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Use of Tebuthiuron to Restore Sand Shinnery Oak Grasslands of the Southern High Plains

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1. Introduction

The Southern High Plains of northwest Texas and eastern New Mexico represents the extreme southwest subdivision of the Great Plains. This 130,000 km² plateau represents a “remnant of the Rocky Mountain piedmont alluvial plain” with borders abruptly demarcated by the Canadian river to the north, Pecos river to the west, and the dramatic Caprock Escarpment to the east (Holliday, 1990; Reeves, 1965; Fig. 1). The southern border is relatively undefined as a gradual merging into the Edwards Plateau. As one of the last regions to be permanently settled in the conterminous United States, the semi-arid Southern High Plains was frequently described as a desolate, never-ending featureless landscape unsuitable for human occupation and agriculture (Wester, 2007). The primary factor underlying the fear of humans traveling across the Southern High Plains was the lack of reliable surface water. However, the discovery of southern extent of the massive underlying Ogallala Aquifer combined with the development of the deep-well technology in the 1940s to mine large quantities of water lead to the conversion of the Southern High Plains to one of the most agriculturally impacted regions of the world (Smith, 2003; Wester, 2007).

Geologically, the Southern High Plains is comprised of two main formations. The Quaternary Blackwater Draw Formation formed by multiple episodes of eolian sheet deposition during the past 1.4 million years (Holliday, 1990). Beneath the Blackwater Draw Formation is the Miocene-Pliocene Ogallala Formation that was created between about 11 million to 1.4 million years ago (Holliday, 1990). Holliday (1990) suggested that the Southern High Plains has likely been a grassland or savanna grassland for about 11 million years based on evidence for an arid to a semi-arid or sub-humid environment. Ecologically, the Southern High Plains is currently considered a short-grass prairie dominated by buffalo grass (*Bouteloua dactyloides*) and blue grama (*Bouteloua gracilis*) prior to settlement (Blair, 1950; Kuchler, 1970). This community has likely been present for approximately 10,000 years (Axelrod, 1985; MacGinitie, 1962). The natural ecological drivers of this system include fire (natural and prescribed), large herbivores (e.g., modern bison [*Bison bison*]), and extreme

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unpredictable environmental conditions (e.g., extended droughts, short periods of intensive precipitation, temperatures ranging from -33 to 44 C) (Stebbins, 1981; Wester, 2007; Wright & Bailey, 1982).

The featureless landscape of the Southern High Plains is relieved only by Holocene dune fields (formed during droughts of the Altithermal period) along its southwestern borders (Holliday, 1989), >20,000 ephemeral playa wetlands scattered across the landscape (Bolen et al., 1989; Haukos & Smith, 1994; Smith, 2003), approximately 40 historically spring-fed saline lakes, and several currently dry, but historically spring-fed tributaries (i.e., “draws”) of the Colorado, Brazos, and Red Rivers (Holliday, 1990). The deep sandy soils associated with the dune fields, found primarily in the southwest portion of the Southern High Plains, along the Texas - New Mexico border, form a unique and distinctive ecosystem about which little is known ecologically.



Fig. 1. The Southern High Plains of northwest Texas and eastern New Mexico (from Morris, 1997).

These sandy soils primarily developed during the warmer, drier conditions between 4,000 – 7,000 years ago following the episodic deposition of sheet sands between 8,000 and 11,000 years ago and represent cumulative effects of drought, eolian deposition, and distribution of ancient waterways (Gile, 1979; Holliday, 2001). Eolian sands in dune fields and sand sheets cover >10,000 km², about 10% of the Southern High Plains, with approximately 5,800 km² existing as dune fields (Holliday, 2001). The Blackwater Draw Formation was locally buried by the deposition of sand during the periods of deposition (Holliday, 1989). Until the early 1900s, active dunes were present in the region (Muhs and Holliday, 1994). The topography of these areas differ dramatically from the surrounding short-grass prairie, which has little relief whereas the sandy soils support parabolic and coppice dunes, blow-outs, and sand sheets that creates a varied and heterogeneous landscape (Holliday, 2001). Although not yet quantified, a wide variation of micro-climates occurs within the landscape, which contrasts with the relatively few micro-climates of the short-grass prairie. According to Muhs and Holliday (2001) the dunes of the Southern High Plains are comprised of the most mineralogically mature sands of the Great Plains. Loss of vegetation cover allowing erosion of the Blackwater Draw Formation destabilizes the dune system and adds new sand to the system (Muhs and Holliday, 2001).

Although there are three identified west to east trending dune fields in the southwestern Southern High Plains – Muleshoe dunes, Lea-Yoakum dunes, and Andrews dunes – the focus of this chapter is on vegetation of the Muleshoe and Lea-Yoakum dunes, which are the northernmost extensive dune fields with associated sand sheets (Holliday, 2001). Relative activity of dunes ranges from least active in the northern Muleshoe dunes to most active in the Andrews dunes, the driest, warmest region (Muhs and Holliday, 2001). The Muleshoe dunes are higher, more vegetated, and relatively stable than the Lea-Yoakum dunes (Holliday, 2001), but support similar plant communities. The primary soil series is Brownfield-Tivoli fine sand (Neuman 1964), but additional soil types (mostly Entisols, Alfisols, Aridisols, and Mollisols) that support similar plant communities can be found (Garrison et al., 1977; Pettit, 1986, 1994). The sandy soils historically contained numerous springs and perched water tables hidden among the dunes (Brune, 2002; Marcy, 1850; Smith, 1985). With the advent of irrigation depleting the Ogallala Aquifer, these springs have dried and the location of most remains unknown.

These dune fields and sandy soils have always supported taller grasses and unique woody shrubs than the short-grass prairie of surrounding clay and sandy loams (Shantz and Zon, 1924). A unique ecosystem of sand shinnery oak (*Quercus harvardii*) and mid to tall grasses (e.g., *Andropogon hallii*, *Andropogon gerardii*, *Schizachyrium scoparium*, and *Sporobolus cryptandrus*) evolved in response to the soil and environmental conditions and represents a relic area of distinctive biodiversity relative to the short-grass prairie. As clay content in the soil increases, cover of sand shinnery oak decreases (Pettit, 1978) as the species grows best on sites with an almost pure sand cover (Small, 1975). Estimated coverage of sand shinnery oak presettlement is 5-25% (Conner et al., 1974; Hodson et al., 1980). The species has been present for at least 3000 years based on pollen profile (Gross and Dick Peddie, 1979; Hafsten, 1961). There is a relatively high diversity of forbs in the community as well (Peterson and Boyd, 1998). Ecological drivers for this system are the same as for the short-grass prairie, but grazing and fire were likely more infrequent historically. Bison were apparently attracted to water but the deep sands were difficult to traverse by such a large mammal so it is unlikely that large herds frequently grazed the interior of these habitats. Fire does occur and

structures the community, but likely not as recurrent as in the short-grass prairie because of the need to accumulate larger fuel loads to carry a fire across the patchy vegetation of the sandy soils. Pettit (1979) stated “These lands are perhaps the most fragile of all ecosystems on the Southern High Plains of Texas and the landowner cannot afford to abuse them.”

Typically not greater than 1 m tall, sand shinnery oak is the plant species most directly associated with this community. Although occurring in other regions of the United States, sand shinnery oak likely has the greatest ecological influence in the sandy soils of the southwestern Southern High Plains (Peterson & Boyd, 1998; Fig. 2). The natural form of sand shinnery oak in this region is that of a low shrub with up to 100 or greater short, aerial shoots from a massive underground stem and root system (Peterson & Boyd, 1998; Pettit, 1986). The underground root system is the primary reproductive structure for sand shinnery oak.

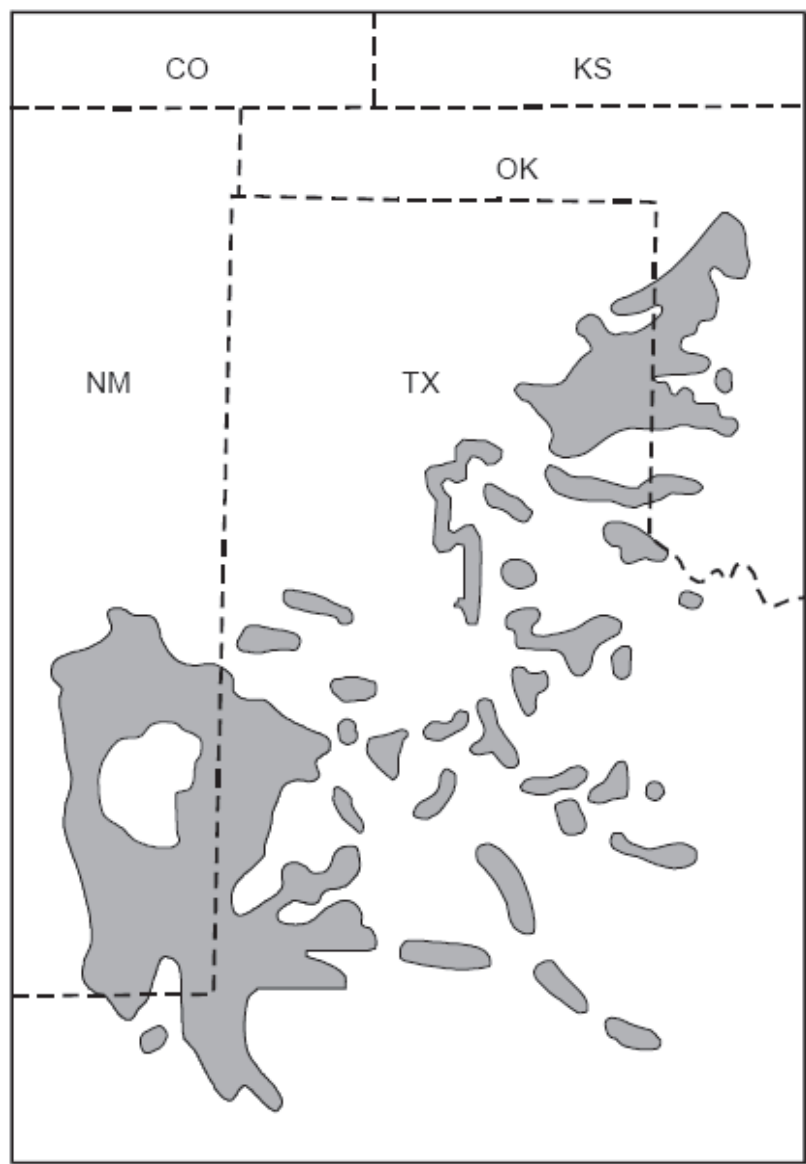


Fig. 2. Distribution of sand shinnery in New Mexico, Texas, and Oklahoma (Peterson & Boyd, 1989).

The stable existence of sand shinnery oak for thousands of years (Beckett, 1976; Gross and Dick-Peddie, 1979) and lack of spread by acorns refutes any claims that sand shinnery oak has increased in abundance and range in the past century. However, historically, in the absence of grazing, grasses frequently overtop and obscure sand shinnery oak (Brown, 1982; Duck and Fletcher, 1944). Furthermore, the roots of sand shinnery oak are also the primary soil stabilization structure. Loss of sand shinnery oak typically results in severe erosion of the sandy soils without the presence of vegetation (Parks, 1937; Moldenhauer et al., 1958).

Historical estimates of area of sand shinnery oak greatly vary, but Peterson & Boyd (1998) estimated that the species covered 405,000 ha in Oklahoma, 607,000 ha in New Mexico, and 1.4 million ha in Texas. The species range has not apparently expanded since the mid-1800s (Gross and Dick-Peddie, 1979; McIlvain, 1954; Peterson & Boyd, 1998). By 1972, approximately 500,000 ha had been converted to cropland or pastureland in Texas (Deering & Pettit, 1972). Current estimates of the area of sand shinnery oak are unreliable; but since 1972, the development of center pivot irrigation systems and advances in herbicide technology have resulted in a considerable reduction of sand shinnery oak habitats in the Southern High Plains (Bailey & Painter, 1994; Dhillion et al., 1994).

Sand shinnery oak has a unique life history. The species is deciduous with bud development in early to late March (Pettit, 1986), leaves open during April and May (Boo & Pettit, 1975; Pettit, 1975), flowering occurs in April and May (Rowell, 1967), and leaf drop normally happens in early November (Boo & Pettit, 1975). Acorns mature in July (Peterson & Boyd, 1998). Ninety-five percent of root growth is during July through September (Zhang, 1996). Most grasses and forbs in sand shinnery oak communities of the southwest Southern High Plains develop following precipitation events from May-July (Galbraith, 1983; Pettit, 1979).

Sand shinnery oak has uniquely evolved in the semi-arid environment of the Southern High Plains to efficiently gather and store water. Up to 50% of plant mass can be water during periods of precipitation (Pettit, 1986). However, during multi-year droughts, sand shinnery oak may not leaf out or may lose its leaves during the growing season to reduce water loss (Jones and Pettit, 1980; Jones and Pettit, 1984). However, the long-term effects of drought are more evident on grasses than sand shinnery oak because of the ability of the oak to store water and carbohydrates (Galbraith, 1983), which permits a relatively rapid response to alleviation of drought conditions compared to grasses that may not return to predrought production until the following growing season.

During spring bud and leaf emergence, catkins, buds, and leaves have a high phenolic content that can be poisonous to livestock (Allison, 1994; Dollahite, 1961; Peterson & Boyd, 1998). Therefore, sand shinnery oak is avoided by livestock at this time or, in most situations, livestock are removed from pastures that are predominately sand shinnery oak. Ingestion of sand shinnery oak buds and leaves during this time may lead to general malaise, reduced conception rates, lower weight gains, and death (Jones & Pettit, 1984). However, sand shinnery oak can be a significant portion of livestock diet especially during late summer and fall (Dayton, 1931; Plumb and Pettit, 1983; Roebuck, 1982).

Sand shinnery oak rarely reproduces through sprouting from produced acorns (Dhillion et al., 1994; Pettit, 1977; Wiedeman, 1960). This is likely the result of insufficient soil moisture because acorns are viable (Pettit, 1977; Pettit, 1986). However, acorn crops occur on average in 3 of 10 years (Pettit, 1986). Therefore, reproduction is primarily sprouting from rhizomes

(Pettit, 1977). Fire will top-kill sand shinnery oak, but vigorous resprouting usually occurs within a year, depending on soil moisture conditions (Slosser et al., 1985). Of great concern, however, is a lack of moisture following a prescribed or natural fire can result in significant wind erosion of the sandy soils (Zobeck et al., 1989).

Sullivan & Pettit (1977) reported that sand shinnery oak was most productive in younger soils. In the southwestern Southern High Plains, monocultures of sand shinnery oak produce 3,300 kg/ha of air-dried above-ground forage (Lenfesty, 1983). Sears et al. (1986) reported growing-season above-ground biomass of sand shinnery to be 1,821 kg/ha but a below-ground growing season biomass of 19,841 kg/ha. This corresponds with the estimate by Pettit (1986) that the ratio of underground to above-ground tissues was 10:1 to 16:1, which is likely greater than that of any other North American shrub. Depth of roots is frequently >5 m but above-ground shoots are rarely exceed 0.75 m tall in the southwestern Southern High Plains (McIlvain, 1954). The below-ground system of a single plant can be 3 – 10 m or more in diameter (Muller, 1951). Density of above-ground shoots can be 30 – 75 individuals/m² (Jones, 1982; Zhang, 1996). Mayes (1994) reported a single clone covering > 7,000 m². The maximum extent and age of individual sand shinnery oak plants are unknown, but age of below-ground structures is likely measured in centuries (Peterson & Boyd, 1998). Individual above-ground shoots usually have a lifespan of 11-15 years (Muller, 1951; Pettit, 1986). Sand shinnery oak can spread at a rate of 1 m per 5 years in fields where the species was previously removed (Sikes & Pettit, 1980), which reduces the likelihood of the species being considered invasive.

Understanding of the need for sand shinnery oak by vertebrates is mixed. Many species depend on the habitats supported by the sand-shinnery oak – grassland complex; including lesser prairie-chicken (*Tympanuchus pallidicinctus*) and dune sagebrush lizard (aka: sand dune lizard; *Sceloporus arenicolus*), which are candidates for listing as endangered or threatened species under the Endangered Species Act of the United States. The endemic dunes sagebrush lizard is restricted to sand shinnery oak habitats (Degenhardt & Jones, 1972; Degenhardt et al., 1996). The species is predominately found in areas of open sand (i.e., blow outs) but uses sand shinnery oak nearly exclusively for forage, thermal cover, and escape habitat. Due to its status of under review for listing as an endangered species, eradication of sand shinnery oak is restricted on public lands containing dune sagebrush lizard habitat (USDI BLM, 1997).

Approximately 100 avian species, including numerous species of conservation concern, such as Cassin's sparrow (*Aimophila cassinii*), use sand shinnery oak habitats for nesting, migration, and wintering. Scale quail (*Callipepla squamata*), northern bobwhite (*Colinus virginianus*), and mourning dove (*Zenaidura macroura*) use sand shinnery oak habitats during the nesting season. Approximately additional 20 species of songbirds nest in sand shinnery oak and 80 species use the habitat at some point during the year (Peterson & Boyd 1998). Raptors present in sand shinnery oak habitats include Mississippi kite (*Ictinia mississippiensis*), northern harrier (*Circus cyaneus*) Harris' hawk (*Parabuteo unicinctus*), Swainson's hawk (*Buteo swainsoni*), sharp-shinned hawk (*Accipiter striatus*), Cooper's hawk (*Accipiter cooperii*), rough-legged hawk (*Buteo regalis*), ferruginous hawk (*Buteo lagopus*), golden eagle (*Aquila chrysaetos*), prairie falcon (*Falco mexicanus*), barn owl (*Tyto alba*), and great-horned owl (*Bubo virginianus*) (Peterson & Boyd, 1998). NMPIF (2007) has identified eight bird priority species of concern using sand shinnery oak communities.

Mule deer (*Odocoileus hemionus*) feed on sand shinnery oak acorns, buds, and leaves (Gray et al., 1978; Krysl et al., 1980; Ligon, 1927). White-tailed deer (*Odocoileus virginianus*) are also found in sand shinnery oak habitats (Ligon, 1927; Raught, 1967). Pronghorn (*Antilocapra americana*) are frequently found in the sandhills using sand shinnery oak (Roebuck & Simpson, 1982). Black-tailed jackrabbits (*Lepus californicus*) and desert cottontails (*Sylvilagus auduboni*) are commonly found in sand shinnery oak habitats (Peterson & Boyd, 1998). Sixteen small mammal species have been reported in areas of sand shinnery oak, but none are endemic (Peterson & Boyd, 1998). The most common mammalian predators are coyote (*Canis latrans*), bobcat (*Lynx rufus*), badger (*Taxidea taxus*), striped skunk (*Mephitis mephitis*), and swift fox (*Vulpes velox*) (Peterson & Boyd, 1998). Reptiles are represented by western box turtle (*Terrapene ornate*) and 25 species of snakes including plains hognose snake (*Heterodon nasicus*), coachwhip (*Masticophis flagellum*), bull snake (*Pituophis melanoleucus*), massasauga (*Sistrurus catenatus*), and prairie rattlesnake (*Crotalus viridis*) (Peterson & Boyd 1998). In addition to the dunes sagebrush lizard, there are 9 lizard species that use sand shinnery oak habitats in southwestern Southern High Plains including prairie lined racerunner (*Cnemidophorus sexlineatus*), western whiptail (*C. tigris*), Great Plains skink (*Eumeces obsoletus*), leopard lizard (*Gambelia wislizenii*), lesser earless lizard (*Holbrookia maculate*), Texas horned lizard (*Phrynosoma cornutum*), and prairie lizard (*Sceloporus undulates*) (Degenhardt and Jones, 1972; Degenhardt et al., 1996; Gorum et al., 1995; Peterson & Boyd, 1998; Wolfe, 1978).

Invertebrates are an important component of sand shinnery oak with at least 23 families represented (Haukos & McDaniel, 2011). Annual biomass of invertebrates dramatically fluctuates, which does not appear to be related to annual precipitation (Haukos & McDaniel, 2011). Many species depend on invertebrates to persist in sand shinnery oak habitats, but little is known about the ecology of invertebrates in these habitats of the Southern High Plains.

The most widely identified vertebrate species of sand shinnery oak in the southwestern Southern High Plains is the lesser prairie-chicken. Although opinions vary regarding the importance of sand shinnery oak for lesser prairie-chickens, the accumulated evidence suggests that the habitats supported by sandy soils, including sand shinnery oak, comprise the core of the historic and current population in the region. Due to a >90% decline in numbers and range (Crawford, 1980; Taylor & Guthery, 1980), the species has been a candidate for listing as an endangered species since the late 1990s under the United States federal Endangered Species Act.

Lesser prairie-chickens consume acorns, galls, catkins, and vegetation of sand shinnery oak and insects associated with sand shinnery oak (Crawford & Bolen, 1976; Davis et al., 1981; Doerr and Guthery, 1983; Riley et al., 1993). Lesser prairie-chickens will lek, nest, and raise broods in sand shinnery oak habitats (Haukos & Smith 1989; Riley et al., 1993; Sell, 1979). Nests are usually constructed in residual grasses but frequently surrounded by sand shinnery oak as protective cover (Haukos & Smith, 1989; Riley et al., 1992; Sell, 1979). Sand shinnery oak provides thermal cover, escape cover, and roosting cover for lesser prairie-chickens (Copelin, 1963; Crawford & Bolen, 1976; Davis et al., 1981; Riley et al., 1993; Sell, 1979).

Crawford (1974) reported that sand shinnery oak comprised 15% of volume of fall foods. Davis et al. (1979) reported that sand shinnery oak acorns comprised 39 and 69% of fall and

winter diets, respectively, of lesser prairie-chickens. They also noted that sand shinnery oak leaf galls (produced by a parasitic wasp) and catkins were also important foods.

From a management perspective, land ownership of sand shinnery oak landscapes on the Southern High Plains has a tremendous influence on management strategies. In Texas, the vast majority of sand shinnery oak habitat is on private land that supports agricultural activities or oil/gas development. Whereas, in New Mexico, there is considerable area of sand shinnery oak habitats held in public trust (~700,000 ha) that is managed by a variety of federal, state, and local governments in addition to nongovernment organizations (Peterson & Boyd, 1998). The sand shinnery oak habitats on public lands in New Mexico are managed for multiple uses including livestock grazing, oil and natural gas development, and hunting.

Although with some debate regarding the cause, current plant assemblages in sand shinnery oak – grass communities tend to be dominated by sand shinnery oak at the expense of grass coverage. Recent estimates of ground cover of sand shinnery oak are 80-90% (Biondini et al., 1986; Dhillon et al., 1994; Pettit, 1994; Plumb, 1984). Frequently, sand shinnery oak is categorized as increasing or invader under grazing pressure comparing to decreasing grass and forb component (Herbel, 1979; Herndon, 1981; Lenfesty, 1983). However, there is little evidence that sand shinnery oak invades or increases in absolute density or abundance in overgrazed grassland despite the perception of development of a monoculture (Dickerson, 1985; Holland, 1994); but rather, when given a competitive advantage due to grazing pressure as an effective water gatherer (Galbraith, 1983; Pettit, 1986; Sullivan, 1980; Zhang, 1996), will reduce or eliminate associated species due to the effects of shading and moisture competition. Thus, overgrazing and suppression of fire has reduced or eliminated the herbaceous (both grasses and forbs) species associated with sand shinnery oak.

Most land managers consider this condition undesirable and noxious, with considerable effort expended to eradicate sand shinnery oak with varying degrees of success since the early 1970s. Restoration of the plant composition to historical proportions requires retarding growth of sand shinnery oak to allow development and growth of herbaceous species to a point of a stable community, which may occur when mid and tall grasses are permitted to fully develop. For example, when tall grasses overtop sand shinnery oak, clones are reduced in vigor and density (Frery, 1957; Muller, 1951). Indeed, Moldenhauer et al. (1958) stated that under natural conditions, grasses were dominant and outcompeted sand shinnery oak.

Clearing of sand shinnery oak and planting crops is effective in reducing oak but is very expensive, removes critical habitat, and results in short-term productivity that requires significant nutrient inputs within a few years of clearing (Peterson & Boyd 1998). Additionally, complete removal of sand shinnery oak for croplands results in short-term success with the high potential for wind erosion of topsoil (Lotspeich & Everhart, 1962). Control of sand shinnery oak using prescribed fire usually is a short-term benefit because of vigorous resprouting within 2-3 growing seasons following the fire (McIlvain, 1954).

The most common method used to reduce or eradicate sand shinnery oak is application of herbicides. Initial efforts were application of phenoxy herbicides including 2, 4-D and 2, 4, 5-T; benzoic acids (i.e., dicamba); and picolenic acid (i.e., picloram) as liquids for absorption through foliage (Peterson & Boyd 1998). Typically, use of these herbicides at >1 kg/ha active ingredient (ai) resulted in the top-killing of 85-95% of sand shinnery oak (Greer et al., 1968; Pettit, 1977). To avoid removal of associated grasses and forbs that occurs at high rates of

application (e.g., 3 – 8 kg ai/ha) necessary to kill sand shinnery oak with a single application, annual spraying for 2-3 years at lower rates has been recommended (Pettit, 1976; Pettit, 1977). Grass production can be doubled to quadrupled for a few years following herbicide application prior to exhibiting a decline (Greer et al., 1968; McIlvain & Armstrong, 1959). Thus, initial use of herbicides to control sand shinnery oak was exceptionally expensive relative to the duration of the effect.

In 1974, a pellet form of tebuthiuron (trade name of Spike® or Graslan®) applied to the soil and absorbed by roots began being used on sand shinnery oak (Peterson & Boyd, 1998). Tebuthiuron causes repeated defoliation of oak, which causes death within 2-3 years following application (Jones & Pettit, 1984; Peterson & Boyd, 1998). At 3 kg ai /ha, sand shinnery oak is killed, but many nontarget grasses and forbs are also killed (Pettit, 1979). Furthermore, at high application rates, much of the increase in annual production is by annual or undesirable grasses (Jacoby et al., 1983; Plumb, 1984). By the mid-1990s, at least 130,000 and 40,000 ha of sand shinnery oak had been treated with tebuthiuron in Texas and New Mexico, respectively (Johnson & Ethridge, 1996). The advantages of tebuthiuron include its relative nontoxicity to nontarget species (Emmerich, 1985), its effectiveness after only one application (Scifres et al., 1981), and elimination of overspray that is a characteristic of liquid herbicides (Scifres et al., 1981).

There is considerable variation of the magnitude of sand shinnery oak kill and resultant grass response to use of tebuthiuron. At the relatively low rate of 0.4 kg/ha, cover of sand shinnery oak was reduced by 95% and grass yield increased 2.5 times controls after 3 years (Jones & Pettit, 1984). At rates of 0.6 – 1.0 kg/ha, oak is usually killed (Peterson & Boyd, 1998). The maximum grass yield of 4 times the control was found at a rate of 0.8 kg/ha (Jones & Pettit, 1984). Doerr (1980) found that rates of tebuthiuron from 0.2 – 1.0 kg/ha increased grass coverage from 88-130% and density of bunchgrasses from 12-32% by decreasing density of sand shinnery oak at least 84%. Forb densities and grass production were decreased in plots with 0.8 and 1.0 kg/ha. Seed production was increased in plots with application rates of 0.2, 0.4, and 0.6 kg/ha. Depending on rate of application, treatment with tebuthiuron tends to decrease vertical screening immediately after application as the shinnery oak dies, but as bunchgrasses recover, vertical screening in treated plots may surpass that in untreated plots (Doerr & Guthery, 1983). Likewise, canopy cover eventually can be greater in tebuthiuron treated plots than in untreated plots (Doerr & Guthery, 1983; Jones, 1982). Doerr (1980) recommended an application rate of 0.4 kg/ha because of the increased grass response in the first year following treatment relative to greater rates. Scifres & Mutz (1978) reported that most forb species were killed at application rates of 2.0 and 3.0 kg/ha. A 25% kill of sand shinnery oak prevents acorn production for up to 2 years, which is a reduction of an important component of forage for lesser prairie-chickens and other wildlife (Peterson & Boyd, 1998). Crude protein in grasses increased by 28% for one growing season post tebuthiuron application (Biondini et al., 1986). Forbs generally increase in diversity and production >2 years after application (Doerr & Guthery, 1983; Jacoby et al., 1983; Jones & Pettit, 1982; Olawsky & Smith, 1991). Sears et al. (1986) found a 17% decrease in sand shinnery oak and 266% increase in herbaceous vegetation within three years of treatment. Six years after treatment, above-ground biomass had decreased due to a 41% decrease in sand shinnery oak, 32% decrease in litter, and 161% increase in herbaceous vegetation (Sears et al., 1986).

Without government assistance it is unlikely that treating sand shinnery oak in New Mexico (lowest precipitation and grass response) would be economical for livestock producers unless changes are made to grazing systems to ensure that grasses persist as a component of the plant assemblage (Peterson & Boyd, 1998). From an economic perspective, long-term cost-effectiveness of treating sand shinnery oak with tebuthiuron varies due to precipitation, beef prices, herbicide cost, and grazing management following treatment (Etheridge et al., 1987a; Etheridge et al., 1987b).

In contrast to plant response, there have been few investigations into faunal response to the use of tebuthiuron to control sand shinnery oak. The vast majority of studies focus on lesser prairie-chickens. At high rates (>1.5 kg ai/ha) application of tebuthiuron has resulted in preferred use by lesser prairie-chickens of untreated areas during nesting and brood rearing, indicating selection for habitats containing some cover by sand shinnery oak, but the extent of this response may be somewhat confounded by grazing pressure (Haukos & Smith, 1989). Sell (1979) found 75% of lesser prairie-chicken nests in sand shinnery oak or sand sagebrush. Haukos & Smith (1989) reported that 80% of nesting lesser prairie-chickens nested in untreated sand shinnery oak. Taylor (1978) reported that lesser prairie-chickens preferred habitats dominated by sand shinnery oak with a grass component during fall and winter. Donaldson (1966; 1969) reported an increase in lesser prairie-chickens in sand shinnery oak treated areas compared to untreated but also indicated that sand shinnery oak was the plant most commonly used even in treated plots. Further, he proposed supplemental winter feeding to make up for loss of acorns due to treatment. Olawsky (1987) reported that acorns were the major food of lesser prairie-chickens in untreated areas, but absent in treated areas, which resulted in lower lipid levels (i.e., lower body condition).

There is little conclusive evidence from Texas or New Mexico that treatment of sand shinnery oak with tebuthiuron benefits lesser prairie-chickens (Pederson & Boyd, 1999). There was no statistical difference in density of lesser prairie-chickens between treated and untreated sand shinnery oak during summer (0.51 and 0.41 birds/ha in treated and untreated plots, respectively) and winter (0.53 and 0.35 birds/ha in treated and untreated plots, respectively) (Olawsky et al., 1988). Martin (1990) reported 86% fewer lesser prairie-chickens in treated versus untreated sites, but indicated detection was difficult in grass pastures. Haukos & Smith (1989) reported that lesser prairie-chickens preferred to nest in untreated sites, likely due to intense grazing pressure in treated sites. Wide-spread eradication of sand shinnery oak is thought to be exceptionally detrimental to lesser prairie-chickens (Davis et al., 1979; Doerr & Guthery, 1980; Olawsky & Smith, 1991; Riley et al., 1993; Sell, 1979; Taylor & Guthery, 1980,). Johnson et al. (2004) observed lesser prairie-chicken hens selecting sand shinnery oak dominated rangelands not treated with herbicide, for nest sites, significantly more than herbicide treated rangelands. Johnson et al. (2004) also reported greater density of shrubs within a 3-m radius surrounding the lesser prairie-chicken nest sites. In New Mexico, Bell et al. (2010) most often located lesser prairie-chicken broods in dense sand shinnery oak areas. Lesser prairie-chicken survival was greatest in habitats with shrub density $\geq 20\%$ (Patten et al., 2005).

Reduction in acorn production due to tebuthiuron treatment is considered detrimental for deer (Bryant & Demarais, 1992; Bryant & Morrison, 1985). Bednarz (1987) reported that lagomorphs populations were reduced following eradication of sand shinnery oak with 2-3 years following spraying necessary for recovery. At a rate of 0.56 kg/ha, Colbert (1986)

found that populations of small mammals were not affected by tebuthiuron treatment. Doerr & Guthery (1980) found rodent populations to be 41% greater on untreated plots compared to plots where 75% of sand shinnery oak was removed. Ord's kangaroo rat seems to be the only small mammal that responds positively to tebuthiuron control of sand shinnery oak (Colbert, 1986; Fischer, 1985; Willig et al., 1993). With the exception of the Great Plains skink, lizards were more commonly found in untreated than treated sand shinnery oak habitats in New Mexico (Gorum et al., 1995; Snell et al., 1997). Martin (1990) reported that reduction of sand shinnery oak by 90% did not change number of birds and avian richness, but Cassin's sparrows may have increased slightly on treated plots and lesser prairie-chickens decreased on treated plots. However, meadowlark populations may be double in treated sand shinnery oak versus untreated (Olawsky et al., 1987).

Recommendations for use of herbicides to reduce sand shinnery oak and increase herbaceous production for the purpose of increasing weight gain of livestock are (1) shinnery oak should not be treated in drought years, which are difficult to predict, (2) areas of large dunes should not be treated due to erosion potential, (3) areas with little cover of existing perennial grass species should not be treated prior to 1-2 seasons of grazing exclusion, and (4) treated areas should not be burned or grazed during the growing season for at least 2 years following treatment (Doerr & Guthery, 1980; McIlvain and Armstrong, 1959). Doerr (1980) suggested that two rates be used to manage for lesser prairie-chickens (0.2 and 0.6 kg/ha) avoiding treatment of sand dunes and following light or no grazing pressure to ensure residual vegetation cover to reduce threat of wind erosion following treatment. Davis et al. (1974) recommended control of sand shinnery oak to be in strips to benefit birds. Unfortunately, these recommendations are rarely followed in practice resulting in significant reduction of dune topography, reduced sustained grass response to treatment, invasion of undesirable and difficult to eradicate plant species, and increased potential for major erosion events (Thurmond et al., 1986; Zobeck et al., 1989). Not only is grazing management critical following application of tebuthiuron to ensure sustain production of desirable grasses, but lesser prairie-chickens, and perhaps other species, respond to intensive grazing following treatment by using untreated sand shinnery oak. Overgrazing of grasses following treatment of sand shinnery oak can result in the conversion to dominance by sand sagebrush, which is much more difficult to control (pers. observ.).

Recently, throughout the southwestern Southern High Plains, there has been interest in restoring the vegetation communities to a more historic grass/shrub balance. Since approximately 2000, rates of wide-spread tebuthiuron application have been reduced (e.g., <1.0 kg/ha) with the avoidance of treating dune areas in an effort to temporarily reduce extent of sand shinnery oak and competitively release grass species to restore the historical balance of sand shinnery oak and grasses (Smythe & Haukos, 2010). Data on community response to reduced tebuthiuron application rates (0.60 kg ai/ha and dune avoidance) to restore the historical oak-grass under moderate grazing pressure initiated three years following herbicide application were collected as part of a 10-year study (Smythe & Haukos, 2009; Smythe & Haukos, 2010). Tebuthiuron was applied at to 532 ha of private land in 2000, which was adjacent to 518 ha of untreated land owned by the state of New Mexico representing the extant shinnery oak-grassland community. This rate of application rate was approximately 50% of previously recommended rates for the area to ensure that sand shinnery oak was not completely eliminated from the community. The control area had not been grazed for 7 years before the study began; tebuthiuron-treated areas had not been

grazed for 2 years pre-tebuthiuron treatment and 3 years post-tebuthiuron treatment. Grazing treatment was a short-duration system in which plots were grazed once during the dormant season (January and February) and once during the growing season (July). Stocking rate was calculated each season based on measured forage production and designed to take 25% of available herbaceous material per season.

There was a 6.5-fold increase in herbaceous plant production and a 29-fold difference in grass seed production on treated versus untreated areas (Smythe, 2006). The treated, ungrazed plots consistently had the greatest visual obscenity, whereas untreated, grazed plots had the lowest. Treated plots had greater visual obscenity at about 0.5 m and greater maximum height of vegetation. Vegetation was tallest in tebuthiuron-treated plots. Overhead cover did not differ among treatments. However, differences in vertical density among treatments occurred only at heights >40 cm.

Nesting grassland birds did not exhibit selection among nest sites based on vertical density, nor did vertical density affect hatching success (Smythe & Haukos, 2009). At lower levels of vegetation, those most important for concealment of nests, there was no difference in vertical density among treatments and no need for birds to select for nest sites among treatments. Average height of shinnery oak on the study site was 46.4 cm. This indicates that at lower vegetational strata, untreated shinnery oak provides similar vertical screening as the predominantly little bluestem communities that replace them after treatment with tebuthiuron (Smythe & Haukos, 2009).

Application of tebuthiuron at 0.60 kg/ha to restore sand shinnery oak communities in New Mexico, resulted in increased density of grassland birds (Smythe & Haukos, 2010). Treated sand shinnery oak plots restored to a grass/shrub mix supported a greater density of spring migrants and breeding birds than untreated plots. Migratory birds represented much of the increased density, whereas resident species exhibited no response. Density (individuals per hectare) of all species ($n = 28$) was not affected by the grazing treatment. Average total density was 40% greater in tebuthiuron-treated plots than in untreated plots. There was no overall tebuthiuron treatment or grazing effect on species richness. Diversity was lower on ungrazed, untreated plots than other treatment combinations in February and March. Increased density on tebuthiuron-treated plots was present in both wet and dry years. This finding differed from Martin (1990), who found no difference in relative abundance of all species between tebuthiuron-treated (using 0.5 kg/ha) and untreated shinnery oak communities in southeastern New Mexico.

Avian species richness, evenness, and diversity were only minimally affected by the tebuthiuron and grazing treatments (Smythe and Haukos 2010). Grasslands generally have low densities of birds, but estimated densities of this study were considerably lower than those reported in several other grassland studies (e.g., Cody, 1985; DeJong, 2001; Giezentanner, 1970; Igl & Ballard, 1999; Wiens, 1973). Current low densities in sand shinnery communities might indicate an ecological sink or reduced habitat carrying capacity. The moderate grazing regime (Holechek et al., 2001) of this study had little effect on grassland bird populations in this region. It is also important to emphasize that grazing was deferred on the study plots for 3 years after the tebuthiuron treatment, longer than the 1- to 2-year deferrals recommended by most current management guidelines (Peterson & Boyd, 1998). These results indicate that short-duration grazing regimes, based on the correct stocking rate

and knowledge of available forage, are not detrimental to grassland bird populations in treated or untreated sand shinnery oak habitats.

Density of songbird nests (nests/10 ha) for all species was similar among treatments (Smythe & Haukos, 2009). The majority of nests of Cassin's sparrow (76%) and meadowlarks (90%) were in little bluestem (Smythe, 2006). Daily rate of nest survival across treatments did not differ between incubation and nestling period for any species or within any treatment. During incubation, daily survival of nests differed between tebuthiuron-treated and untreated plots as survival was 6.3% higher in untreated plots than in treated plots. However, during the nestling period the opposite trend was apparent as daily survival of nests was 17.3% greater in tebuthiuron-treated plots than in untreated plots.

In Smythe & Haukos (2009; 2010), the moderate grazing regime did not significantly impact vertical density of vegetation. Grassland birds selected nest sites based on overhead cover, presumably as a defense against avian predators; however, average overhead cover did not differ among treatments. Likewise, greater vertical cover in tebuthiuron-treated plots did not always result in higher daily rates of survival of nests. This may indicate that grasses and shrubs are needed during different periods of brood rearing and, thus, both are required in a restored shinnery oak community. Our results indicate that carefully managed application of tebuthiuron and grazing in shinnery oak communities do not adversely impact density or success of nests of grassland birds; however, current high rates of depredation and low rates of nest success overall do not bode well for grassland birds in this community.

Tebuthiuron treatment at low rates with appropriate grazing management may create a consistent grass/shrub mix normally restricted to years of above-average precipitation. This could increase densities of some migratory grassland bird species such as Cassin's Sparrow and does not appear to harm resident species. A carefully managed, moderate grazing regime also does not appear to negatively impact grassland bird density; however, grazing must be managed to maintain restoration efforts, and continued monitoring is needed to determine the long-term effects of restoration.

2. Conclusion

In areas where shinnery oak has become essentially a monoculture, tebuthiuron can be used to create vegetation heterogeneity that may benefit migratory grassland birds (Smythe & Haukos, 2009). A restored sand shinnery community then has a codominant mix of grass and shrubs. However, tebuthiuron treatment is not an excuse for continuing poor land management practices such as overgrazing. The goal of tebuthiuron use should be to increase the grass component within the shinnery oak community, not to eliminate shinnery oak entirely. It is important to realize that higher application rates desired by landowners to meet livestock goals may not be beneficial to grassland birds. Creating homogeneous grassland from homogeneous shrubland is likely not the best approach for grassland birds, and beneficial habitat for grassland birds could be created at lower application rates than occurred in this study. Tebuthiuron should not be applied to shinnery oak communities in poor condition, because on sandy soils, it can be difficult to obtain a high canopy cover of plants after sand shinnery oak is removed (Pettit, 1979). Adequate perennial bunchgrasses (≥ 8 plants/m² suggested) must preexist in areas to be treated (Doerr, 1980; Jones, 1982).

Ethridge et al. (1987a) found that an application rate of 0.56 kg/ha was the maximum application that remained profitable. Doerr (1980) recommended a rate of 0.4 kg/ha to produce high densities and canopy coverage of forbs as well as grass seed as food for lesser prairie-chickens.

Grazing should be deferred for at least 1 year after tebuthiuron treatment to allow for adequate recovery; in this study, grazing was deferred for 3 years (Smythe & Haukos, 2009). Grazing too soon after application can result in serious erosion (Pettit, 1979). Grazing should be deferred for longer periods under drought conditions, and stocking rates should be calculated based on available forage and frequently reevaluated to maintain the benefit of tebuthiuron treatment. Grazing should be performed in a manner that mimics historic heterogeneous vegetation mosaics, where certain areas are grazed more intensively than others (Vickery et al., 1995). This will support a variety of grassland species that prefer different vegetation heights and densities. Short-duration grazing regimes may provide greater control over livestock effects on the landscape and accordingly make a heterogeneous vegetation mosaic easier to maintain.

Rainfall and the resulting vegetative conditions should always factor into any land management practice (Smythe & Haukos, 2009). The variability of weather in the Great Plains produces highly different conditions from year to year, and any management plan should be reevaluated each year to ensure that it is adequate for the conditions present. Knowledge of available forage is essential to calculating the correct stocking rate. It is critical to manage tebuthiuron-treated shinnery oak communities carefully to maintain the benefits of restoration. Carefully managing shinnery oak communities for bird populations can also provide benefits to humans, but the converse is not necessarily true.

3. References

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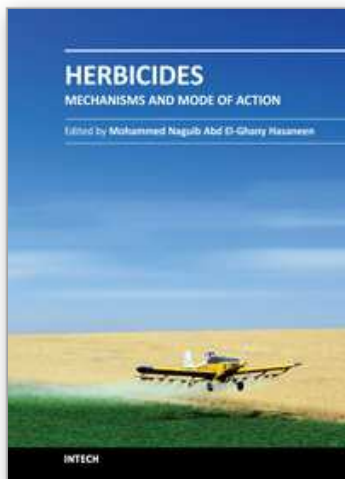
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This volume contains two sections: Mechanisms of herbicidal action (chapters 1-4) and Mode of action of selected herbicides on controlling diseased, weed growth and productivity and/or growth and development of field crops (chapters 5-10). Topics by chapters are: molecular mechanism of action, immunosensors , laboratory studies, molecular modeling, weed resistance, community response, use of herbicides in biotech culture, gene flow, herbicides and risk, herbicides persistence. These recurring themes reinforce my view, held over a very long time, that experience with one crop or problem can sometimes be relevant, often to an unexpected extent, to an apparently dissimilar situation in a different crop. I hope that readers interested in herbicides and pesticides will be satisfied with all the chapters in the book as its content might be of interest and value to them in the future.

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