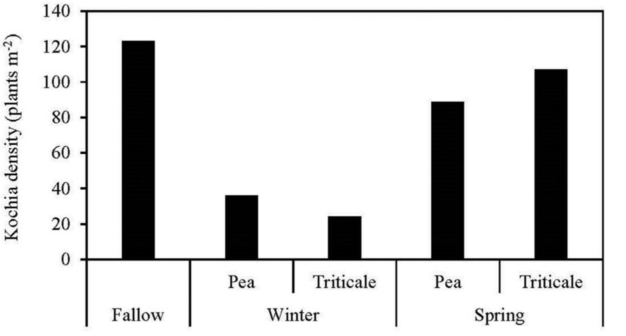

FIGURE 2 Kochia suppression with cover crops in place of fallow in a wheat–fallow rotation. Source: Petrosino et al., 2015

1.3 | Benefits, challenges, and limitations of cover crops

1.3.1 | Benefits of cover crops

Cover crops provide several benefits including enhanced soil health, weed suppression, reduced herbicide applications, increased soil residue, annual forage for livestock, and improved precipitation-use efficiency (Blanco-Canqui et al, 2015; Kelly et al, 2021; Kumar et al., 2020). Cover crops planted during the fallow phase can provide soil cover until planting the next grain crop (Holman et al., 2018; Nielsen et al., 2015). Furthermore, legume CCs provide increased rooting activity that can aid in the accrual or maintenance of SOC and can contribute N to improve soil fertility (Blanco-Canqui et al., 2015; DeLaune et al., 2019; Lewis et al., 2018). The SOC benefits of CCs can be enhanced when reduced tillage and NT management are adopted along with cover cropping (Thapa et al., 2019). The combination of increased soil cover and SOC can improve soil structure and aggregation, thereby reducing soil susceptibility to wind and water erosion (Blanco-Canqui & Ruis, 2020). Cover crops, especially grasses like triticale, can increase water-stable and dry aggregates compared to fallow (Table 2; Blanco-Canqui et al., 2013).

Wind erosion is the greatest concern in late winter and early spring in the Great Plains (Allmaras, 1983). The presence of CCs or their residues can provide protection from the prevailing winds (Blanco-Canqui et al., 2015). Although not common, high intensity storms in late spring and early summer can cause water erosion in fields with little vegetation cover. Furthermore, CCs can improve soil water-holding capacity, and the water infiltration rate (Blanco-Canqui et al., 2013; Burke et al., 2021), although in dryland systems CCs often decrease water availability to the subsequent crop (Holman et al., 2018; Nielsen et al., 2015).

Although potential improvements in soil properties with CCs have gained the attention of dryland producers, the greatest interest in CCs has been for their benefits in weed suppression (Baraibar et al., 2017; Osipitan et al., 2018). Cover crops can suppress weeds and reduce herbicide needs and usage during the fallow phase of dryland cropping systems (Holman et al., 2018), which can improve the sustainability of long-term NT systems across the Great Plains and other semiarid regions. Reducing the number of herbicide applications required to maintain NT fallow with CCs can reduce the selection pressure for HR weeds in dryland crop production in the Great Plains (Kumar et al., 2020). Cover crops can also be strategically planted to target specific weeds by producing substantial biomass before weed germination and emergence (Figure 2; Petrosino et al., 2015). Fall-planted winter triticale suppressed kochia density compared with spring triticale because the weeds emerged ahead of the spring-planted CC (Petrosino et al., 2015). Reductions in weed number, biomass, and seed production with CCs as part of an integrated weed management system can mitigate current weed infestations and limit future infestations by restricting seed production and deposition to the soil seed bank (Kumar et al., 2020).

Integration of CCs creates grazing opportunities for livestock (dual-use of CCs) and may provide economic benefit to producers to offset potential loss in revenue when water used by CCs results in yield decreases (Blanco-Canqui et al., 2020; Holman et al., 2018, 2021). Cover crop provide high quality feed for growing livestock (Carr et al., 2020; Holman et al., 2018, 2020). Integrated-crop livestock systems with CCs may be especially beneficial to farmers by helping to delay livestock grazing of native rangelands, providing longer rest periods between grazing. Deferring grazing on rangelands or pastures and grazing CCs instead can help extend the length of the grazing season or improve persistence of pastures because of less grazing pressure. More discussion of CCs use for forage is provided in the section on management options for cover crop integration in semiarid Great Plains.

Because fallow is an inefficient practice for precipitation storage, CCs can be used to improve the precipitation-use efficiency of dryland cropping systems (Holman et al., 2020; Nielsen et al., 2015; Stewart & Peterson, 2015). Precipitation storage efficiencies are greatest during the first few months of

TABLE 2 Cover crop effects on soil properties from selected papers in the semiarid U.S. Great Plains

Cover crop (location/crop rotation) and property (units)	Depth	Fallow	Cover crop	Difference	Reference
	cm			%	
Winter triticale (Garden City, KS/wheat–fallow); 5-yr study					Blanco-Canqui et al., 2013
Bulk density, g cm^{-3}	0–7.5	1.57	1.39	–11	
Mean weight diameter of wet aggregates, mm	0–7.5	0.48	0.82	71	
Wind erodible fraction, %	0–7.5	0.58	0.40	–31	
Soil organic carbon, Mg ha^{-1}	0–7.5	8.7	11.4	31	
Spring triticale (Garden City, KS/wheat–fallow); 5-yr study					Blanco-Canqui et al., 2013
Bulk density, g cm^{-3}	0–7.5	1.57	1.44	–8	
Mean weight diameter of wet aggregates, mm	0–7.5	0.48	0.75	75	
Wind erodible fraction, %	0–7.5	0.58	0.38	–34	
Soil organic carbon, Mg ha^{-1}	0–7.5	8.7	11.6	33	
Oat (Akron, CO and Sydney, NE/wheat–proso millet–fallow); 1-yr study					Calderón et al., 2016
Microbial biomass, nmol g^{-1} soil	0-5	73.9	152.2	106	
Arbuscular mycorrhizal fungi, nmol g^{-1} soil	0-5	1.7	3.8	124	
10-species mixture (Akron, CO and Sydney, NE/wheat–proso millet–fallow); 1-yr study					Calderón et al., 2016
Microbial biomass, nmol g^{-1} soil	0–5	73.9	144.4	95	
Arbuscular mycorrhizal fungi, nmol g^{-1} soil	0–5	1.7	3.7	118	
Rye (Lamesa, TX/continuous cotton, limited irrigation); 3-yr study					Lewis et al., 2018
Bulk density, g cm^{-3}	0–15	1.64	1.74	6	
pH	0–15	7.5	7.0	–7	
Total N, mg kg^{-1}	0–15	408	447		
NO_3–N, mg kg^{-1}	0–15	8.0	6.0	–33	
Soil organic carbon, Mg ha^{-1}	0–15	5.5	9.3	69	
Oat (Clovis, NM/wheat–fallow, limited irrigation); 3-yr study					Ghimire et al., 2019
Soil organic carbon, Mg ha^{-1}	0–15	13.8	14.0	1	
POXC, kg ha^{-1}	0–15	795	840	6	
Six-species mixture (Clovis, NM/wheat–sorghum–fallow, limited irrigation); 3-yr study					Ghimire et al., 2019
Soil organic carbon, Mg ha^{-1}	0–15	13.8	13.5	–2	
POXC, kg ha^{-1}	0–15	795	838	5	
Oat (Clovis, NM/wheat–fallow, limited irrigation); 3-yr study					Thapa et al., 2021
Microbial biomass, nmol g^{-1} soil	0–15	68.4	89.6	31	
Arbuscular mycorrhizal fungi, nmol g^{-1} soil	0–15	3.71	6.83	84	
Six-species mixture (Clovis, NM/wheat–sorghum–fallow, limited irrigation); 3-yr study					Thapa et al., 2021
Microbial biomass, nmol g^{-1} soil	0–15	68.4	91.7	34	
Arbuscular mycorrhizal fungi, nmol g^{-1} soil	0–15	3.71	6.83	84	

fallow after crop harvest, and usually diminish by the following spring as the soil profile reaches maximum water holding capacity and rising air temperatures increase evaporation (Stewart & Peterson, 2015). Replacing a portion of the fallow period with a CC can increase precipitation-use efficiency as CCs transpire water from the soil that otherwise would be lost by evaporation (Holman et al., 2020; Nielsen et al., 2015; Stewart & Liang, 2015).

1.4 | Challenges and limitations of cover crops in dryland crop production

Challenges associated with limited and erratic precipitation in the Great Plains have restricted CC adoption in dryland production systems (Holman et al., 2018, 2020; Sanderson et al., 2018; Schlegel & Havlin, 1997). Such challenges include CC establishment difficulties, highly variable CC biomass production, incompatibility with some conventional residual herbicides, and soil water depletion prior to planting the following grain crop. Colder temperatures, low precipitation, and soil water following the harvest of primary crops make CC establishment a major challenge for dryland producers (Holman et al., 2020; Liebig et al., 2015; Sanderson et al., 2018). For example, soil water is often low following wheat harvest, so successful CC germination and establishment depend on timely precipitation in July and August. Additionally, while the top 15 cm of the soil generally is moist when CCs are planted in the spring following corn or grain sorghum harvest the previous fall, timely rains still are needed for optimum establishment (Holman et al., 2020). Even with adequate soil water availability, colder temperatures in the late fall and spring periods can limit the germination of most CCs species, particularly in northern and central Great Plains subregions.

Cover crop biomass production can vary substantially from year to year (Holman et al., 2018, 2020; Nielsen et al., 2015). In years with adequate precipitation, substantial biomass can be produced to provide soil benefits (Blanco-Canqui et al., 2013), weed suppression (Mesbah et al., 2019; Petrosino et al., 2015), and forage for grazing or haying (Holman et al., 2018; Simon et al., 2021). However, in dry years, low biomass production can limit these ecosystem services. Additionally, when CC biomass is limited, weed management becomes a challenge as weeds are not adequately suppressed (Petrosino et al., 2015) and may produce viable seed before the time CC termination was intended. Early termination may be necessary in these situations to prevent future weed infestations.

Another potential cause of smaller CC biomass production is injury from residual herbicides. Some herbicides have long carryover periods that may limit CC establishment or compromise their safety as livestock feed (Rector et al., 2019). In dryland cropping systems, residual herbicides are frequently used to control weeds when growing grain crops as well as during fallow. Depending on the herbicide formulation, increased persistence can be observed in dry soils, which has direct implications on the amount of herbicide contained in the soil in the following year (Kumar et al., 2020). The potential for herbicide injury from the remaining herbicides requires producers to reassess herbicide programs to ensure compatibility with the CC species selected. The influence of residual herbicides on the safety of CCs intended for forage is a major concern. Some herbicides persist in plants at levels that are harmful for livestock (Jhala et al., 2016). Producers must be aware of these restrictions before planting CCs for forage.

Above all else, the most significant limitation to CC adoption in the Great Plains and other semi-arid regions is water used by CCs (Holman et al., 2018). The grain yield depression induced by a previous CC water use can be substantial in years with low growing season precipitation (Holman et al., 2018; Nielsen et al, 2017; Nielsen & Vigil, 2014; Schlegel & Havlin, 1997). In years with above-average precipitation, wheat yields were unaffected by CCs compared with fallow, but in dry years, yields were reduced by as much as 70% (Holman et al., 2018, 2020). Terminating CCs in early June in a W–S–F cropping system in the central Great Plains provides a fallow period for soil water recharge compared to a later CC termination ahead of winter wheat planting (Holman et al., 2021). This will limit the impact of CCs on soil water availability for establishment of the subsequent wheat crop.

1.5 | Management options for cover crop integration in semiarid Great Plains

The challenge in the Great Plains and other semiarid regions is to implement CC production systems that use less plant available water but produce enough biomass to improve soil health and the economic profitability. Grazing or haying of CCs is an option that can provide additional revenue through forage harvest and livestock integration. The Great Plains region has a significant livestock industry, though it became largely separated from crop production by the mid-1990s, relying heavily on external feed imports (Krall & Schuman, 1996). This trend has been reversing as an increasing number of producers are interested in integrating livestock and crop production enterprises (Kumar et al., 2019).

Using CCs for forage provides an opportunity for the reintegration of crop–livestock systems on dryland farms to build soil health, control HR weeds, and maintain resilience and overall productivity. Most of the grass and broadleaf plant species used as CCs have high forage yield and nutritive value potential (Holman et al., 2020, 2021; Nielsen et al., 2017; Obour et al., 2019, 2020). Harvesting CCs as annual forage can offset losses in revenue resulting from wheat or sorghum yield depression following CCs. However, haying CCs as forage reduces the amount of residue left on the soil surface and could negate the soil conservation benefits of CCs, even if economically profitable. An ideal management strategy would be to graze CCs or harvest CCs for hay at greater cutting heights that leave adequate residue to protect the soil from erosion.

Aggregate stability and wind erodible fractions were not different when CCs were hayed leaving 15 cm of stubble compared to standing CCs near Garden City, KS (Blanco-Canqui et al., 2013). A more recent study from this same location showed aggregate stability, SOC, and water infiltration rates were unaffected by haying compared to standing CC (Simon et al., 2020), suggesting that CCs managed for annual forage but leaving tall stubble provide similar soil health benefits as CCs planted solely for cover. Though not measured, it is plausible that belowground root biomass of CCs contributed substantially to the maintenance of SOC and other soil properties, even when aboveground biomass was removed. No published information exists on the long-term (>10 yr) effects of haying CCs on SOC, physical and soil structural properties, nutrient cycling and biological properties of soils in the semi-arid Great Plains. Previous research showed baling corn residue as forage decreased SOC stocks, soil microbial biomass, and increased wind erodible fraction compared with no residue removal (Ruis et al., 2018). Therefore, producers haying CCs should exercise good judgement in leaving enough residue behind to accomplish soil conservation goals.

Grazing CCs with livestock could retain more residue than haying and offer a balance between soil conservation benefits and the short-term economic benefits. Manure and urine deposition by cattle grazing CCs can enhance soil nutrient cycling (e.g., N, P, and K), increase SOC, improve microbial community structure, and increase soil enzyme activity (Franzluebbers, 2007; Franzluebbers & Stuedemann, 2015; Sekaran et al., 2021). These benefits make CC grazing a better option than haying. Most CC grass species planted in the Great Plains have significant regrowth potential (Kelly et al., 2021; Obour, Simon, et al., 2021), thereby providing adequate residue cover to protect soil and meet conservation goals. High yield potential exists for many CC species adapted to the Great Plains in wet years (Holman et al., 2018; Lewis et al., 2018; Liebig et al., 2015), while both the stocking rate and grazing duration can be adjusted to retain residue in dry years. Across 3 site-years in western Kansas, CC biomass production after cattle grazing was 3,312 kg ha^{-1} compared with 4,190 kg ha^{-1} for the non-grazed CCs (Obour, Simon, et al., 2021), demonstrating the regrowth potential of the CC species used. Similarly, CC biomass after cattle grazing was only 18% less than non-grazed CC in a study conducted in eastern Colorado, western Kansas, and southwestern Nebraska (Kelly et al., 2021).

Most producers grazing CCs in the Great Plains recognize the importance of maintaining soil cover and adopt a grazing strategy that provides adequate surface cover to protect the soil from wind and water erosion. Even so, high year-to-year variability in CC biomass (and forage) production poses a major challenge to grazing in this water-limited environment. Spring planted CC forage accumulation in western Kansas averaged 2,500 kg ha^{-1} in a 6-yr study, but varied only 1,600 kg ha^{-1} in 2019 to 3,218 kg ha^{-1} in 2017 (Figure 3; Simon et al., 2021). In a long-term experiment near Garden City, KS, dry matter yield ranged from 1,100 to 11,100 kg ha^{-1} for forage sorghum, 500 to 5,100 kg ha^{-1} for winter triticale, and from 20 to 5,400 kg ha^{-1} for spring oat (Holman et al., 2020). Producers face challenges in planning for grazing, given the amount of variation in biomass production by CC. Producers wanting to graze CCs should adopt flexible management plans where herd size can be adjusted based on the amount of available forage. In addition, crop rotation schemes must be flexible so changes can be made when conditions favor forage production. Cattle may need to be moved to native rangelands earlier than expected if available forage from CCs is not enough to support grazing (Brummer et al., 2018; Johnson et al., 2020). In years with plentiful precipitation for CC growth, range productivity is also high, making hay or ensilage a better use of the forage. The stored hay from CC can be fed to livestock in years when forage productivity are low.

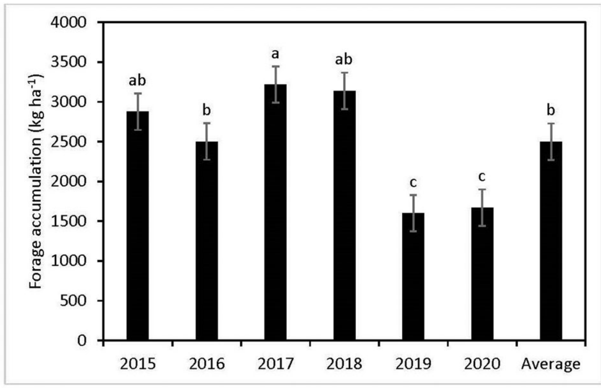

FIGURE 3 Year-to-year variability in spring-planted cover crop forage accumulation near Brownell, KS. Bars followed by same letter (s) are not significantly different ($P < .05$). Error bars represent one standard error of mean. Source: Simon et al., 2021

A major concern of grazing CCs in NT production systems is soil compaction from excessive animal trampling that may suppress subsequent crop yields and requires remediation (Baumhardt et al., 2011). In addition, there is a danger of overgrazing CCs, particularly in dry years that could result in little residue cover with concomitant negative effects on SOC, aggregate stability, and water infiltration rates. Nevertheless, field studies conducted in the Great Plains reported little to no differences in soil properties with grazed compared with non-grazed CCs (Blanco-Canqui et al., 2020;

FIGURE 4 Planting into dry soil destroys crop residue. Picture on the left is spring pea/triticale cover crop residue compared to summer fallow residue (with no cover crop planting) on the right. Picture credit: John Holman, Kansas State Univ., Southwest Research & Extension Center, Garden City, KS

Kelly et al, 2021; Obour, Simon et al., 2021). Aggregate size distribution and mean weight diameter of water stable aggregates (MWD) were unaffected by grazing CCs in west-central Kansas (Obour, Simon et al., 2021). Similarly, soil bulk density, pH, SOC, and concentrations of nutrients did not differ between grazed and non-grazed CCs in that study. Across 10 site-years in the central Great Plains, aggregate stability significantly increased with grazed or non-grazed CCs, and grazing CCs did not increase soil surface bulk density compared to fallow after 1 yr of grazing (Kelly et al., 2021). These results agree with Blanco-Canqui et al. (2020) who showed that grazing CCs had no negative impact on soil bulk density, SOC, or aggregate stability in an irrigated corn-CC production system in Nebraska.

Increased profitability by utilizing CCs for forage is only possible when there is sufficient soil water available and relatively cool air temperatures to grow a CC. When growing conditions are affected by soil water availability or colder temperatures, planted CCs may fail to establish or produce adequate biomass for hay or grazing. In such situations, it can be less costly if the field was left fallow. Furthermore, drilling CCs into sorghum or wheat stubble in dry years destroyed the little residue cover and predisposed fields to greater erosion in western Kansas (Figure 4). A mitigation option is a flex-CC system where CCs are grown only in years where stored soil water and projected growing season precipitation favor adequate biomass production (i.e., >2,000 kg ha^{-1}) (Holman et al., 2018). If stored soil water is low or precipitation forecast is not favorable, then the field is fallowed to store soil water for the subsequent cash crop (Holman et al., 2018). The challenge with this practice is the limited accuracy of precipitation models to predict rainfall amounts over the growing season. Nevertheless, previous studies in the central Great Plains support the idea of flex-CC as an opportunity cropping practice to intensify dryland crop production in some years (Lyon et al., 2007).

2 | SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH EFFORTS

Cover crop integration in dryland cropping systems has been limited because of its potential negative impacts on cash crop yields. Ongoing research efforts showed using CCs for forage provides an opportunity for crop–livestock integration to maintain soil health, suppress weeds, and provide a range of other ecosystem services. Still, data are limited on best management practices for grazing CCs in dryland NT systems across the Great Plains. More importantly, because of the East–West precipitation gradient and differences in potential evapotranspiration rates between northern and southern sections of the Great Plains, research-based recommendation generated in one region may not be directly applicable to others. For instance, in the central Great Plains, warm- and cool-season grass CC species tend to produce more biomass when planted as monocultures or in simple mixtures compared to complex mixtures (cocktails). Moreover, legume CCs tend to produce little biomass and have limited weed suppression potential.

Cover crops that produce greater biomass yields also tend to use more soil water and reduce soil water available for the subsequent crop. Notwithstanding, CC effects on soil water use depends on termination date and the amount of precipitation after termination to replenish soil water. Earlier termination date can reduce water use by CCs (Holman et al., 2018; Nielsen et al., 2015), but early termination could result in little biomass for soil health benefits. Terminating spring-planted CCs by 1 June (approximately at heading) produced adequate residue cover and increased post-termination precipitation storage efficiency compared to fallow in the central Great Plains (Holman et al., 2021; Kelly et al., 2021). Identifying species, seeding rates, and CC termination dates that produce sufficient biomass but less soil water use (in the top

60 cm which affects crop emergence and establishment) needs to be explored.

Regional or site-specific research is needed to determine the best CC species or mixtures that can balance grazing, weed suppression, and soil health outcomes. Furthermore, planting window may differ based on the cropping system and location. For example, in the central and southern Great Plains, CCs perform well when spring planted into corn or sorghum stubble, while post-wheat CCs may be more practical for growers in subregions of the Great Plains where W–F is the predominant cropping system.

A small number of short-term studies across the region showed using CCs for forage had minimal or no effect on soil properties. Still, more questions remain on the amount of CC biomass that could be removed through grazing relative to residue cover to prevent long-term adverse effects on soil properties. Data on long-term grazing impacts on soil compaction, wind erodible fraction, and water infiltration rates are unavailable. The grazing potential of CCs and impacts on economic sustainability of agriculture in dryland systems require further investigation. Additional research needs include determining soil fertility requirements of CCs, evaluating species for biomass production and water use, and updating fertilizer recommendations to account for CC production systems. Cover crops are usually not fertilized, but when used as forage it may be beneficial to supply adequate plant nutrients to increase productivity and nutritive value.

Exploring flex-CC could be most beneficial to subregions in the Great Plains that receive <500 mm annual precipitation because planting CCs only in favorable years will reduce the risk of cash crop failure in dry years while offering an opportunity to intensify the cropping systems to build soil health. Presently, most research on weed suppression by CCs has measured CC biomass and weed density (Mesbah et al., 2019). It is possible that weed emergence patterns and species dominance could shift with CC integration. Improvement in soil biological communities with CCs (Table 2; Calderon et al., 2016; Thapa et al., 2021), could also result in seed predation and weed suppression. Both scenarios can reduce the weed seedbank. Future research efforts should focus on investigating weed seedbank dynamics and persistence of HR weeds, particularly kochia and palmer amaranth, across the Great Plains. Additional research efforts should also examine residual herbicide activity on CC establishment and productivity.

Best management guidelines for CCs in the semi-arid Great Plains will continue to change as more long-term data become available. Results of current short-term studies showed grazing CCs had no negative impacts on soil properties and offers opportunity to intensify dryland crop production and maintain soil properties. Developing cropping systems that retain more residue will be crucial to improving water infiltration and precipitation use efficiency in the face of future climate change scenarios that are predicted to cause greater fluctuations in rainfall distribution across the region. Generating the data needed to fine-tune CC management will require multi-state and multidisciplinary collaborations among scientists across the semi-arid Great Plains.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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