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The Declining Ogallala Aquifer and the Future Role of Rangeland Science on the North American High Plains[☆]

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ABSTRACT

The Ogallala Aquifer region, located in the Great Plains of the central United States, is the largest freshwater aquifer in North America, supporting one of the most agriculturally productive regions in the world. In this paper, we discuss the history of settlement and water use in this region, from the Homestead Act and the Dust Bowl to modern irrigation systems. While many improvements to irrigation technology and water-efficient crops have helped to prolong the life of the Ogallala, continued use of this finite resource is leading to a tragedy of the commons, wherein difficult land management decisions will have to be made by this century's end. We posit that the art and science of rangeland management stands uniquely poised to tackle this challenge directly through creative integration, where appropriate, of native rangeland restoration, improved pasture management, integrated crop-livestock systems, and regenerative agricultural practices aimed at preserving soil and rangeland health, thereby providing continuity in the ability of the Ogallala region to continue to provide food, fiber, and other ecosystem services both locally and globally. Furthermore, we provide discussion on future research, extension, and educational needs to consider as the exploration for adaptive solutions are developed and evaluated in the coming decades.

Introduction

Rangelands; native or reclaimed areas dominated by grasses, grasslikes, forbs, or shrubs that have the potential to be grazed (Bedell 1998; Allen et al. 2011), cover approximately 268 Mha of the continental United States (Reeves and Mitchell 2011). They have often been described as marginal lands not suitable for cultivation, with herbivory being the only, or most common, economic use (Stoddart et al. 1955; Pratt et al. 1966; Holechek et al. 1998), despite the fact that many of the most productive farmlands in the world came from converted prairie soils (Herrick et al. 2012). One such area is the Ogallala Aquifer (hereafter "Ogallala") region of the North American Great Plains. Underlying 450 660 km^2 across eight US states (Fig. 1) (Dennehy 2000; Dennehy et al. 2002), this aquifer has been essential to the US High Plains economy for more than 80 yr (Deines et al. 2020). As the largest freshwater aquifer in North America, and one of the largest in the world, the Ogallala supports approximately 30% of all crop and animal production in the United States (Dennehy 2000). It accounts for 15% of all groundwater withdrawals in the conterminous United States (Lovelace et al. 2020), making this region critical to the global food supply chain (Opie et al. 2018). Additionally, the Ogallala provides critical drinking water to 82% of the people living within the aquifer

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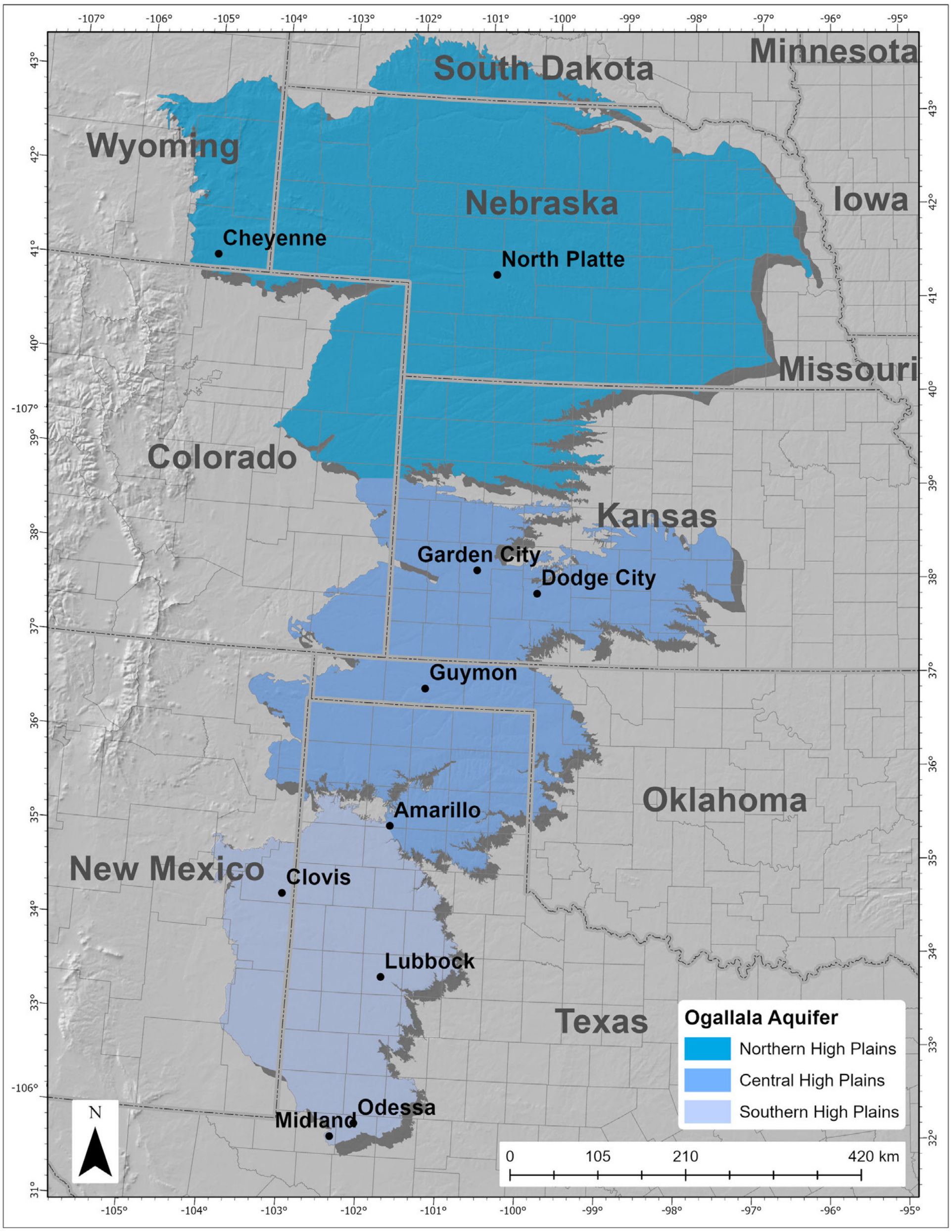

Figure 1. Ogallala Aquifer region and subregion boundaries based upon Stanton et al. (2011) within the US high plains in North America.

boundary (Dennehy et al. 2002). However, water is being depleted at a much higher rate than can naturally recharge, with available water supplies in many areas of the aquifer having already been reduced by more than 40% to 75% since predevelopment (pre-1935) (NRC 1996; Haacker et al. 2016). Much of the most agriculturally productive areas of the aquifer from Texas north through Kansas are at risk of depletion by the yr 2100 (Haacker et al. 2016; Smidt et al. 2016).

With the potential end of large-scale irrigation projected over the central and southern portions of the Ogallala in the next 100 yr, previous research in the Ogallala region has focused on water-saving regulations, technology, infrastructure, practices, and crop genetics (Cooper et al. 2014), often with the expectation that farm production will revert to dryland practices when the aquifer is depleted (Wheeler et al. 2008; Amosson et al. 2009; Dobrowolski and Engle 2016; Cotterman et al. 2018; Deines et al. 2020). However, barring some unforeseen advances in agronomic practices and crop genetics, 24% of the soils overlying the aquifer, including 13% that are currently under irrigation regimes, may not be suitable for cropland production without irrigation (Deines et al. 2020), meaning that conversion to grasslands (pasture or rangeland) may be the best and most sustainable use of these marginal agricultural soils when the aquifer is depleted (Dobrowolski and Engle 2016). While there have been several studies conducted on the impacts of the declining aquifer on intensive agricultural production and water usage, there has been little attention focused on the important role that rangeland management can play within a socioecological context as part of the ecosystem services portfolio of a post-Ogallala landscape. In this paper, we will 1) briefly review the history of the Ogallala region, from presettlement through the present, 2) examine what has led to this modern-day “tragedy of the commons,” 3) the impending reduction of cropland production, and 4) how the art and science of rangeland management may be called on to lead interdisciplinary

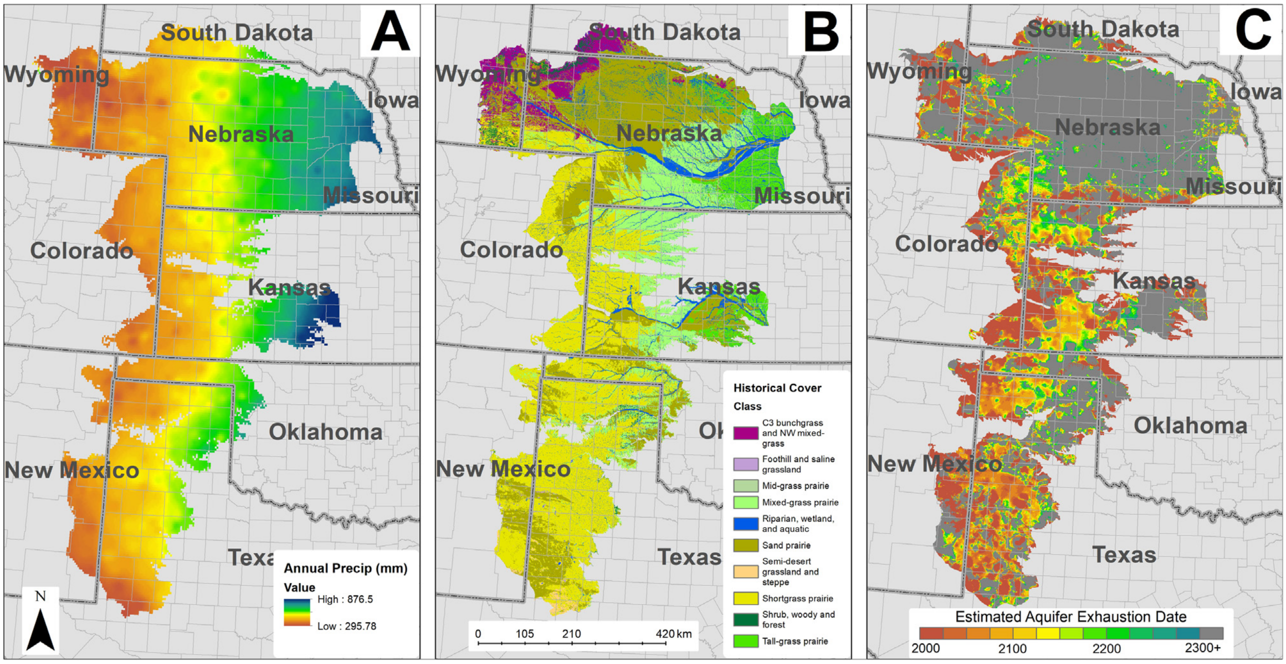

Figure 2. **A,** Long-term average annual rainfall (mm) (PRISM 2014); **B,** historical presettlement plant communities (derived from Callan et al 2016); and **C,** estimated date of groundwater depletion (derived from Haacker et al. 2016) of the Ogallala Aquifer region.

solutions to provide critical ecosystem services from derelict farmland.

Ogallala History Through the Early 1950s

The Ogallala aquifer is an unconfined (not trapped by an impervious layer) aquifer spanning from Texas (31°44’36.312”N) north to South Dakota (43°39’49.608”N) and from eastern Nebraska (96°15’31”W) to Wyoming (105°55’16.64”W; see Fig. 1) (Weeks and Gutentag 1981). The Ogallala was formed by silt and gravel deposited from the erosion of the Rocky Mountains during the Miocene and Pliocene, 24 to 2 million yr ago (Gutentag et al. 1984; McGuire 2009; Willett et al. 2018). The Ogallala formation has been described as braided stream deposits made up of broad, thinning, and shallow channels throughout (McMillan et al. 2002). Fluvial and eolian sediments then accumulated in the valleys, streams, and lowland areas across the ancient Great Plains (Diffendal 1982; Swinehart et al. 1985; Goodwin and Diffendal Jr 1987; Willett et al. 2018). This created a relatively smooth and gently sloping surface across the western Great Plains region that extended east over 1 000 km from the Rocky Mountains (Willett et al. 2018). The groundwater contained within the Ogallala formation was deposited from 25 000 to 10 000 yr ago (Clark and Brauer 2010; Steward et al. 2013). Though the aquifer is technically capable of recharge, the rate of recharge is extremely low to nonexistent ($<$ 0.06 cm/yr in Texas up to 15 cm/yr in central Kansas) in much of the central and southern portion (Gutentag et al. 1984; Luckey and Becker 1999). In every practical sense, Ogallala water is a nonrenewable resource that has often been referred to as “fossil water”(Clark and Brauer 2010).

Before European settlement, the Ogallala region exemplified the vast Great Plains prairie ecoregion (Fig. 2) (Holecheck, J.L., 1981; Holechek et al. 1998). Annual precipitation for this region follows an west-to-east gradient ranging from 295 to 876 mm per yr, respectively (see Fig. 2A) (PRISM 2014). Dominant historical vegetation types included various prairie assemblages (tallgrass, shortgrass, mixed, sandy, foothills, and midgrass), as well as forested, shrub-steppe, semidesert, riparian, and wetland vegetation communities (see Fig. 2B) (Shiflet 1994; Holechek et al. 1998; Callan et al. 2016; Reese et al. 2016). The historical native plant cover over the majority of the Ogallala region consisted of shortgrass prairie (34%), sand prairie (29%), and mixed-grass prairie (16%) (Callan et al. 2016; Reese et al. 2016).

The shortgrass prairie region varied greatly from north to south. The northern portion was quite diverse and was dominated by cool-season grasses such as bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), needlegrasses (*Hesperostipa* sp., *Nassella* sp.), as well as warm-season species such as little bluestem (*Schizachyrium scoparium* [Michx.] Nash), blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), and sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.) (Holechek et al. 1998). The southern shortgrass prairie was predominantly little bluestem, silver bluestem (*Bothriochloa laguroides* [DC.] Herter), blue grama, buffalograss (*Bouteloua dactyloides* [Nutt.] J.T. Columbus), sideoats grama, vine mesquite (*Panicum obtusum* Kunth), tobosagrass (*Pleuraphis mutica* Buckley), and threeawns (*Aristida* sp.) (Holechek et al. 1998). Later, mesquite (*Prosopis glandulosa* Torr.) and Texas wintergrass (*Nassella leucotricha* [Trin. & Rupr.] Pohl) would become much more prevalent in this region under increasing grazing pressure. The sand prairie of the Nebraska sandhills region was dominated by tallgrass species such as little bluestem, big bluestem (*Andropogon gerardii* Vitman), prairie sandreed (*Calamovilfa longifolia* [Hook.] Scribn.), and switchgrass (*Panicum virgatum* L.), as well as needlegrasses, gramas, and junegrass (*Koeleria macrantha* [Ledeb.] Schult.) (Shiflet 1994). Much of the vaunted, true tallgrass prairie is outside of the Ogallala region to the east, though the aquifer underlies portions of it in Kansas and eastern Nebraska, making up approximately 6% of the historical plant community (Callan et al. 2016; Reese et al. 2016). It was dominated by the “big four” species of big bluestem, little bluestem, switchgrass, and Indiangrass (*Sorghastrum nutans* [L.] Nash), as well as a mixture of gramas, needlegrasses, and western wheatgrass (Shiflet 1994; Holechek et al. 1998). The remainder of the Ogallala region was made up of cool-season bunchgrass and northwestern mixed-grass prairies in Wyoming; shrubland, woodland, forest, and semidesert steppe;

and foothills and saline grasslands (Callan et al. 2016; Reese et al. 2016).

The Ogallala region is part of the historical range of many important wildlife species, such as the American bison (*Bison bison* L.), white-tailed deer (*Odocoileus virginianus* Zimmermann), pronghorn antelope (*Antilocarpa americana* Ord), elk (*Cervus canadensis* Erxleben), black-tailed prairie dogs (*Cynomys ludovicianus* Ord), greater prairie-chicken (*Tympanuchus cupido* L.), lesser prairie-chicken (*Tympanuchus pallidicinctus* Ridgway), northern bobwhite (*Colinus virginianus* L.), various ground nesting songbirds, and pollinators (Harrington and Harman 1995; Knopf and Samson 1995; Johnsgard 2009; Hanberry et al. 2021). Across the Great Plains region, it is estimated that as much as 70% of the rangeland systems have been lost (Samson et al. 2004), leading to landscapes that are greatly diminished, fragmented, and genetically disconnected (Johnson 2001). Lesser prairie-chickens, for example, have seen their distribution diminished by more than 90% in the past century (Fuhlendorf et al. 2002), with woody plant encroachment on remaining habitat fragments becoming an increasing issue (Coppedge et al. 2001a). Recent research suggests that black-tailed prairie dogs may have had a key role in the reduction of woody species growth on rangelands (Hale et al. 2020), further underscoring the connectedness of various trophic levels and ecological processes. Furthermore, reductions in baseflow of streams due to draw-down of groundwater have negative implications for the health of streams and fisheries habitat in the Great Plains (Falke et al. 2011; Perkin et al. 2015)

Given the characteristic frequent droughts, along with little surface water, this area became known early on as the “Great American Desert” (Egan 2006; Opie et al. 2018) and was relegated to livestock use where surface water was available. From 1870 to 1880, farmers were enticed to the region through free land grants promised by the Homestead Act of 1862 (Dennehy et al. 2002; Augustine et al. 2021) and the Enlarged Homestead Act of 1909 (Holechek et al. 1998). This led to a boom-bust dryland farming system that expanded during favorable years and crashed in the drought years, resulting in a constant ebb and flow of human immigration and emigration (Dennehy et al. 2002; Opie et al. 2018; Augustine et al. 2021). An uncharacteristically wet period from 1878 to 1887 led to an influx of settlers under the sensationalist claim that “rain follows the plow.” Yet many of them went bankrupt and left once the rains stopped (Dennehy et al. 2002; Opie et al. 2018). The most well-known consequence of the dryland farming era was the Dust Bowl of the 1930s, which led to widespread soil loss and the creation of the Soil Erosion Service (now called the Natural Resources Conservation Service) (Holecheck, J.L., 1981), bringing the potential of drought resistance through irrigation and crop/soil stability to the forefront of discussion (Opie et al. 2018).

The Ogallala formation was first described by the US Geological Survey in the 1890s, though at the time it was thought to be of little agricultural value, limited by the available technology at the time (Darton 1903; Webb 1959; Hornbeck and Keskin 2014). Windmill pumps from the era were only capable of producing enough water to irrigate approximately 2 ha of farmland or to provide drinking water for 30 head of cattle (Cunfer 2005). The mechanical pumps of the 1890s to early 1900s were far too costly for the average farmer and worked best in areas with a shallow water table (Opie et al. 2018). Improvised pumps using automobile motors became prevalent after World War II, and gravity-fed flood irrigation became a preferred method (Opie et al. 2018). However, irrigation was still not widespread throughout the Ogallala region until after the advent of the center-pivot irrigation system in 1952 (Splinter 1976; Supalla et al. 1982; Hornbeck and Keskin 2014; Ajaz et al. 2020), and the adoption of this technology may have been aided by the drought of 1951–1956 (Dobrowolski and Engle 2016).

Ogallala History from the 1950s to Present

Despite early, and often inefficient, attempts at irrigation, it has been estimated that by 1960 only 3% of the predevelopment groundwater storage had actually been harvested from the Ogallala (Steward et al. 2013). By 2010, roughly 30% of the Ogallala had been depleted. Currently, approximately 410 km^3 of water has been harvested from the Ogallala since predevelopment, a volume roughly equal to that of Lake Erie (Haacker et al. 2016; Smidt et al. 2016). Total groundwater withdrawal peaked in 1974 (McGuire 2009), yet water for irrigation remains the single greatest use (94%) (Lovelace et al. 2020). While only 23% of the total Ogallala region is irrigated (Gollehon and Winston 2013; Ajaz et al. 2020), yields on irrigated fields are often two to four times greater than those on dryland fields (Smidt et al. 2016). Property value per hectare can be up to five times greater for land with Ogallala access compared with their dryland counterparts (ASFMRA 2021).

As irrigated acreage began to expand, additional agricultural industries started to increase in the region. Before the 1950s, the predominant crops in the Ogallala region were mainly wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), and sorghum (*Sorghum bicolor* [L.] Moench); however, increased production potential from irrigation and increasing livestock populations began to cause a shift to corn and soybean preference in the northern Ogallala region (Hudson 1994; Dennehy et al. 2002). By the 1980s, confined animal feeding operations had become well established within the Ogallala region due to the plentiful groundwater resources, geographic isolation from large urban areas, and proximity to areas of feed grain production (Opie et al. 2018). Grain-based feeds are the predominant component of diets of animals in confined animal feeding operations (Klopfenstein et al. 2013), with livestock now consuming approximately 35% of the US corn supply (USDA ERS 2021). This, in turn, has led to the vertical integration of industries, through which more irrigated grain is produced to feed a larger number of animals, to sustain a steady demand of meat for slaughterhouses (Kilmer 1986; Steward et al. 2013), all supported by the underlying Ogallala.

The Energy Policy Act of 2005 brought additional incentives for intensification of agricultural production within the Ogallala region (Searchinger and Heimlich 2009; Wallander et al. 2011). Subsidies for corn ethanol production greatly increased irrigated acreage and total corn production (Fig. 3) to support the US mandate for renewable energy (Searchinger and Heimlich 2009; Nickerson et al. 2011; Wallander et al. 2011; Brown and Pervez 2014). Five years before the mandate, 60% of the US corn supply was used as livestock feed (Klopfenstein et al. 2013); by 2010, only about 43% was used as feed grain, while 42% was used for ethanol production (Klopfenstein et al. 2013). Currently, there are 211 ethanol conversion plants in the United States, with 35 occurring within the Ogallala region and an additional 8 within 50 km of the aquifer boundary (NREL 2019). Combined, the effects of ethanol and feed grain demand on crop prices has caused a massive shift to more intensively irrigated crops. Since 1980, there has been a 50% decline in small grain (e.g., sunflower, flaxseed) production across the entire Great Plains region in favor of row crops such as corn and soybeans (Smart et al. 2020).

Ultimately, the agricultural economy of the Ogallala region generates more than $20 billion (USD) each year, constitutes about 27% of all irrigated land area (Buchanan et al. 2009), and makes up > 95% of all groundwater withdrawals (Dennehy et al. 2002; Lovelace et al. 2020). Moreover, the Ogallala region is responsible for 10% of the total farm crop value of the United States (USDA NASS 2012; Smidt et al. 2016; Lauer et al. 2018). This, in turn, helps to sustain local economies and agricultural support industries dependent on groundwater availability (Kromm and White 1992; White 1994; Sanderson and Frey 2015). Failure to prepare

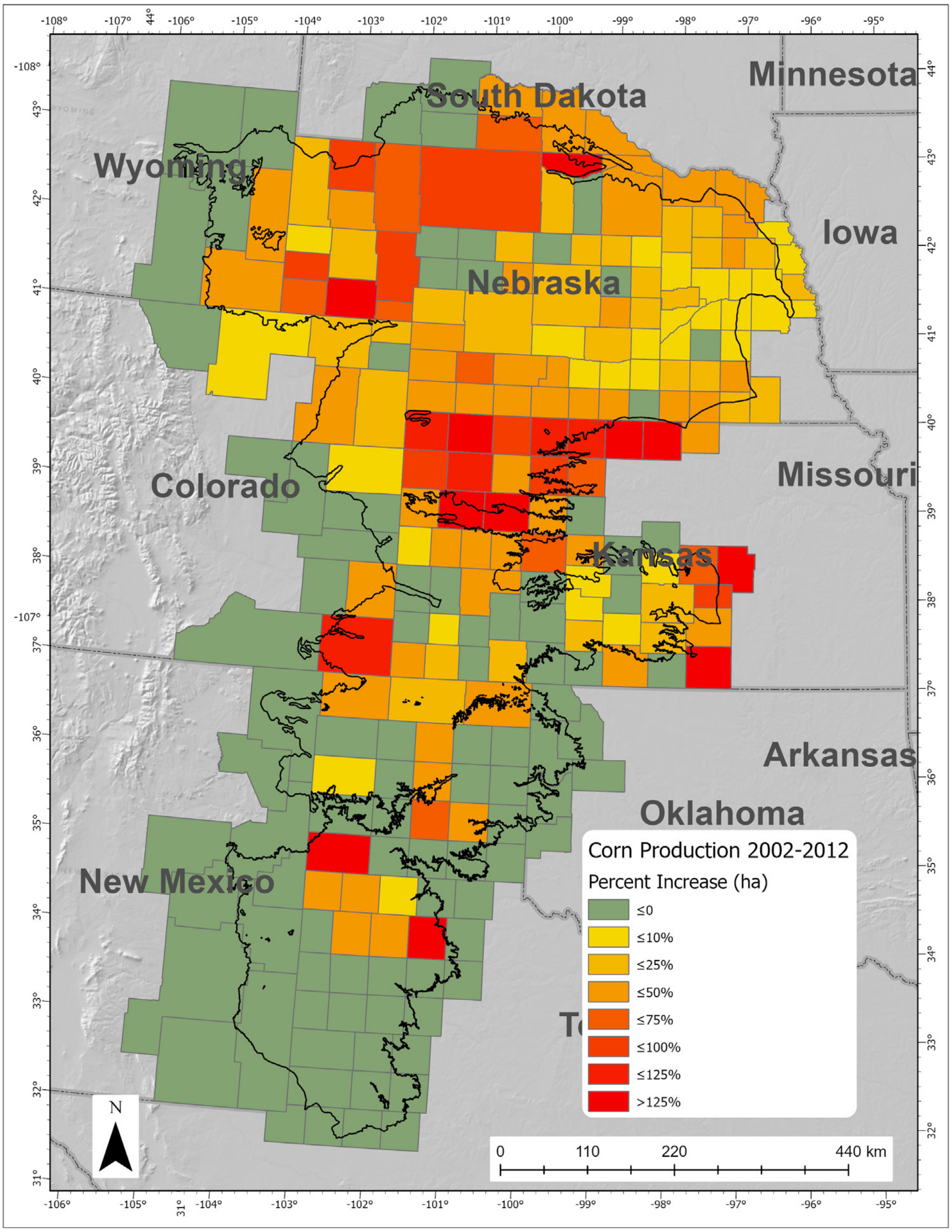

Figure 3. Percent increase in land area planted to corn by county from 2002-2012, following the US ethanol mandate of 2005. Data from USDA Census of Agriculture (USDA NASS 2002, 2012).

for the inevitable ecological and economic impacts of shifting away from such a heavy reliance on this dwindling resource could potentially imperil the United States and global food supply chain (Supalla et al. 1982; Cruse et al. 2016).

Water-Saving Strategies

Crop genetics have improved substantially since 1970. Dryland corn yields today are comparable with irrigated yields from 40 yr ago (USDA NASS 2012; Smidt et al. 2016). Older, gravity-fed irrigation technology typically had water use efficiencies from 30% to 62% (AAF 2016; Ajaz et al. 2020). Technological advancements in irrigation, such as center pivots, low-elevation spray applicators, low-energy precision application, and subsurface irrigation, have all helped to increase water use efficiency, up to 95% in many cases (Smidt et al. 2016; Ajaz et al. 2020). Land use methods such as cover crops and no-till farming (Tonitto et al. 2006; Blanco-Canqui et al. 2013; Poeplau and Don 2015; Aryal et al. 2018; Kelly et al. 2021), as well as use of less water-intensive crops (Chen et al. 2018), have all helped to increase the lifespan of the aquifer. But with little to no recharge, these methods only serve to delay the date of depletion. In many instances, new technologies may actually promote an increase in total irrigated land surface, as greater efficiency means the same amount of water can be used across a greater land area (Upendram and Peterson 2007; Pfeiffer and Lin 2014; Cruse et al. 2016; Grafton et al. 2018), whereby the net savings on total water use may be negligible.

Nonagricultural Water Usage

As communities in the Ogallala region continue to grow, demands for reliable and clean drinking water will become increasingly important. Currently, approximately 1,112 million L of groundwater are used each day for public and self-supplied do-

Table 1
Ten largest urban areas within the Ogallala Aquifer Region, United States (US Census Bureau 2022). Reliance on Ogallala water was derived from each city's water department's website or annual water quality reports, where available (see supplement).

City	State	Population	Ogallala reliance (%)
Lubbock	Texas	257 141	65
Amarillo	Texas	200 393	45
Midland	Texas	132 524	33
Odessa	Texas	114 428	NR
Cheyenne	Wyoming	65 132	30
Grand Island	Nebraska	53 131	100
Hutchinson	Kansas	40 006	100
Clovis	New Mexico	38 567	100
Hobbs	New Mexico	40 508	100
Kearney	Nebraska	33 790	100

NR, not reported, indicates an annual municipal water quality report that mentioned groundwater but did not include a percentage of groundwater use.

mestic purposes (Lovelace et al. 2020). In fact, 82% of all people living within the Ogallala boundary are reliant on groundwater for their primary drinking source (Dennehy et al. 2002). There are 33 cities with populations $>$ 10 000 overlying the Ogallala (ESRI 2021) that receive all or part of their public water supply from groundwater (Table 1), including large metropolitan areas in the southern High Plains such as Lubbock, Amarillo, Midland, and Odessa in Texas, where risk of depletion is the greatest (see Fig. 2C). This adds further stress on the aquifer and may require cities to explore additional sources of water, such as surface water development, or piping water from outside of the region. Though much of the aquifer in the southern High Plains is expected to be unavailable to high-volume pumping by 2100 (see Fig. 2C) (Haacker et al. 2016), there may, in some cases, still be enough saturated thickness for low-flow, rural domestic wells for some time thereafter (Rawling and Rinehart 2018; Suter et al. 2019).

Another widespread use of groundwater in the region is for the extraction of minerals, oil and natural gas, all defined together as “mining” by the US Geological Survey (Lovelace et al. 2020). Total average yearly extraction of groundwater in the Ogallala region for mining purposes is approximately 1.93×10^8 L d^{-1} (Lovelace et al. 2020). Once water has been used in the extraction of oil and gas, it is no longer suitable for human consumption and is often stored in geologic formations below the Ogallala (Opie et al. 2018). From 2004 to 2015, unconventional oil and gas development (e.g., hydraulic fracturing) experienced a period of rapid growth, affecting $>$ 200 000 ha of land nationwide (Moran et al. 2017). An additional 2.0×10^7 ha are expected to be impacted directly by 2040 (Trainor et al. 2016). Potential areas at risk of new oil and gas expansion include the southern and central High Plains in Texas and Oklahoma and the northern High Plains centered around the Colorado, Nebraska, Wyoming boundary (Trainor et al. 2016). Though important for the functioning of the global economy, oil and gas production may have lasting effects on the landscape through the fragmentation of rangeland and cropland areas, reduction in net primary productivity, altering of wildlife habitat and behavior, and providing vectors for non-native plant introduction (Allred et al. 2015).

Ecosystem Services

As we near the point of exhaustion of the Ogallala on the central and southern High Plains, drastic changes in land use and land cover must take place. It has been long assumed that much of the irrigated lands in the Ogallala will revert to dryland farming (Wheeler et al. 2008; Amosson et al. 2009; Dobrowolski and Engle 2016; Cotterman et al. 2018); however, many of the soils in this region are marginal at best and will not be suitable for agronomic production *sans* irrigation (Deines et al. 2020), especially in light of potential climate change impacts on precipitation and temperature patterns in the coming decades (Field et al. 2012; Ojima et al. 2021). For instance, climate velocity is a metric used to quantify the rate (km yr^{-1}) that a climatic isoline (e.g., temperature, evapotranspiration, water deficit) is moving (Loarie et al. 2009). A recent analysis examining climate velocity trends in the contiguous United States during the period from 1916 to 2005 indicates that the US Great Plains has been under a drying trend with a climate velocity of nearly 10 km per decade (Dobrowski et al. 2013). More recently, it has been shown that a megadrought spanning from 2000 to 2021 in North America was the driest period in this region since at least the yr 800 (Williams et al. 2022). US Department of Agriculture (USDA) cold hardiness zones, a benchmark often used for agricultural and horticultural plantings, are expected to shift substantially north at a rate of 21.4 km $decade^{-1}$ by 2070 (Parker and Abatzoglou 2016), creating potential climatic issues for crops and cool-season C3 grasses. By 2050, worldwide total agricultural production would need to double to meet global demand (Ray et al. 2013; Valin et al. 2014; FAO 2017). In the long term, the Ogallala region will not be able to sustain the level of crop production that it has in the past. In order to meet national and global food demands, advancements in dryland farm production methods and genetics will be key, together with increased importance on the production of food and fiber on lands that are no longer suitable for other intensive agricultural endeavors. Rangelands provide many critical ecosystem services (Daily 1997; MA 2005; Havstad et al. 2007; Allred et al. 2015; Angerer et al. 2016; Zhao et al. 2020), at both local and global scales, that will be crucial to meet future food and fiber demands and to prevent further degradation of soil and surface water resources.

Ecosystem services (Table 2) are a framework for describing and analyzing the social and ecological goods and services from socioecological systems that are categorized as either provisioning, regulating, cultural, or supporting in nature (MA 2005; Mocior and Kruse 2016; Sala et al. 2017). Rangelands, with their widespread spatiotemporal and ecological diversity, provide a robust portfolio of societal benefits, the breadth of which is much greater than on many other natural and anthropogenic systems (Yahdjian et al. 2015).

The most notable and quantifiable ecosystem service provided by rangelands is the production of food, fiber, and milk from grazing animals (Havstad et al. 2007; Brown and MacLeod 2011; Sala et al. 2017). Livestock are best suited to convert herbaceous vegetation that would otherwise have limited economical value into protein, fiber, milk, and numerous other commercial by-products on lands that are often not suitable for farmland production (Phillips and Coleman 1995; Schiere et al. 2002; Lemaire et al. 2005). However, in the United States, only 10% of total livestock feedstuff comes from rangelands (Havstad et al. 2007), contrasted to 70% globally (Brown and Thorpe 2008); the rest is primarily from grain-based feeds (Klopfenstein et al. 2013) that are fed as a supplement to grazing animals or as a finishing ration before slaughter. Inexpensive fuel costs and the desire to maximize production per unit area have led the dairy and beef industries to rely less on pastures and more on cheaper, high-energy grains, thus diminishing the evolutionary advantage that ruminants have to convert forage biomass into human available protein (Clark and Poincelot 1996; Schiere et al. 2002). At present, purely grass-fed beef accounts for only 4% of the US beef market (Cheung and McMahon 2017), though rising fossil fuel and feed expenses may lead to an increased reliance on grasslands to meet future livestock nutrition needs (Havstad et al. 2007; Brown and MacLeod 2011). As lands in the Ogallala region transition away from irrigated agriculture, the remaining irrigated lands' production demands may become greater to meet feed grain requirements, potentially resulting

Table 2
Ecosystem service classes and examples.

Ecosystem service	Description	Example
Provisioning	Food, fiber, medicine	Meat; wool; pharmaceuticals
Regulating	Natural processes	Carbon sequestration; water purification; flood control
Cultural	Educational, enlightenment	Aesthetics; spiritual attainment; cognitive development; recreation
Supporting	Ecosystem functioning	Soil formation; primary production; habitat; biodiversity

in increased groundwater use in already stressed areas. Increasing the percentage of grass-fed beef or transitioning cattle from forage to grain finishing at a later age may be necessary to lessen the demands for an already stressed aquifer. Moreover, adjusting intensive agricultural areas from feed grain and ethanol production to crops for human consumption can increase the worldwide food supplies considerably (West et al. 2014; Teague et al. 2016). Furthermore, conversion of marginal croplands back to grasslands can then fill a need for additional forage to maintain or expand meat, fiber, and milk production.

Regulating and provisioning ecosystem services on rangelands and pastures include promoting soil and rangeland health (Lal et al. 1991; Pellant et al. 2005; Derner et al. 2018; Lal 2020), sequestering carbon (Follett et al. 2000), providing clean surface water (Rauzi and Hanson 1966; McDowell et al. 2008), absorbing pollutants (Lemaire et al. 2005), providing habitat for wildlife and pollinators (Niemuth et al. 2021), and serving as a genetic repository for offsite restoration practices (Brown and MacLeod 2018). Properly managed perennial grasslands may help to filter runoff of nutrients, sediments, and pathogens (Larsen et al. 1994; Agouridis et al. 2005), which currently make up 58% of all Clean Water Act Section 303(d) surface water quality impairments in the central and southern High Plains (USEPA 2014). Nutrients and bacteria are common contaminants of concern that come from livestock waste (Muirhead et al. 2005; Muirhead et al. 2006; McDowell et al. 2008). Cattle retain approximately 25% of nitrogen consumed in forage, excreting the rest (Whitehead 2000; Singh et al. 2020). Rangelands that make effective use of best management practices that trap and filter runoff can keep nutrients and pathogens on site (Larsen et al. 1994; Agouridis et al. 2005; Wagner et al. 2012), capture and store more water (Rauzi and Hanson 1966; Wood and Blackburn 1981; Bossio et al. 2010), aid in developing rangeland and soil health (Sherwood and Uphoff 2000; Pellant et al. 2005; Derner et al. 2018; Harmel et al. 2021), and reduce methane (CH_4) emissions through aerobic breakdown of waste (Singh et al. 2020).

Native rangeland vegetation diversity provides important ecosystem services for wildlife habitat and biodiversity. Wildlife provide many ecosystem services, such as ecotourism (O'Farrell et al. 2011; Bagstad and Wiederholt 2013), food (Golden et al. 2014), sanitation (Morales-Reyes et al. 2015), and supporting healthy food webs (Xiao et al. 2018). Non-native invasive herbaceous species, native and non-native woody species, and land fragmentation have caused an extensive loss and degradation of habitat for wild ungulates and grassland birds (Coppedge et al. 2001a, 2001b; Samson et al. 2004; Brennan and Kuvlesky Jr 2005; Ellis-Felege et al. 2013; Jackson et al. 2020). Many species of songbirds select native prairie grasses over their non-native counterparts (Ellis-Felege et al. 2013). Unwanted non-native infestations may result in lower forage quality, forcing wild ungulates to seek out and overuse remaining native vegetated areas (Trammell and Butler 1995).

Regenerative Approaches to Restoration and Management

Regenerative, or sustainable, agricultural methods related to promoting soil health have been gaining in popularity in recent years (Derner et al. 2018). Rangeland soils harbor approximately 10–30% of total global soil carbon storage (Scurlock and Hall 1998; White et al. 2000; Conant 2010; Ghosh and Mahanta 2014), providing a stable repository that is much more resilient to natural disturbance than carbon stored aboveground in forested areas (Dass et al. 2018). In contrast, most cropland soils lose about 0.06% of their soil organic carbon annually (Lal and Bruce 1999; Dalal and Carter 2019). In the United States, many former prairie soils have lost 30–50% of their historical carbon pool, which represents a substantial sink that can be filled through conversion to grasslands or through other regenerative conservation and management practices (Lal 2002, 2004a). Permanent soil cover from perennial forages can transfer carbon much deeper in the soil due to their extensive root systems, thereby increasing the soil's total potential storage capacity (Gentile et al. 2005; Bell et al. 2012). Converting abandoned farmland to perennial vegetation such as pastures and native rangeland can increase soil carbon storage by as much as 90–253%, respectively (Römkens et al. 1999; Yang et al. 2019). Restoring soil organic carbon can rebuild soil aggregation and resilience, increase soil biodiversity, and improve infiltration, water holding capacity, and ion exchange (Beven and Germann 1982; Thurow 1985; Thurow et al. 1986; Lal 1997b, a; Lal and Bruce 1999; Whisenant 1999), which all correlate into overall rangeland health. Conversely, loss of soil carbon leads to loss of aggregation, which leads to compaction, crusting, increased runoff, and erosion of soils (Valentin and Bresson 1997; Lal and Bruce 1999; Whisenant 1999). This further emphasizes the need to assuage the effects of future abandonment of exhausted croplands.

Cover crops have played an important role in cropland soil conservation and regenerative agriculture for many years now. They have shown to be able to increase soil organic matter, aggregation, and fertility; create resiliency against undesirable species; and promote pollinator establishment (Lal 2004b; Tonitto et al. 2006; Blanco-Canqui et al. 2013; Poeplau and Don 2015; Kelly et al. 2021); however, cover crops often compete with cash crops for soil moisture in water-stressed environments (Nielsen et al. 2015; Nielsen et al. 2016; Kelly et al. 2021). Of note, though, is that most studies involving the effects of cover crops on cash crop production typically only last 2–3 yr (Tonitto et al. 2006), implying that long-term soil health benefits such as aggregation, microporosity, and soil organic matter accumulation are not yet fully understood.

In a traditional cover cropping system, all crop residue is left on the soil surface (Lal et al. 1991), but in integrated livestock-cropping systems, cattle are used to partially harvest cover crops to provide an additional revenue stream, promote soil health (Franzluebbers and Stuedemann 2008; Smart et al. 2020; Kelly et al. 2021), and improve water quality (Faust et al. 2018; Smart et al. 2020). Integrating perennial crops for livestock use can have profound positive ecological and economic benefits, creating an agricultural system that is more resilient to the effects of climate extremes, with minimal effects to cash crop production (Peterson et al. 2020). Integrating cattle into a legume-grain cropping strategy greatly increased the ability of the soil to sequester carbon through manure additions (Drinkwater et al. 1998). In the southern High Plains region of Texas, integration of cattle into a cotton-rye-wheat system increased microbial C and N and protozoa populations compared with a traditional cotton monoculture (Acosta-Martinez et al. 2004), as well as reduced total water, fertilizer, and chemical inputs (Allen et al. 2005). Incorporating livestock grazing into cropping systems adds an extra layer into grazing management on rangeland and pasture areas, effectively reintroducing mobility into local grazing systems, where livestock are rotated off site seasonally to graze cover crops (Liao et al. 2020). Until recently, federally subsidized crop insurance programs did not allow cover crops to be harvested before November 1 without a financial penalty, presenting an economic disincentive to adoption. However, beginning in the summer of 2021, the USDA Risk Management Agency had acknowledged the added benefits of using cover crops as an animal feed by allowing producers to graze, hay, or chop cover crops without penalty (USDA RMA 2021).

Discussion and Future Directions

Ecosystem services from cropland, pastureland, and rangelands are going to increase in demand as the global world population reaches 11 billion in the yr 2100 (FAO 2017). A global shift in land use is already under way to accommodate ever-increasing food supply demands, further reducing potential grassland areas (de Fraiture et al. 2007; Bossio et al. 2010; Angerer et al. 2016; FAO 2017) and further reducing critical wildlife habitat (Fuhlendorf et al. 2002; Lark et al. 2020). In the central and southern Ogallala region, there is a potential for reversal of land use from cropland to grasslands. As groundwater resources are depleted, the regional cooling effects of irrigation (Cook et al. 2015b) will be dampened, thereby exacerbating expected warming trends in the Central Plains (Polley et al. 2013; Cook et al. 2015a; Ojima et al. 2021). Failure to maintain soil cover may lead to a return of the "Great American Desert."

Much of the land in the Ogallala region was plowed a century or more ago. In light of past use and the uncertainty of future climatic shifts in this region, as well as the proliferation of non-native invasive species, expectations of returning abandoned croplands to a historical condition must be tempered somewhat (Hobbs et al. 2011; Perryman et al. 2021). Focus must be made on processes or sustainability (Tabeni et al. 2016; Xie et al. 2020) rather than obtaining an idealized climax state or community, which likely does not exist under nonequilibrium theory. Abandoned farmland that is managed passively (natural revegetation) may in time return to seminative plant communities, but critical functions such as soil stability and infiltration rates may remain hindered (Tabeni et al. 2016). Research has shown the ecological benefits of Conservation Reserve Program (CRP) lands (Ribaudo 1989; Dunn et al. 1993; Johnson and Schwartz 1993; Munson et al. 2012; Li et al. 2017; Tanner and Fuhlendorf 2018; Yin et al. 2021), which often include introduced species in their reseeding mixtures (Coppedge et al. 2001c), resulting in novel landscapes where vegetation species composition is altered from a native state (Hobbs et al. 2011; Belnap et al. 2012; Tanner and Fuhlendorf 2018), yet ecosystem functions and/or services may be comparative to native communities. This underscores the philosophy that "good enough" may suffice under niche situations given that soils, climate, socioeconomic, and local biogeochemical processes have long been separated from their presettlement state (Perryman et al. 2021). Native communities should be favored where possible, while realizing in some cases it may be best to work with these novel communities. Research addressing which novel systems are supportive to soil health and ecosystem functioning is needed, as well as the potential for assisted succession (Cox and Anderson 2004) via interseeding (Lesica and Cooper 2019) where soils and climate are favorable. In many cases, lands with CRP and rangeland cover have an equal or greater market value in the High Plains region than unirrigated farmland, providing further incentive to rehabilitate abandoned dryland areas (ASFMRA 2021).

One issue with voluntary cost-share measures such as the CRP program is that they can incentivize restorative measures for strictly economic, rather than altruistic, reasons (Laycock 1988; Gerard 1995; Derner et al. 2018). Fluctuations in global grain prices often force the pendulum to swing back, and many landowners will revert these reclaimed parcels back to farmland practices (Hellerstein and Malcolm 2011; Herrick et al. 2012; Smart et al. 2020). In fact, economic choices are generally the primary driver of anthropogenic land use alteration (Lambin et al. 2001) and are, in the most basic way, the root cause of the current state of the Ogallala region. Since 2007, 25% of CRP lands have reverted back to cropland (Morefield et al. 2016), representing a substantial setback to soil carbon storage in the Great Plains, as well as a loss of habitat for pollinators (Otto et al. 2018). Management incentives, such as those commonly incorporated into the quinquennial Farm Bill, or through other means such as Candidate Conservation Agreements and conservation easements, must focus on merging the principles of rangeland and soil health to find unique ways for the Ogallala region to continue to provide a variety of economically viable ecosystem services on a local, national, and global scale (Lal 2020).

In portions of the Ogallala region where soils and climate may support continued agricultural use without irrigation, combining ecosystem services, such as with integrated crop-livestock systems, could help to provide diverse land uses and economic benefits to rural communities that depend on agricultural support services while providing added benefits of soil, water, wildlife, and aesthetic services as well. Land use decisions should follow sustainable development principles that allow for the capability for continued production of goods and services to forthcoming generations (WCED 1987; Pearson and Gorman 2010; Pearson 2013). While individual management practices may have economic values associated with the costs of implementation, the rangeland restoration literature is deficient of the socioeconomic data necessary to envisage the immense rural economic transition that is looming when vast spreads of row-crop farmland will have to be retired or retooled (Wortley et al. 2013; Brown and MacLeod 2018). How will this transition affect local, regional, and global economies and markets? How will the adjusted markets affect managers' decision-making processes? A meta-analysis of the literature assigning socioeconomic benefits and detriments to regional-scale shifts in land use and implementation would be indispensable to the planning horizon of the whole Ogallala region.

To prepare for potential shifts in land use, research focus should be placed on developing state-and-transition and social-ecological models that incorporate spatial and temporal heterogeneity and patterns to derive solutions that are focused on delineating and understanding the current and potential future placement of natural and novel landscapes and their effects on landscape processes and ecosystem services (Turner 1989; Li and Mander 2009; Young et al. 2014; Wilcox et al. 2018). Restoring historical ecological processes such as pyric herbivory is beneficial to livestock production (Fuhlendorf et al. 2009; Limb et al. 2011), wildlife (Fuhlendorf et al. 2010; Doxon et al. 2011; Davis et al. 2016), and hydrological processes throughout much of the Ogallala (West et al. 2016).

Landscape ecology will provide a framework toward understanding anthropogenic effects on patterns and processes at multiple spatial scales for rangelands and wildlife habitat management (Li and Mander 2009; Fuhlendorf and Brown 2016; Tanner and Fuhlendorf 2018; Perotto-Baldivieso 2021). Landscape ecology principles can further aid in understanding drifting vegetation zones and biodiversity (Morin et al. 2008; Chevin et al. 2010) due to a changing climate (Thuiller et al. 2005; Boone et al. 2018) and support the development and placement of management practices on lands that can sustain multiple simultaneous ecosystem services. Use of remote-sensing models and decision-support tools may assist landowners to make proper land use planning, management, and stocking decisions (Jones et al. 2020; Wardropper et al. 2021; Rhodes et al. 2022). Modeling future land use and land ownership demographics, along with local socioeconomic values, may provide key information in the long-term planning of land management practices and paradigms (Turner et al. 1996; Wear et al. 1996; Turner 2005; Fitzhardinge 2012).

Native prairie remnants, as well as reclaimed pasture, CRP lands, and other novel landscape features do not exist in isolation but rather within a matrix of multiple land uses that includes many anthropogenically altered states that may exert influence on their ability to reach their full potential to provide ecosystem services (Saunders et al. 1991; Wiens 2009). In particular, the reinsertion of perennial, more naturally functioning systems into the current mosaic dominated by annual farmland will affect the connectivity, dispersal, edge, and habitat suitability for desirable plants, livestock, and wildlife (including arthropods) at multiple spatial scales (Johnson et al. 1992; Pascual-Hortal and Saura 2006, 2007). Habitat connectivity (Taylor et al. 1993) for Great Plains species should continue to be a major focus of research, particularly under dynamic land use scenarios under future socioecological conditions.

Of particular importance to the region are the playa wetlands (numbering nearly 72 000) within the southern and central High Plains (Playa Lakes Joint Venture 2019). These naturally occurring features of the High Plains are ephemeral wetlands that have been shown to be a possible source of natural localized recharge within the Ogallala region (Bolen et al. 1989; Gurdak and Roe 2010; Gitz and Brauer 2016). Reminiscent of the prairie potholes found in the northern United States and elsewhere, playas are thought to have been formed by dissolution of the restrictive calcium carbonate (caliche) layer found throughout the southern and central high plains, leading to depressions that collected fine clay particles that periodically capture rainfall runoff (Gurdak and Roe 2010). Hydrologically, each playa is within a closed-system watershed, where the playa rests within the lowest point (Bolen et al. 1989). As such, playas are high in biodiversity within this semiarid “Great American Desert,” with avifauna being the most predominately associated taxa (Haukos and Smith 1994). While playas may most commonly be associated with hosting migratory waterfowl and the endangered whooping crane (*Grus Americana* L.), a number of upland and ground-nesting species also frequent playa areas for food and nesting habitat (Haukos and Smith 1994). Due to the general lack of other naturally occurring sources of surface waters in the southern High Plains, playas provide critical habitat for amphibians, reptiles, snails, and numerous macroinvertebrate species within this ecoregion (Sublette and Sublette 1967; Haukos and Smith 1993, 1994). Restoring and incorporating playa ecology into future management practices is crucial to the biodiversity and the potential to recoup any kind of groundwater recharge in the Ogallala region.

Understanding the interrelationships between grasslands and traditional croplands, versus those with sustainable agricultural practices and integrated crop-livestock systems, may help us to strengthen the ecosystem services provided by expanding the effective area of the overall landscape mosaic (Wiens 2009) and will be increasingly important to the management of the Ogallala region. The exacerbating effects of abandoned energy infrastructure on the fragmentation and potential for restoration of both natural and agroeconomic systems must be coaddressed in the implementation of restoration measures (Allred et al. 2015; Moran et al. 2017). Acknowledging that the benefits of many rangeland restoration practices may not manifest immediately (Brown and MacLeod 2018), long-term research, such as that from Long Term Ecological Research and Long Term Agroecosystem Research programs, must be properly leveraged to aid in the understanding and illustration of the benefits of restoring these ecosystem services.

Absent from most of the discussion thus far is the northern Ogallala region, centered mostly in Nebraska (see Fig. 1), which has an estimated groundwater depletion date of sometime within the next 600 yr (Scanlon et al. 2012; Haacker et al. 2016). Most climate change scenarios indicate that the northern Great Plains may have a longer and more favorable growing season in the future (Lant et al. 2016), meaning that this region may become an increasingly important component of the US grain and plant fiber economy. However, much of this region is part of the Nebraska Sandhills ecoregion and therefore is not arable. But as demands for potable water in the Great Plains become ever more prevalent, the incentive to exploit this resource for other uses may emerge. Given that this region encompasses the most intact temperate/tropical grassland in the world (Scholtz and Twidwell 2022), understanding how future socioecological scenarios will impact ecosystem resiliency and connectivity will be critical for its conservation.

Research and extension programs must come together to focus on the social-environmental nexus of management benefits to the land and society in order to garner public support, as well as buy-in from skeptical stakeholders and landowners (Derner et al. 2018) in this region where the landscape is predominately privately owned (Goodwin and Moseley 2012). Unfamiliarity with different production systems and/or a lack of infrastructure (e.g., fencing, corrals, stock water) may cause hesitation from landowners that could impede the transition of croplands back to grasslands or into integrated crop-livestock systems (Krall and Schuman 1996; Prokopy et al. 2015; Kumar et al. 2019). This is an area where state extension programs can excel in providing training and educational resources to help manage this process. Research focusing on the sustainability of human-environment systems is lacking in the developed world (Xie et al. 2020), and the Ogallala region would be an ideal proving ground for the sustainability of the combination of natural, agroeconomic, integrated crop-livestock systems, pasturelands, and rangelands. Such a widespread alteration in the production system of the High Plains would also cause a shift in the balance of local support industries from predominately intensive agriculture-based (fertilizer, herbicide, seed, grain elevators) to ranching-based enterprises (trailers, fencing, feed, veterinary, livestock auctions, and processing facilities). Finally, undergraduate range, wildlife, animal science, and agronomy curricula should provide multidisciplinary overlap to familiarize future managers with diverse regenerative agricultural systems and foster creative out-of-the-box thinking to management problems (Derner et al. 2018; Spratt et al. 2021).

Conclusion

The art and science of rangeland management is uniquely poised to provide the knowledge and skills necessary to adapt the Ogallala Aquifer Region to changing land use objectives, protect the soil bank, and provide a diverse portfolio of ecosystem services while promoting historical ecological processes. While available grassland areas are decreasing globally, there is potential in the Ogallala Aquifer region of the US Great Plains to reclaim, restore, and diversify ecosystem services of marginal cropland areas that are likely to be abandoned in the next 80−100 yr. The forthcoming depletion of the Ogallala will have ramifications at the local, state, and global level as the food supply chain in the “world’s breadbasket” is forced into a new management paradigm. Future research must focus on transforming abandoned lands to useful commodities that protect soils, while delivering critical ecosystem services to a transitioning agricultural, ecological, climatic, and social state. Looking at the big picture, rangeland science has the principal foundations to address these challenges; what is needed is interdisciplinary application of regional, and site-specific practices, realizing that there will not be a “one-size-fits-all” solution to rehabilitate abandoned lands. Managers must be able to triage sites on the basis of the potential for successful establishment of perennial vegetation cover, perhaps by leveraging the current irrigation infrastructure to establish perennial vegetation while sufficient water is remaining to do so. In many cases, traditional rangeland restoration and management practices may be the most straightforward solution, while in others, more creative adaptations using innovative approaches may be warranted. Using landscape level analyses of groundwater availability, soil, climatic, landscape pattern, and structural assessments, critical areas can be highlighted for prioritization of incentive programs to areas with the greatest chance for resiliency against environmental and economic drivers.

As rangeland ecologists, our primary goal must be to leave the land in better condition than what was passed down to us. Whether it be for croplands, rangelands, pastures, or a combination thereof, maintaining and protecting the health of the soil profile is paramount, lest we repeat the mistakes of the Dust Bowl. Integrating a shared vision that combines multiple disciplines, demographics, landscapes, and ecosystem services will be key to the future success of the Ogallala Aquifer region. Sustainable conservation will require locally based knowledge that incorporates social, cultural, ecological, and economic characteristics across multiple spatial and temporal scales. Finally, interdisciplinary social-ecological frameworks may aid in understanding where human and natural systems are coupled, the potential legacy effects of past management, and societal needs for ecosystem services. Little time remains in the usability of the central and southern High Plains portions of the Ogallala Aquifer region, and we must be prepared to address the challenges ahead, while providing food, fiber, and other beneficial ecosystem services locally and globally.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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