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Johnsongrass (*Sorghum halepense*): a review of its invasion, management, and spread in the changing climate of the Southern Great Plains

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Review

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Abstract

Johnsongrass [*Sorghum halepense* (L.) Pers.], an invasive tallgrass, actively inhabits grassland ecosystems of North America. The grasslands ecoregions of the Southern Great Plains are particularly susceptible to *S. halepense* invasion and dominance because of its preferential growth in continental climate zones coupled with its ability to readily colonize recent disturbances associated with declining livestock grazing and anthropogenic energy and housing development. Controlling *S. halepense* via chemical or mechanical inputs can reduce this plant species' abundance temporarily, but are typically followed by *S. halepense* reestablishment. *Sorghum halepense* does, however, provide high-quality forage and appears to withstand the frequent drought and flooding events associated with climate change in Southern Great Plains ecosystems. In this review, the benefits and drawbacks of *S. halepense* in Southern Great Plains grassland ecosystems are discussed and areas where research on this species could be expanded are identified.

Introduction

Johnsongrass [*Sorghum halepense* (L.) Pers.], a tussock grass from northern Africa and central Asia, actively inhabits grassland ecosystems of North America (Klein and Smith 2021; Paterson et al. 2020; Figure 1). Feltus et al. (2004) suggested that *S. halepense* is a naturally occurring hybrid between two sorghum species: *Sorghum bicolor* (L.) Moench, an annual, polytypic African species, which includes cultivated sorghum, and *Sorghum propinquum* (Kunth) Hitchc., a perennial southeast Asian native of moist habitats (Celarier 1958; Doggett 1976; Paterson et al. 1995). Currently, *S. halepense* can be found throughout much of Asia, Africa, Europe, North and South America, and Australia (McWhorter 1971). In the United States, *S. halepense* was initially planted as a forage hay crop (Bennett 1973). As on other continents, however, *S. halepense* escaped cultivation and spread throughout every U.S. state except for Alaska, Maine, and Minnesota; as far north as Canada; and as far south as Argentina (Hickman et al. 2018; USDA-NRCS 2023; Warwick et al. 1986). Clements and DiTommaso (2012) suggested that the ability of *S. halepense* to advance longitudinally and establish in regions that were once considered uninhabitable for this species is derived from wide climatic and environmental tolerance, a relatively short generation time, effective forms of reproduction and dispersal, and competitive ability that allows for colonization in numerous environments (Holm et al. 1977; Warwick and Black 1983). Consequently, *S. halepense* has, for more than a century, been a common weed in cultivated agricultural systems (Heard 1917; Monaghan 1979; Schwinning et al. 2017; Squires and Walsh 2021; Vinall 1921).

The dominance of *S. halepense* in intact grasslands is a relatively recent occurrence largely due to changes in land management associated with declining livestock grazing, increased energy development (renewable and fossil fuel), and anthropogenic housing development (Klein and Smith 2021; Paterson et al. 2020; Rocateli and Manuchehri 2017). The Southern Great Plains are particularly susceptible to *S. halepense* because of a preferential climate coupled with rapid land use disturbances (Lakoba et al. 2021; Omernik and Griffith 2014). Barney and DiTomaso (2011) found that *S. halepense* growth has a 50% to 90% climatic match between all 20 designated ecoregions of the continental United States and was greatest in the plains and prairies. The Great Plains, notably the Southern Great Plains, are also increasingly fragmented due to commercial land development for housing or energy development from windmills, solar farms, or oil and gas production (de Castro and Zenteno 2023; Engle et al. 2008; Scholtz et al. 2018). Land fragmentation creates vulnerability to weed invasions by increasing the number of successful sites for weed seedling establishment (Aicher et al. 2011; Duncan et al. 2009) and supporting seed transport along these recent disturbances, like along roadways (Grman et al. 2015; McConkey et al. 2012); once these species are in the seedbank, established seedlings of invasive species commonly outcompete native species by growing earlier and at higher densities than native plant species (Reid and Holl 2013; Yelenik and D'Antonio 2013). In addition,

Figure 1. Johnsongrass [*Sorghum halepense* (L.) Pers.] diagram and associated distribution map. Illustration by Chris J. P. Grisham and map from USDA-NRCS PLANTS database(USDANRCS2023).

livestock grazing has been decreasing in the Southern Great Plains, as moving livestock among smaller and fragmented paddocks is difficult for producers, while neighboring subdivisions can prove to be problematic neighbors for livestock operations (Brunson et al. 2016; BurnSilver and Mwangi 2007). Some might argue that *S. halepense* would be a preferential weed to eliminate from these systems, as it can outcompete many physiologically similar native tall grasses (Schwinning et al. 2017); others see benefits in *S. halepense*, especially for grazing livestock, as this species can provide high-quality forage throughout the grazing season (Rocateli and Manuchehri 2017; Watson et al. 1980). The objective of this review is, therefore, to provide a background of *S. halepense* invasion and discuss the benefits and drawbacks of this grassland invader in the Southern Great Plains.

Sorghum halepense *Growth and Plant Community Characteristics*

Sorghum halepense spreads through the rapid development of rhizomes and prolific seed production (McWhorter 1961; Ryder et al. 2018; Tóth and Lehoczky 2006). It has been shown to produce approximately 100 m of rhizomes per plant each year that are able to withstand subzero winter temperatures with a survival rate of up to 71% (Anderson et al. 1960; Johnson et al. 2003). These rhizome networks can also account for up to 70% of the entire plant dry weight (Paterson et al. 2020). As a self-pollinating plant, *S. halepense* produces up to 80,000 seeds per plant in a single season that can remain viable for up to 10 yr in the soil (Dweikat 2005; McWhorter 1961). *Sorghum halepense* also has a broad seed depth germination rate ranging from 64% at 1 cm-depth to 30% at 20-cm depth, and up to 6% of its seeds can germinate from depths as great as 25 cm (Tóth and Lehoczky 2006).

Once established, *S. halepense* creates a feedback cycle whereby it can outcompete many native perennial grass species by growing earlier and faster and having higher biomass than functionally similar native perennial grasses (Kelly et al. 2020; Schwinning et al. 2017). Reichmann et al. (2016), for example, reported that during early development, *S. halepense* plants gained up to 4-fold more biomass than the North American prairie grasses switchgrass (*Panicum virgatum* L.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], and big bluestem (*Andropogon gerardii* Vitman) within the first 17 d of growth, largely due to increased leaf area, higher atmospheric carbon uptake, and photosynthetic nitrogen-use efficiency. Schwinning et al. (2017) also found that when *S. halepense* was grown with these same warm-season (C_4) tallgrass species in a greenhouse experiment, native perennial grasses had 95% less biomass compared with when they were grown alone, while *S. halepense* only lost 11% of non-root biomass.

Response to Climate Disturbances

Extreme climate disturbances, like drought and freezing conditions, are increasing in frequency across the Southern Great Plains (Ojima et al. 2020). Current climate change projections suggest that these climatic extremes will likely become a regular occurrence in the future (Knapp et al. 2020; Lakoba et al. 2021). Clements et al. (2022) further suggest that *S. halepense* will likely expand longitudinally (north and south) due to higher global temperatures at northern and southern latitudes.

Long-term and large-scale research sites are likely the best place to evaluate historical climate effects, as other site-specific data, like plant production and management strategy, typically have an associated recorded history. For this effort, the previous 32 yr of precipitation data at six long-term rangeland research sites in the Southern Great Plains were acquired to gain a better understanding of the dynamic precipitation in these areas. Historical climate data, including precipitation and temperature, were acquired from the gridMET database (https://webapps.jornada.nmsu.edu/weather; Abatzoglou 2013) for the years 1990 to 2022. The six long-term research sites included USDA-Agricultural Research Service sites in Woodward, OK (36.3745°N, 99.2455°W), El Reno, OK (35.5335°N, 97.9549°W), Riesel, TX (31.4755°N, 96.9247°W), and Temple, TX (31.0982°N, 97.3428°W), and research sites associated with Oklahoma State University in Pawhuska, OK (36.6634°N, 96.3410°W) and Texas A&M University in LaCopeda, TX (27.66661°N, 98.20892°W). An ANOVA on the differences in average daily precipitation (mm) at these six sites across the years of 1990 to 2005 and again from 2005 to 2022 was then run using JMP (SAS Statistical Software © 2022, SAS Institute, Cary, NC). Results on precipitation trends from 1990 to 2005 indicate that only 2004 had significantly higher precipitation compared with all other years, and this was only at

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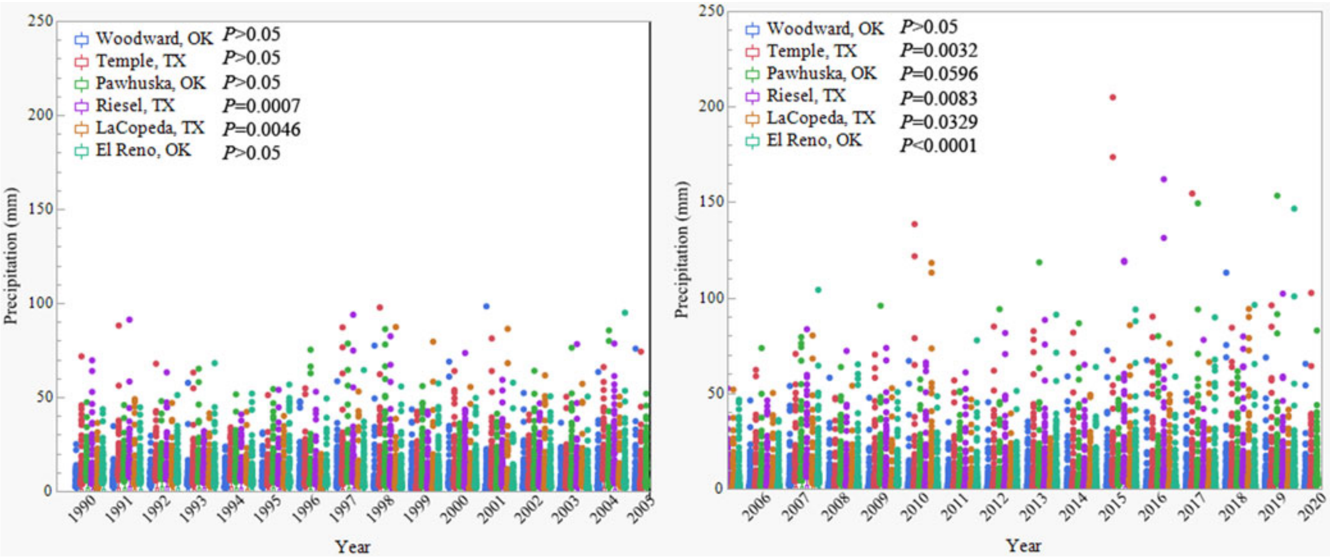

Figure 2. Historical average daily precipitation (mm) ± SE for the years of 1990–2020 across six long-term Southern Great Plains grassland research sites to demonstrate the variation in precipitation from 1990 to 2005 and from 2005 to 2020. Sites are all colocated at long-term plant production monitoring regions in the Southern Great Plains. P-values refer to one-way ANOVA models of year by average daily precipitation, where $P < 0.05$ refers to a significantly different relationship and $P > 0.05$ indicates no significant differences in precipitation across years.

the Riesel and Temple, TX, sites; all other sites and years were similar. Drought and flooding had become more frequent for the years 2005 to 2022, where four of the six sites had significantly different precipitation across years, and one site was moderately significant (Pawhuska, OK; $P = 0.0596$). Across all significant sites, from 2005 to 2022, 2011 was significantly lower and 2015 had significantly higher precipitation ($P < 0.05$; Figure 2). Collectively, these results indicate that precipitation is becoming more dynamic in recent years, and dynamic precipitation fluctuations will likely facilitate plant species that can withstand these perturbations, which often are plant species with rapid adaptation mechanisms.

Sorghum halepense appears to be well suited to adapt to these changing climate conditions. This is partially because *S. halepense* seeds quickly adapt to modified temperature and water environments (Fletcher et al. 2020). Its physiologically adaptive climate traits, as described earlier, especially in comparison to native species growing in these ecosystems, may result in *S. halepense* becoming a widespread species of concern (Schwinning et al. 2017). Currently, however, there are limited and/or hypothetical expectations on how species and plant communities within ecosystems respond to dynamic climatic cycles like these (Briske et al. 2015; Knapp et al. 2020; Polley et al. 2012, 2019).

Chemical Control of *Sorghum halepense*

Sorghum halepense is extremely resistant to herbicides (Heap 2012). This is because herbicide-sprayed *S. halepense* plants can cross within selfing populations, store genetic variation in seedbanks, and evolve phenotypic plasticity (Clements et al. 2004). In 2002, for example, a glyphosate-resistant biotype was discovered in Argentina that covered 10,000 ha (Binimelis et al. 2009). Moreover, given its historical link to *S. bicolor* species and strong ability to cross with *S. bicolor*, chemical control of *S. halepense* near *S. bicolor* crops is extremely difficult, as chemical applications could directly affect *S. bicolor* production and potentially create more herbicide-resistant strains of *S. halepense* (Tang and Liang 1988; Warwick and Black 1983). In Texas and Nebraska, for example, Morrell et al. (2005) reported that up to 32% of unique *S. bicolor* alleles were identified in *S. halepense* populations adjacent to long-term *S. bicolor* production sites. The evidence strongly suggests that engineered genes and herbicide resistance could potentially be transferred into *S. halepense* and widely disseminated (Morrell et al. 2005). Presently, susceptible *S. halepense* plants may be able to be controlled using acetolactate synthase–inhibiting herbicides like sulfosulfuron, nicosulfuron, primisulfuron, or imazapic; acetyl-CoA carboxylase–inhibiting herbicides like clethodim or sethoxydim; or 5-enolpyruvylshikimate-3-phosphate synthase inhibitors like glyphosate (McCollough and Shilling 2022). Appropriate use of these herbicides has been shown to result in an 88% to 97% efficacy rate (Johnson et al. 2003). Repeated herbicide use can, however, create herbicide resistance. Hernández et al. (2015), for example, ascertained that recurrent nicosulfuron application to seedling- and rhizome-emerged *S. halepense* has created resistant *S. halepense* biotypes with 33 to 46 times higher herbicide resistance than susceptible control plants. Similarly, *S. halepense* has also shown glyphosate resistance, likely in part because glyphosate has evolved as a preferred herbicide, with more than 8.6 billion kg sold since 1974, coupled with *S. halepense*'s adaptive phenology (Baylis 2000; Benbrook 2016; Fernández et al. 2013; Heap and Duke 2018; Vila-Aiub et al. 2007). Presently, there is an agenda to reduce synthetic herbicide applications, notably glyphosate, as many of these products have recently been identified as carcinogens (IARC 2017; Tarazona et al. 2017; Williams et al. 2016).

Biological Control of *Sorghum halepense*

Biological control can be an ecologically viable way to tackle weed invasions (McFadyen 1998; Zachariades et al. 2017). Classical biological control includes introducing host-specific, coevolved natural enemies (biological control agents) from a weed's native range to the introduced range to keep the invasive species under control (McFadyen 1998). Historically, however, few invasive grasses have been targeted for biological control (Pemberton and Lee 1996; Schwarzländer et al. 2018). This is likely because there are

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few coevolved enemies of grasses that are host specific (Gill and Blacklow 1984; Pemberton 2002). Witt and McConnachie (2004), for example, noted that in Australia, the biggest obstacle to the biological control of invasive dropseed species (*Sporobolus* spp.) is that there are 13 native *Sporobolus* spp., which will largely govern which agents can be selected for biocontrol. Given the high risk of non-target damage posed to economically valuable crops, like *S. bicolor*, and/or native biodiversity, it is unlikely that biological control will be a practical control mechanism for *S. halepense* in U.S. grasslands (Sutton et al. 2019; Wapshere 1990). Targeted grazing, alternatively, may be a viable control method, as *S. halepense* used as forage can provide multiple socioeconomic benefits to producers that, managers suggest, compensate for negative ecological effects.

Mechanical Control of *Sorghum halepense*

It has been suggested that *S. halepense* spread can be well controlled using mechanical inputs like hand weeding, mowing, or tilling (Arle and Everson 1955; Ceseki et al. 2017; Heard 1917; Johnson et al. 2003). Mechanical control is, however, only a temporary fix in most perennial grassland regions, as hand weeding and tillage are impractical in large-scale perennial grasslands, and frequent mowing can deplete carbohydrate reserves of all species, even favoring the invaders (McCollough and Shilling 2022; Simberloff et al. 2012). Entsminger et al. (2017), for example, suggested that frequent mowing (four times per year) produced lower native species abundance along native seeded roadways compared with mowing only once per year or onetime mowing events accompanied by additional seedings of desirable species. Consequently, while mechanical control may not be an effective means to eliminate *S. halepense*, using mechanical control to reduce weed abundance before seeding desirable species that can fill the niches once occupied by weed species may be an effective ecologically based management strategy.

Sorghum halepense *in Rangelands and Pasturelands*

Land managers hold conflicting views of *S. halepense* on native rangelands and introduced pasturelands (Bennett et al., 1973; Hawkins et al. 1958; Rankins and Darrell 1995; Rocateli and Manuchehri 2017). *S. halepense* provides quality forage with approximately 10% to 14% crude protein and 55% to 60% total digestible nutrients and is preferred by large-mouth herbivores, like horses and cattle, across grassland ecosystems (Bennett et al., 1973; Watson et al. 1980). Cattle show a strong grazing preference for *S. halepense* and have been known to kill *S. halepense* plants by overgrazing this species (Andrae 2009; Sherrill 1947). However, *S. halepense* can contain high amounts of nitrate and prussic acid, also known as hydrocyanic acid, during early life-history stages and following distinct climactic events, like first frost or first rain after prolonged drought (Harris and Shearer 2003; Selk 1988; Slade 1903; Vinall 1921). Nitrate poisoning occurs when accumulated nitrates in the plant material (primarily plant stems) are converted to nitrite in the rumen (Selk 1988). Nitrite is absorbed from the rumen and converts blood hemoglobin to methemoglobin. Because methemoglobin cannot transport oxygen to body tissues, ruminant animals die from oxygen insufficiency (Selk 1988). Prussic acid, alternatively, interferes with oxygen use at the cellular level (Vinall 1921), and animals generally die from asphyxiation within a few minutes when a lethal dose of prussic acid is consumed (Harris and Shearer 2003; Selk 1988; Slade 1903; Vinall 1921). Recommendations from both researchers and land managers on the best way to manage high nitrate and prussic acid levels are to avoid grazing when the risk of these toxic compounds is high, such as in early spring, after freezing events, or for approximately 10 d following the first rain after prolonged drought (Harris and Shearer 2003). Timing *S. halepense* grazing in the Southern Great Plains can be complicated, however, as the climate in the Southern Great Plains is notably dynamic, and weather patterns are becoming more extreme (Harmel et al. 2003; Ojima et al. 2020).

Grazing Management for *Sorghum halepense* Invasion

The high forage quality of *S. halepense* and ability to manage this species through grazing has largely limited *S. halepense* spread in grazing lands (Hawkins et al. 1958; Watson et al. 1980). Heard (1917), for example, suggested that the best eradication measure for *S. halepense* was to irrigate to establish a good stand followed by heavy sheep grazing. In native rangelands, where soils are undisturbed, *S. halepense* has more species to compete with and less opportunity to dominate (Paterson et al. 2020). This is especially true when grazing occurs on native rangelands, as livestock show a strong preference for *S. halepense*, given its forage quality relative to native grasses, and will often preferentially graze *S. halepense* out of the plant community (Bennett et al., 1973; Watson et al. 1980). Pasturelands, alternatively, differ from native rangelands, as they are periodically plowed every 5 to 20 yr, seeded with productive introduced species, and receive regular fertilization and herbicide management inputs (Sollenberger et al. 2020; USDA-NRCS 2024). *Sorghum halepense* can, therefore, have a greater ability to dominate pasturelands, as there are fewer physiologically similar species to compete with and reduced competition from broadleaf herbaceous species (Rocateli and Manuchehri 2017). While *S. halepense* is still preferentially grazed in pasture, many pasturelands have an established grazing system where livestock are rotated throughout the year (Badgery et al. 2017; Paine et al. 1999; Williams and Hammond 1999). Livestock, therefore, may only have access to a specific pasture once per year in rotationally grazed systems. When temporal grazing disturbances are limited by rotation, *S. halepense* should be quite productive (Paterson et al. 2020; Rocateli and Manuchehri 2017). At a long-term agroecosystem study site in Riesel, TX, for example, areas that are rotationally grazed for more than 10 yr were found to have almost two times the plant production compared with areas that were continuously grazed (unpublished data). It was postulated in this paper that the reason for this high forage availability was the preferential growth of *S. halepense* in pastures that were not subjected to continuous grazing (unpublished data). While this hypothesis has yet to be tested, as total plant production was not sorted by species, it seems plausible that, especially in pasturelands that have rotational grazing, *S. halepense* could improve forage availability and forage quality by growing in tandem with seeded introduced species.

Conclusions

Sorghum halepense has been a challenging invader on croplands for decades and has more recently started increasing on intact native range and pasture grassland ecosystems. The spread and dominance of *S. halepense* is not only due to its morphology of rapid development of rhizomes and prolific seed production but also due to changing land use, like less livestock grazing due to higher anthropogenic development on Southern Great Plains grasslands. Once established, *S. halepense* can outcompete many native perennial grass species by growing earlier and faster and having higher biomass than functionally similar native perennial grasses. *S. Sorghum halepense* also appears to be well suited to adapting to extreme weather, like frequent drought and flooding that are actively occurring across the Southern Great Plains. While chemical, biological, and mechanical control can be used to control *S. halepense*, these options are costly and/or impractical to use across much of the Southern Great Plains grazing lands. Alternatively, there can be multiple socioeconomic benefits of having *S. halepense* on grazing lands, not least among them the potential for higher and more nutritious forage for grazing livestock. It is, however, likely that higher forage availability will only be possible when grazing can be excluded for a period to allow *S. halepense* to regrow, as *S. halepense* is often preferentially grazed out of the plant community in continuously grazed systems. There is still much work to be done to fully comprehend the benefits and drawbacks of *S. halepense* growing on grazing lands, but as this review has indicated, this species should be monitored to balance its increasing spread with greater forage stability and availability in the dynamic climate conditions facing the Southern Great Plains.

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