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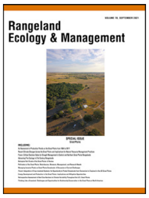

Woody Vegetation Cover, Attrition, and Patch Metrics over Eight Decades in Central Texas, United States*

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ABSTRACT

Woody plant encroachment into rangeland ecosystems is a widespread and often unwelcomed circumstance affecting rangeland management decisions worldwide. In the rangeland management profession, varying philosophies have been employed in the management of woody plant encroachment. Following World War II, total eradication of woody plant cover was commonly practiced, eventually giving way to a mosaic approach that benefits livestock, wildlife, and recreational objectives, with cover increasing or even stabilizing in many areas. Cultural practices such as land fragmentation, lifestyles not dependent on agricultural income, and shifts in herbivory from predominately browsers to grazers may also be contributing factors. Modern image analysis technologies, such as object-oriented feature extraction and patch metric analyses, can shed light on past paradigm shifts through spectral and textural assessment of modern and historical aerial photography. In this study, woody plant cover and patch metrics were analyzed for a period spanning from 1938 to 1940 through 2018 in the Bennett and Sulphur Creek watersheds of the Lampasas Cut Plain of Central Texas. Object-based feature extraction was used to calculate woody plant cover, and Fragstats was used for landscape patch metrics. Total woody cover was compared with past stewardship paradigms. There was a net decrease of total woody plant cover from 1938 to 1940 through 2018, with variation in between as management paradigms shifted. A pattern of decline, regrowth, and stabilization, like that observed in other research, was noticed for the Bennett Creek watersheds but was not apparent in Sulfur Creek. Patch size/shape varied as well, but fractal patch complexity was relatively stable through time. Raster algebra analysis showed that $<$ 10% of the initial woody cover from 1938 to 1940 remained in 2018, although total cover went through various expansion/reduction phases. This research underscores the importance of long-term datasets and locally based knowledge in the application and interpretation of historical management paradigms.

Introduction

The intrusion of woody plant species into grass-dominated rangelands is a much documented and often maligned phenomena affecting rangelands worldwide (Archer 1994 and 1995; Archer and Stokes 2000, Asner et al. 2004; Briggs et al. 2005). A combination of various factors such as modified fire return intervals, altered livestock grazing regimes, climate change, altered CO_2 concentrations, nitrogen depositions, and rural demographic changes are all believed to be contributors of woody plant encroachment (Young et al. 1948; Scifres 1980; Schlesinger et al. 1990; Archer 1994; Miller and Wigand 1994; Van Auken 2000; Drummond et al. 2012; Berg et al. 2015; Berg et al. 2016). Rangelands are an important natural resource, making up approximately 34% of the conterminous United States (Vogelmann et al. 2001) and 40% of the earth's total land surface (Chapin et al. 2001; Bailey 2009), contributing to one-third of worldwide net terrestrial productivity (Field et al. 1998). Woody plant encroachment therefore can have negative implications on hydrological and biogeochemi-

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cal processes, including biodiversity, primary and secondary productivity, wildlife habitat, as well as the cycling of water, nitrogen, and carbon (Houghton et al. 1983; Archer 1994; Vitousek et al. 1997; Ramankutty and Foley 1999; Huxman et al. 2005; Huang et al. 2006; Wilcox 2007; Tennesen 2008). In the following sections, we explore woody plant management paradigms in the literature and remotely sensed cover trends over an 80-yr period in central Texas, United States.

Woody Plant Expansion

As early as the 1890s, woody plant encroachment had become a noticeable concern in Texas, with estimates of up to 26 million ha of affected rangelands (Smith 1899; Bray 1904; Young et al. 1948). The introduction of barbed wire in the 1870s led to the confinement of livestock (Hamilton and Ueckert 2004) while providing vertical structures (fenceposts and wire) that served as vectors for woody plant seed dispersal by birds (Phillips 1910; Holthuijezen and Sharik 1985). Young et al. (1948) estimated that woody plant encroachment cost the Texas ranching industry $18.5 million USD (~$196 million adjusted 2019 dollars) in lost rangeland productivity. It is well documented that in much of the United States, brush control became a top priority within the rangeland management profession in the early 20th century (Moses 1956; Holechek 1981; McKenzie et al. 1984; Hamilton et al. 2004). In 1933, the Soil Erosion Service, later renamed the Soil Conservation Service, was founded and is now known as the Natural Resources Conservation Service (NRCS) (Holechek 1981). Throughout its 88-yr history, the NRCS has assisted landowners on numerous land management practices, including woody plant removal. The Agricultural Adjustment Act of 1938 established one of the first programs for federal assistance in the removal of woody plants (Cartwright 1966). The 1940s were marked by the development of 2,4-D, which became a widely used herbicide for the control of woody and other noxious plants (Holechek 1981).

In the years following World War II, the spread of large tractors, surplus heavy equipment, and anchor chain enabled woody plant management efforts to expand considerably (McKenzie et al. 1984; Hamilton and Hanselka 2000; Hamilton et al. 2004). The heavy equipment industry, which had emerged around 1900, received a boon of production during World War II that continued to grow following passage of the 1949 Housing Act and the 1956 Federal Interstate Highway Act (US Senate 1956; Lassiter and Kruse 2009; Ammon 2016; Caterpillar 2021).

By the 1950s, the Texas Agricultural Experiment Station (now Texas A&M AgriLife Research) had conducted extensive field experiments on chemical and mechanical woody plant removal and their effects on grass recovery and productivity (Moses 1956). Brush management had become a major land management practice, often focused on total brush eradication (Moses 1956; Carter 1958; Holecheck 1981; McKenzie et al. 1984; Hamilton and Ueckert 2000; Hamilton and Hanselka 2000; Hamilton et al. 2004).

Over time, the philosophical attitude toward woody plant eradication shifted and a new paradigm of woody plant management began to take hold in the late 1950s (Hamilton and Hanselka 2000; Hamilton et al. 2004), as it was shown that not all kinds of brush removal methods were economically reasonable on every rangeland type (Allison and Rechenthin 1956). In addition, the adoption of steel “T” fence posts in the 1950s dramatically reduced the demand for juniper fence posts (Cartwright 1966; Ferguson 2019).

Concurrently, in the 1960s and 1970s there were considerations that leaving some woody species was desirable for wildlife habitat and browse (Scifres 1980; Hamilton et al. 2004). In central Texas, for example, the golden-cheeked warbler *(Dendroica chrysoparia)* and black-capped Vireo *(Vireo atricapilla)* are two species that are highly dependent on woody cover. The golden-cheeked warbler is an Ashe juniper obligate species, requiring mature trees for nest-building sites and materials (Kroll 1980), while the black-capped vireo prefers areas of mixed juniper and oak (*Quercus* spp.) (Bailey and Thompson 2005). Both species are reliant on edge-to-area ratios (Kroll 1980; Bailey and Thompson 2005; Magness et al. 2006; Pope et al. 2013) and may therefore benefit from woody treatments that exercise a mosaic structure. In South Texas, a brush management systems approach was used that integrated the use of herbicides, mechanical treatments, fire, and grazing management to enhance grazing for livestock and wildlife and created patch mosaics that could provide edge and cover (Scifres 1980; Scifres and Koerth 1986; Hamilton et al. 2004).

Remote Sensing/Feature Extraction

One persistent challenge when trying to understand historical land cover changes over time is the lack of widespread long-term in-situ field data. Quality, long-term datasets are generally localized in nature and do not capture the full scope of variability in vast heterogenous ecosystems (Washington-Allen et al. 2006; Rango et al. 2008). Thus, past data collection methods may not fully address modern research questions. Moreover, as management priorities evolve, so do the variables measured; leading to information that is not necessarily repeated to the same degree through space and time (West 2003). However, high-resolution aerial photography datasets from fixed-wing aircraft became commercially available to portions of the United States just after World War I (Lillesand et al. 2015) and can be useful for examining changes in vegetation over space and time. Today, many historical imagery datasets are maintained in private collections and state and federal government repositories.

Historical aerial photographs provide a trove of information useful for not only for the study of rangelands but also understanding historical agricultural practices (Zomenii et al. 2008; Berg et al. 2016), carbon storage (Asner et al. 2003), hydrology (Berg et al. 2016), urban growth (Herold et al. 2005), and even identifying archaeological sites (Stichelbaut 2011). By using remote-sensing classification analyses on historical aerial photographs, changes in woody plant cover and patch metrics may be assessed from a time period predating implementation of modern rangeland improvement practices.

Image classification has long been the nucleus of remote sensing—transforming imagery into a useful geographic commodity (dos Santos et al. 2012) that is the foundation of many environmental and socioeconomic uses (Lu and Weng 2007). Traditional pixel-based classifications assign pixels (cells) of an image into classes based on each pixel’s spectral characteristics. This can lead to noisy classifications that have a salt-and-pepper appearance (Lu and Weng 2007). Object-oriented classification is more robust than pixel-based classification, by first segmenting an image into objects based on spectral, textural, and spatial attributes (Baatz and Schape 1999; Franklin et al. 2000; Thomas et al. 2003; Laliberte et al. 2004; Mitri and Gitas 2004). Object-oriented approaches have been shown to increase image classification accuracy by 10−15% (Franklin et al. 2000) and are successful in delineating tree canopies (Gibbes et al. 2010; Poznanovic et al. 2014). In Idaho, Davies et al. (2010) found a strong correlation between ground measurements of western juniper (*Juniperus occidentalis* subsp. *Occidentalis* Hook.) and classifications made with high-resolution US Department of Agriculture National Agriculture Imagery Program (NAIP) imagery.

Our objective was to quantify landscape-level total woody plant cover and patch metrics for five watersheds within the Lampasas Cut Plain in central Texas over a period of 80 yr and compare that with published land management paradigms through time. In this paper, we specifically address the following questions: How

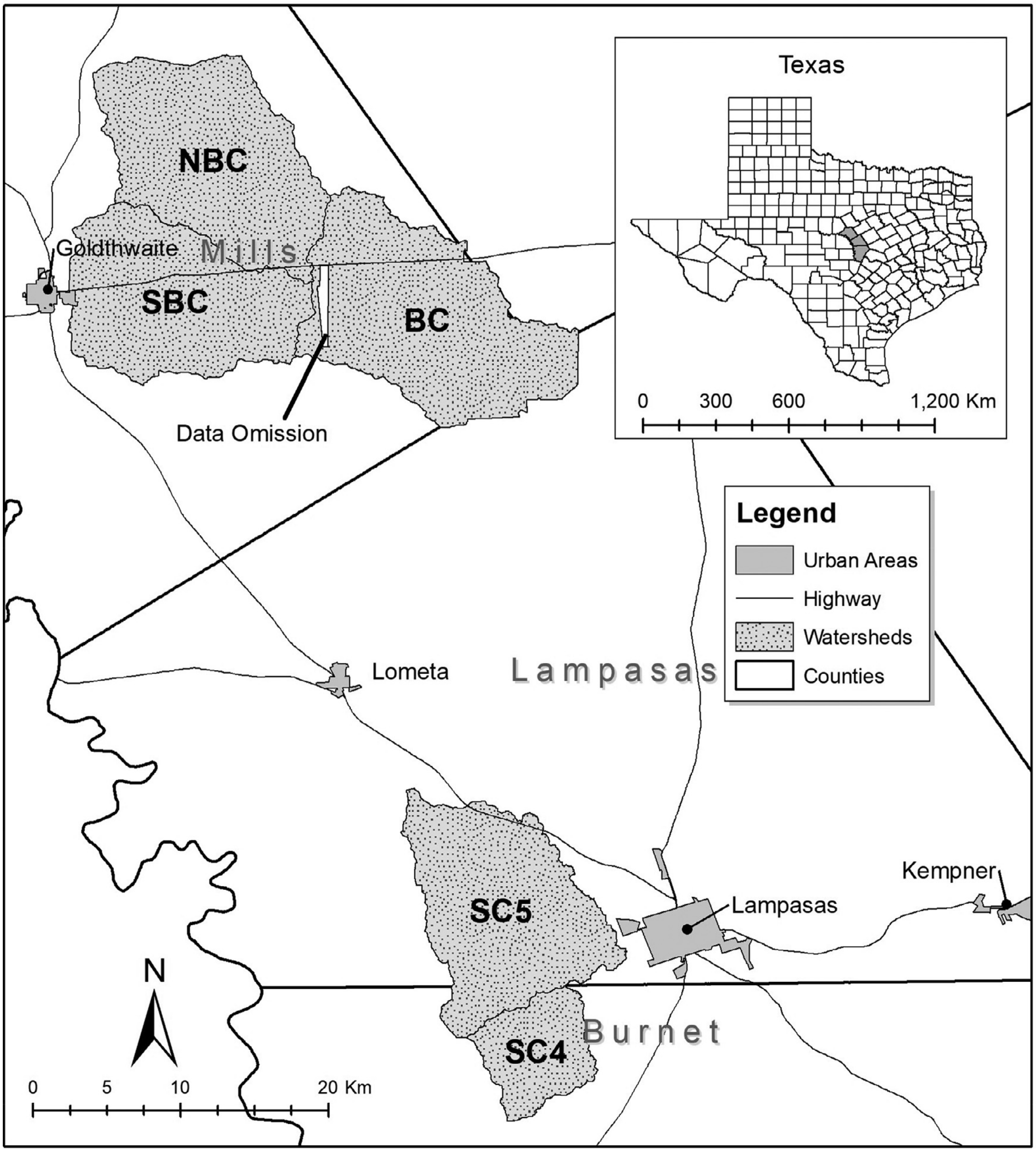


Figure 1. Study area. The five watersheds are located in central Texas in Mills, Lampasas, and Burnet Counties. BC indicates Bennett Creek; NBC, North Bennett Creek; SBC, South Bennett Creek; SC4, Sulfur Creek 4; SC5, Sulfur Creek 5. Note the hole in Bennett Creek (BC) watershed coverage due to missing/incomplete data.

much woody cover was present in the past? Did brush management practices implemented in the region follow 20th century land management paradigms? How has the landscape responded since then; were there any other localized factors that may have contributed to the woody plant expansion or decline; and how much of the initial woody cover (from the beginning of the available spatial data) remains?

Methods

Study Area

For this study, we selected five watersheds located in Lampasas, Burnet, and Mills Counties of central Texas (Fig. 1). As of the 2010 US Census, Mills County had a total population of 4 936, while Lampasas and Burnet had 19 677 and 42 750, respectively (US Census Bureau 2019). These five watersheds are within the Lampasas Cut Plain and are identified as Bennett Creek (BC), North Bennett Creek (NBC), South Bennett Creek (SBC), Sulphur Creek 4 (SC4), and Sulphur Creek 5 (SC5). The Bennett Creek watersheds are primarily located in Mills County, while the Sulphur Creek Watersheds span Lampasas and Burnet Counties.

The Lampasas Cut Plain of central Texas is located within the US Environmental Protection Agency Limestone Cut Plain Ecoregion (Griffith et al. 2007). This area is a transitional zone between the prairies and woodlands of north Texas and the Edwards Plateau region of central Texas (Berg et al. 2016), where mean annual precipitation is 746 mm (NOAA CPC 2018). Precipitation follows a bimodal pattern, with peaks in May and October. The Lampasas Cut Plain is marked by shallow soils over a limestone substrate. Lowland areas typically contain grasslands; however, some areas may include pasture and cropland (Griffith et al. 2007). The mesas are capped by Edwards Limestone and support oak and juniper savannah (Griffith et al. 2007). Dominant woody vegetation throughout

Table 1
Acquired imagery metadata.

County	Image yr	Acquisition Date	Image type	Source	Cell size (m)
Mills	1938	Dec 1937-Nov 1938	BW	P2	0.40
	1958	Dec 1957-Nov 1958	BW	APFO	0.51
	1975	Nov 1975	BW	APFO	1.02
	1980	Nov 1980	BW	P2	0.63
	1995	Jan 1995	CIR	P2	1.01
	2004	Dec 2004	CIR	NAIP	1.00
	2008	Sept-Nov 2008	NC/CIR	NAIP	1.00
	2012	Oct 2012	NC	NAIP	1.00
	2014	Jul 2014	NC	NAIP	1.00
	2018	Oct-Nov 2018	M4B	NAIP	0.60
Burnet/Lampasas	1940	Feb-Apr 1940	BW	P2	0.45
	1958	Dec 1957-Nov 1958	BW	APFO	0.24
	1974	Feb 1974	BW	APFO	1.02
	1982	Dec 1982	BW	P2	0.90
	1995	Jan-Feb 1995	CIR	P2	1.01
	2004	Sept-Dec 2004	CIR	NAIP	1.00
	2008	Sept-Nov 2008	NC/CIR	NAIP	1.00
	2012	Oct 2012	NC	NAIP	1.00
	2014	Jul 2014	NC	NAIP	1.00
	2018	Oct 2018	M4B	NAIP	0.60

BW indicates black and white; CIR, color infrared; NC, natural color; M4B, 4-Band; P2, P2 Energy Solutions; APFO, USDA Aerial Photography Field Office; NAIP, USDA National Agriculture Imagery Program.

the region includes the evergreens Ashe juniper (*Juniperus ashei* J. Bucholz) and escarpment live oak (*Quercus fusiformis* Small) and the deciduous shrub honey mesquite (*Prosopsis glandulosa* Torr.) (Griffith et al. 2007; Berg et al. 2016). This region is mostly rural, with a few scattered small communities. Primary drivers of the local economy are agribusiness, tourism, and hunting leases (Alvarez and Plocheck 2017).

Imagery

Historical aerial imagery was acquired from the USDA Farm Service Agency's Aerial Photography Field Office (APFO), the USDA NAIP, and P2 Energy Solutions (formerly Tobin International). Imagery dates ranged from 1938 to 1940 to 2018 and are composed of black and white, natural color, color infrared, and four-band images (Table 1). Fall and winter imagery was preferred to take advantage of senescent herbaceous vegetation contrasting against the predominately evergreen woody overstory. Hard copy imagery from APFO and P2 Energy were digitally scanned and georectified to 2004 NAIP imagery ($<$ 1 m error). All imagery was resampled to 1-m resolution using nearest-neighbor, converted to grayscale, and finally smoothed by a 3×3 kernel low-pass filter to reduce noise (Laliberte et al. 2004). Due to an isolated combination of poor image quality and missing slivers of coverage in a portion of the BC watershed, we chose to remove that spatial extent from each year within the dataset for consistency (see Fig. 1).

Woody Cover Classification

Woody cover was delineated via object-oriented classification using the Example-Based Feature Extraction tool in ENVI 5.2. This was a supervised classification, using the support vector machine (SVM) algorithm to identify and classify objects. One major drawback to historical panchromatic (black and white) imagery is that it lacks the additional spectral data required to identify woody plants by species (Browning et al. 2009). Fortunately, the ability to classify vegetation as woody/nonwoody in panchromatic imagery has been shown to be comparable with classifications with modern imagery (Browning et al. 2009). Therefore, all images were classified into two classes: woody and nonwoody. The nonwoody classification included anything not deemed to be woody vegetation, such as roads, surface water, farmland, pasture, rangeland, and impervious surfaces. Classification accuracy was assessed via a random stratified sampling of 100 points from each class (woody, nonwoody) per watershed for each of the available years. Classifications were deemed accurate if the point correctly identified woody or nonwoody objects.

Patch/Landscape Metrics

Landscape patch metrics were calculated using FRAGSTATS version 4.2 (McGarigal et al. 2012). FRAGSTATS is a freely available landscape metrics computation program, provided through the University of Massachusetts, that is capable of calculating dozens of landscape metrics. Ritters et al. (1995) established that fewer indices are often better, as many of them are redundant in nature. Cain et al. (1997) further demonstrated that measures of diversity, texture (contagion), and fractal dimension were more reliable measures of patch structure. Metrics that were generated in this study for each year of imagery included number of patches (NUMPAT), patch density (DENS), percentage of land area (PLAND), area-weighted mean patch size (AWPAT), area-weighted mean shape (AWSHP), area-weighted fractal dimension (AWFRAC), and contagion (CONTAG).

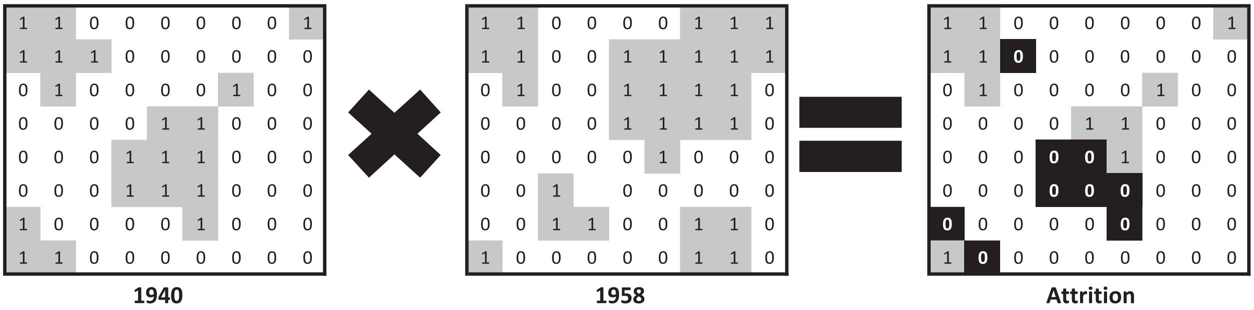
NUMPAT, DENS, and PLAND are simple metrics used to classify the number, density, and percent of total land area of a patch type. Area-weighted means were chosen for patch size, shape, and fractal dimension as they are landscape-centric rather than patch-centric metrics and represent the conditions of a raster cell chosen at random (McGarigal 2015). AWPAT, also referred to as correlation length, represents the distance one may travel along a random vector within a patch before encountering a new patch type (Keitt et al. 1997; McGarigal 2015). AWSHP is a widely used landscape metric designed to measure the complexity of patches (Forman and Godron 1986). AWSHP is a limitless metric, where a value of 1 would represent a square patch. The AWSHP value increases with increasing patch complexity. AWFRAC is a more robust measure of shape complexity. Simple geometry with a straight-line boundary, such as a circle or a square, will have a value of 1, while increasingly complex shapes will approach an AWFRAC value of 2, where nearly the entire area consists of boundaries (Mandelbrot 1977; Krummel et al. 1987; Forman 1995; McGarigal 2015). CONTAG is inversely related to edge density and is an often-used measure of patch aggregation, or clumpiness (Turner 1989; McGarigal 2015). As CONTAG approaches zero, the patch types are completely dispersed (i.e., every single cell is a different patch type). As CONTAG increases, large patches begin to form, until CONTAG reaches 100, where a single patch type would dominate (Li and Reynolds 1993; McGarigal 2015). The methodologies of each metric may be found in the FRAGSTATS documentation (McGarigal 2015).

Woody Cover Attrition

Woody plant cover attrition from 1938/1940-2018 was estimated by assigning each raster cell a value of 1 (woody) or 0 (nonwoody). Using map algebra in ArcGIS 10.3, a simple multiplication was made beginning with the first 2 yr of data (i.e., 1938×1958). The resulting output raster was then multiplied against 1974, and so forth. Cells that remained woody throughout the entire 1938/40-2018 timeframe would maintain its cell value of 1 throughout all multiplications (Fig. 2).

Land Use History

Finally, available historical livestock (cattle, sheep, and goat) populations, farm size, and number of farms were obtained from the USDA Census of Agriculture for the yr 1935–2012



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0	0	0	1	1	1	0	0	0
0	0	0	1	1	1	0	0	0
1	0	0	0	0	1	0	0	0
1	1	0	0	0	0	0	0	0

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0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0

Figure 2. Woody plant cover attrition was calculated by multiplying successive rasters against one another, where a cell value of 1 signifies woody plant cover and 0 nonwoody. Through each iteration, what remained of the original woody plant cover dwindled.

Table 2
Image classification accuracy (%) based on identification of 100 randomly generated points per class per watershed.

Yr	Watershed														
	BC			NBC			SBC			SC4			SC5		
	W	NW	OVR	W	NW	OVR	W	NW	OVR	W	NW	OVR	W	NW	OVR
1938/40	89	100	94.5	84	97	90.5	92	96	94.0	80	100	90.0	86	98	92.0
1958	92	97	94.5	83	99	91.0	89	95	92.0	94	88	91.0	87	100	93.5
1975	90	99	94.5	86	95	90.5	87	96	91.5	87	98	92.5	92	97	94.5
1982	88	99	93.5	80	93	86.5	74	96	85.0	90	93	91.5	91	93	92.0
1995	74	98	86.0	75	97	96.0	83	99	91.0	92	97	94.5	85	96	90.5
2004	94	98	96.0	85	97	91.0	96	97	96.5	98	92	95.0	90	100	95.0
2008	95	100	97.5	96	98	97.0	97	94	95.5	99	92	95.5	96	99	97.5
2012	93	96	94.5	95	97	96.0	96	98	97.0	97	96	96.5	90	95	92.5
2014	96	96	96.0	96	99	97.5	95	97	96.0	95	97	96.0	97	99	98.0
2018	91	100	96.5	98	97	97.5	94	95	94.5	98	92	95.0	97	93	95.0

W indicates woody; NW, nonwoody; OVR, overall accuracy; BC, Bennett Creek; NBC, North Bennett Creek; SBC, South Bennett Creek; SC4, Sulfur Creek 4; SC5, Sulfur Creek 5.

Table 3
Attrition of woody cover from 1938/1940 through 2018. Values are in percent of 1938/1940 cover remaining.

Yr	BC	NBC	SBC	SC4	SC5
1938/40	100.00	100.00	100.00	100.00	100.00
1958	37.83	54.63	25.09	31.96	49.56
1975	22.08	22.75	10.93	18.24	22.49
1982	16.62	15.50	6.62	15.42	17.68
1995	11.82	12.37	8.13	12.90	14.75
2004	10.02	10.40	4.58	11.50	12.93
2008	9.11	9.21	4.11	10.93	11.72
2012	7.47	6.69	3.05	10.19	10.19
2014	7.33	6.48	2.93	9.88	9.84
2018	6.17	5.82	2.68	9.05	9.10

BC indicates Bennett Creek; NBC, North Bennett Creek; SBC, South Bennett Creek; SC4, Sulfur Creek 4; SC5, Sulfur Creek 5.

(USDA-NASS 2014). Animal unit equivalents were also calculated and summed across all three classes (NRCS 2020) to provide a consistent metric of grazing presence on the landscape. Historical data on livestock types, populations, and farm demographics may aid in deciphering woody cover dynamics over time.

Results

Image Classification

Classification accuracy for all watersheds was high (Table 2). Overall map accuracy in 47 of the 50 image classifications were > 90 %; the remaining three were > 85%. Woody cover class accuracy was > 90% for 32 images, 80–89% for 14 images, and 74–75% for three images. The three lowest woody classifications occurred in 1995 and 1982 imagery. Classification accuracy of nonwoody objects was quite high, with 49 classifications above 92% and a single classification of 88%.

Total Woody Plant Cover and Patch Metrics

Class and landscape level metrics for all watersheds are available in Figures 3 and 4. The three Bennett Creek watersheds had a net loss of woody cover from 1938 to 2018, while the Sulphur Creek watersheds had a net increase (see Fig. 3, A). However, the timeframe in between is marked with periods of woody cover decline and regrowth. All but one watershed (SC5) had declines in total woody cover from 1938 to 1940 to 1958. Woody plant cover began to rebound between 1958 and 1975 for BC, SBC, and SC4, while woody cover for NBC and SC5 began to increase after 1975. NBC and SBC follow similar trends of rebound and decline post 1995, as do SC4 and SC5. BC is an outlier among all of the watersheds, as the woody plant cover has remained near or below 20% since 1958.

Area-weighted fractal dimension was variable between the watersheds (see Fig. 3, B). All five watersheds declined from 1938 to 1940 to 1975. After 1975, the Bennett Creek and Sulphur Creek watersheds diverge. The three Bennett Creek watersheds all reach their lowest fractal dimension in 2008 and begin rising back up through 2018. SC4 and SC5 remained more stable through the 1980s and 1990s and begin to climb in 2012. Contagion values for all watersheds ranged from 40.5 to 67.89 (see Fig. 3C). Contagion increased from 1938 to 1940 to 2018 for all Bennett Creek watersheds and declined across the Sulphur Creek watersheds (see Fig. 3C).

Number of patches and patch density increased for all five watersheds, illustrating that the landscape is more segmented and patchier in 2018 than in 1938/1940, regardless of whether woody cover increased (SC4, SC5) or decreased (BC, NBC, SBC) over the previous 7 decades (see Fig. 4A and 4B). Area-weighted mean patch size was variable throughout the time series as patches coalesced and fragmented (see Fig. 4C).

Area-weighted mean patch shape was also variable between the watersheds (see Fig. 4D). All three Bennett Creek watersheds began with high shape complexity in 1938/1940 and declined initially as woody cover was reduced early on. NBC and SBC have maintained relatively low patch complexity since 2004, while BC has had a moderate level of shape complexity rebound. The Sulphur Creek watersheds have slightly increased their shape complexity over time.

Woody Plant Attrition

Data for woody plant cover attrition are found in Table 3 and Figure 5. From 1938/1940 to 1958, approximately 45–75% of the original woody cover had been displaced. By 1975, the initial woody cover had been reduced by 77–89%. The rate of attrition

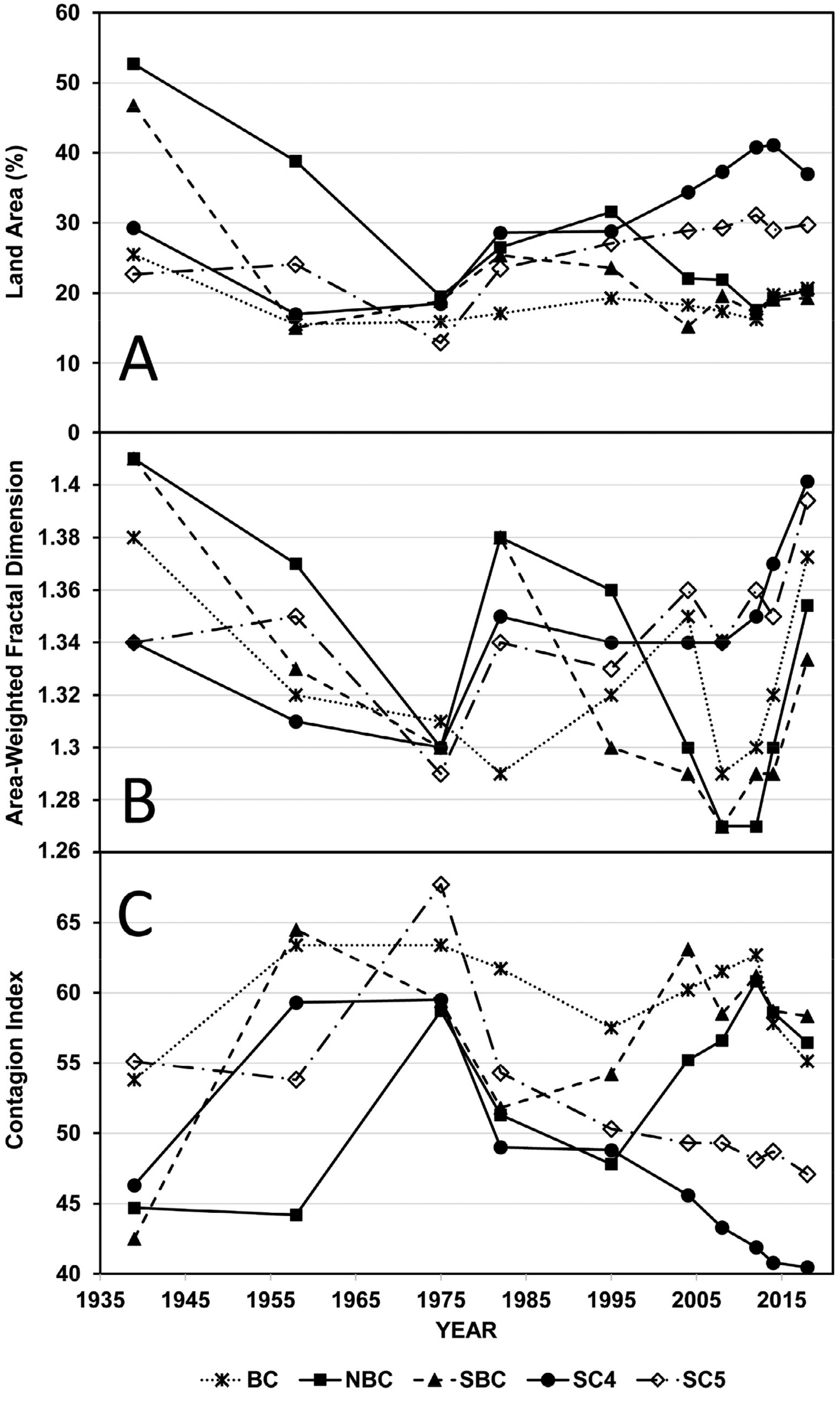

Figure 3. FRAGSTATS-generated metrics. **A,** Percent land area of woody vegetation. **B,** Area-weighted fractal dimension. **C,** Contagion index. BC indicates Bennett Creek; NBC, North Bennett Creek; SBC, South Bennett Creek; SC4, Sulfur Creek 4; SC5, Sulfur Creek 5.

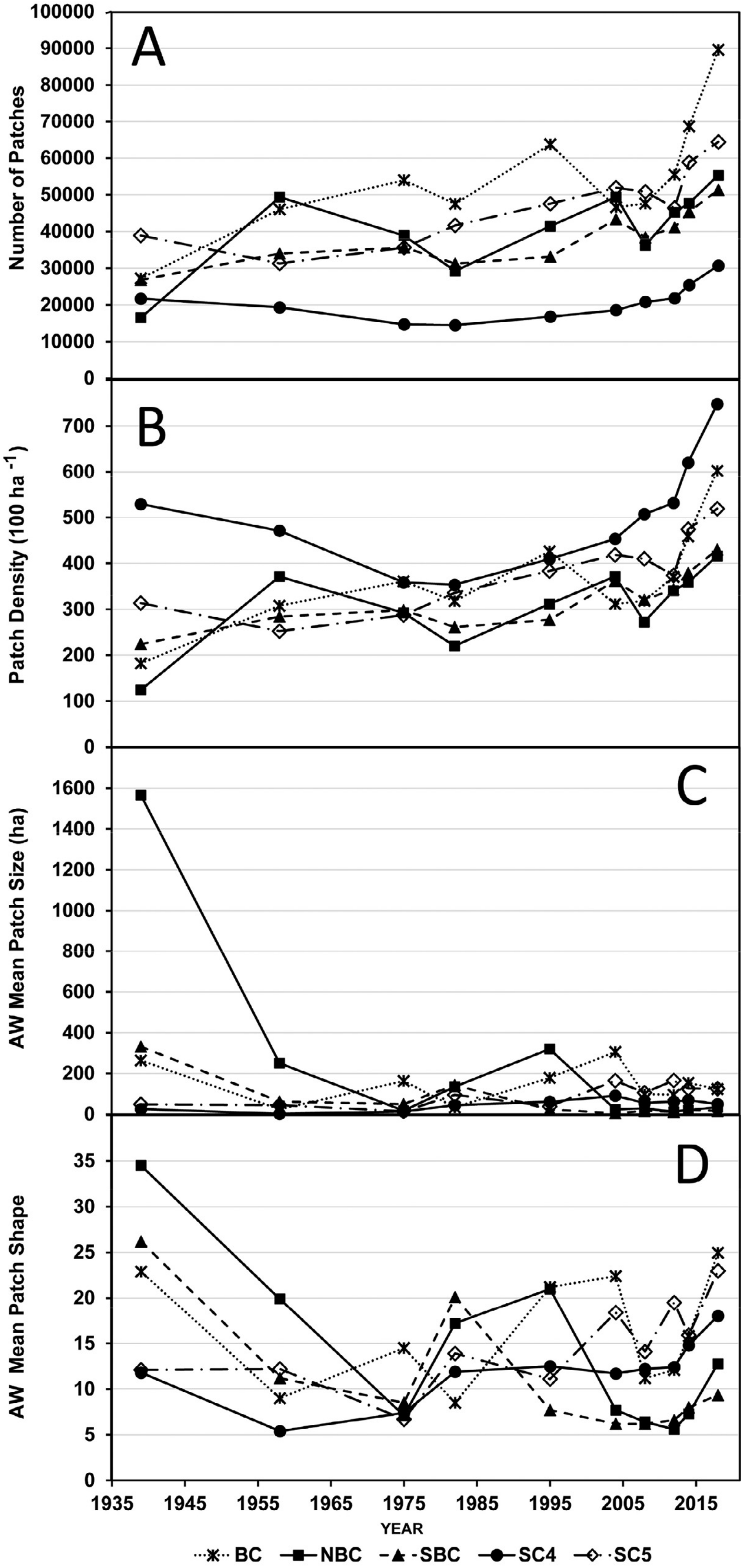

Figure 4. FRAGSTATS-generated metrics. **A,** Total number of patches. **B,** Patch density. **C,** Area-weighted mean patch size in hectares. **D,** Area-weighted mean patch shape. BC indicates Bennett Creek; NBC, North Bennett Creek; SBC, South Bennett Creek; SC4, Sulfur Creek 4; SC5, Sulfur Creek 5.

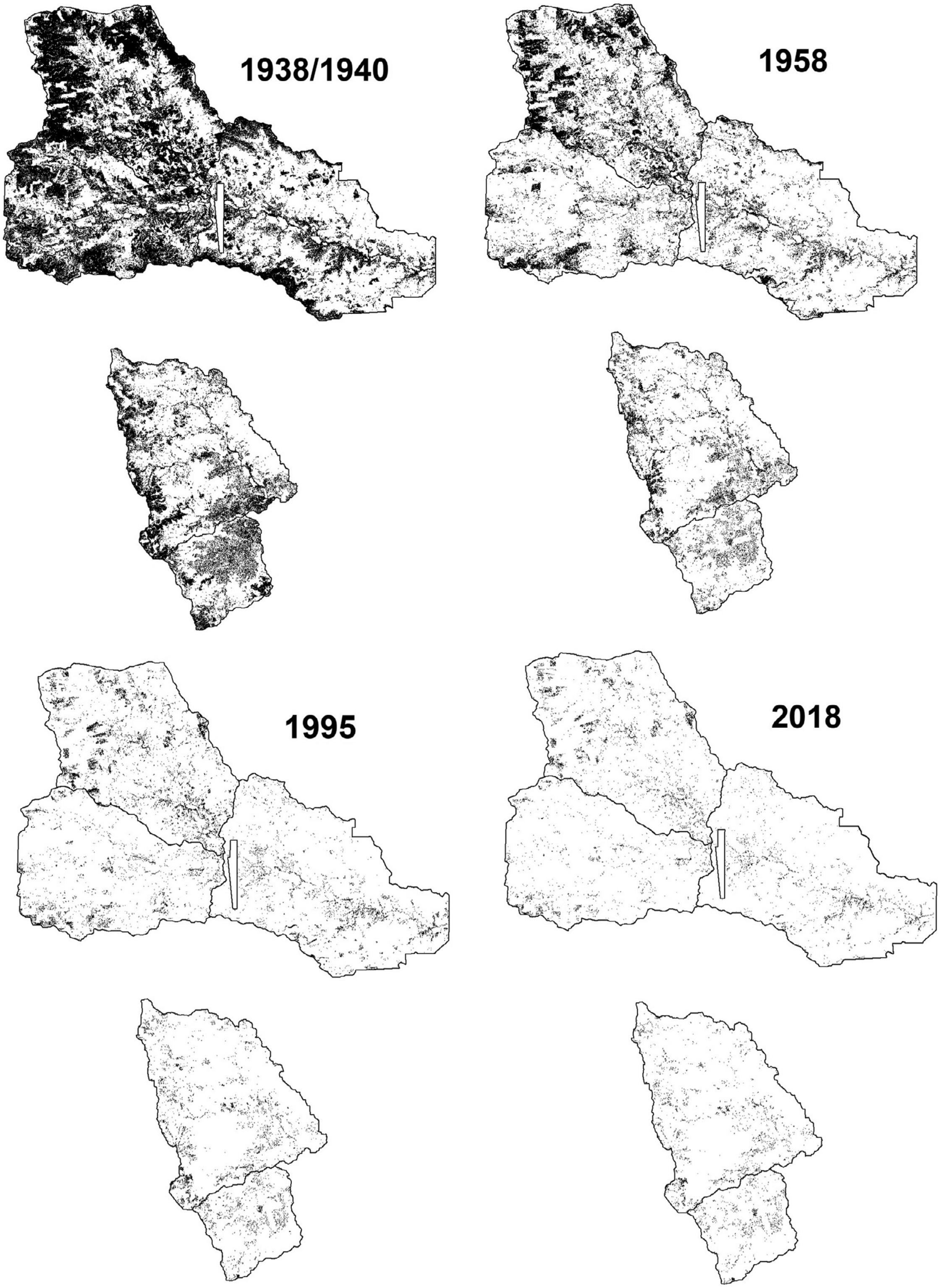

Figure 5. Woody plant cover attrition as seen at 1938/1940 (top left), 1958 (top right), 1995 (bottom left), and 2018 (bottom right). Black areas represent woody plant cover that has not been lost between 1938 to 1940 and 2018.

begins to slow by 1982, where, by 2018 each watershed contains < 10% of the original 1938/1940 woody plant cover.

Livestock Population and Farm Size

Livestock population and average farm size for Mills, Lampasas, and Burnet Counties are found in Figure 6. Mills County historically had a high number of sheep and goats as the primary herbivores. The sheep population reached a maximum of 133 737 head in 1940, while the goat population peaked in 1964 at 118 009 (see Fig. 6A). Sheep and goat populations in the 2012 census were 34 294 and 23 325, respectively. The cattle population has varied from a low of 16 279 in 1940 to a maximum of 48 901 in 1978 (see Fig. 6A). In 2012, there were 32 663 head of cattle in the county. To-

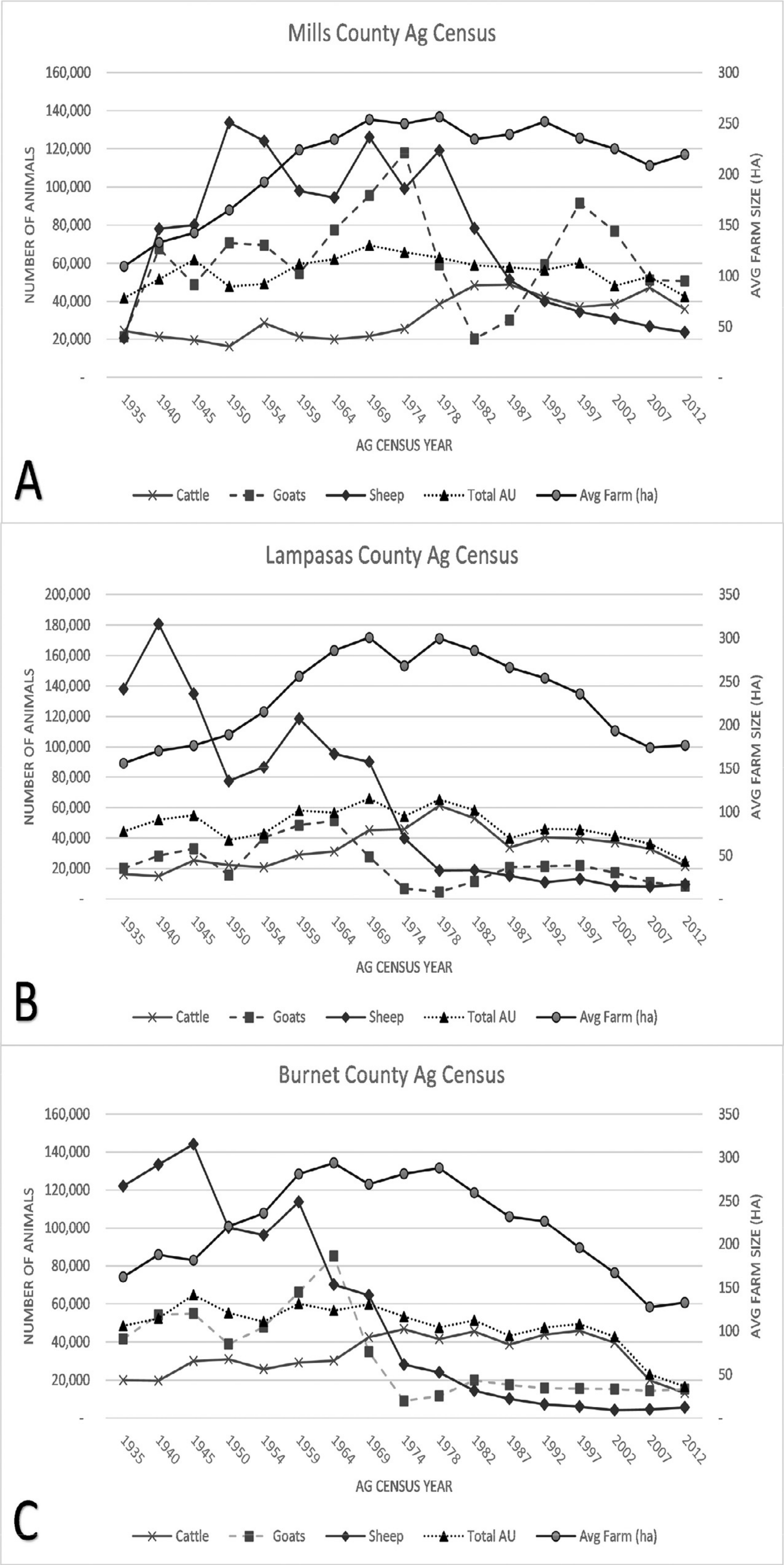

Figure 6. US Department of Agriculture National Agriculture Statistics Service (NASS) data for **A,** Mills, **B,** Lampasas, and **C,** Burnet Counties. Individual livestock classes are reported as total number of head. Total animal unit *(AU)* was derived from NRCS conversion estimates for Texas. Average farm size is in hectares.

tal animal units (AUs) were 41 745 in 1935, peaking in 1969 at 69 429, and decreasing to 42 568 in 2012. Average farm size gradually increased from 109 ha in 1935, reaching a maximum of 256 ha in 1978 and decreasing to 219 ha by 2012.

Lampasas and Burnet Counties had similar sheep population trends compared with Mills County (see Figs. 6B and 6C). Sheep numbers peaked in Lampasas County in 1940 at 180 731 and in Burnet County in 1945 at 144 120 head (see Figs. 6B and 6C). Goats were less prevalent here than in Mills County, with maximum populations of 51 453 in 1969 and 85 110 in 1964 for Lampasas and Burnet Counties, respectively (see Figs. 4B and 4C). By 2012, goat populations had been reduced to 8 576 and 15 208, respectively (see Figs. 6B and 6C). The cattle populations in Lampasas County have ranged from 16 255 in 1935 to 21 636 in 2012, with a maximum of 61 232 in 1978 (see Fig. 6B). Burnet County followed a similar trend of rise and decline, beginning with 19 889 head of cattle in 1935, peaking in 1978 at 46 786 and dropping to 13 175 in 2012 (see Fig. 6C).

Both Lampasas and Burnet Counties had dramatic reductions in total animal units from 1935 to 2012 (see Figs. 6B and 6C). Lampasas County had 44 317 AU in 1935, reaching a maximum 65 906 AU in 1969 and declining to 24 747 AU in 2012. Burnet County began with 48 523 AU in 1935, climbing to 60 168 in 1959, and ending with 16 629 in 2012.

Average farm size for Lampasas and Burnet Counties tracked closely together (see Figs. 6B and 6C). Lampasas County went from an average farm size of 156 ha in 1935 to a maximum of 301 ha in 1969 and dropping to 177 ha in 2012 (see Fig. 6B). Burnet County began at an average farm size of 162 ha in 1935, peaking at 294 ha in 1964 and declining to 133 in 2012 (see Fig. 6C).

Discussion

During the period of this study, the Bennett Creek watersheds all had an overall net decrease in total woody plant cover, while Sulphur creek had a net increase. However, these snapshots in time often do not tell the whole story. Each watershed did have a demonstrable reduction in total woody cover up to 1982, with the greatest decline occurring from 1938 to 1958. This is indicative of the post–World War II mindset of brush eradication on rangelands coupled with the newfound availability of heavy machinery and harvesting of juniper for fence posts. A local subculture supplanted from Appalachia to central Texas, known as the “Cedar Cutters,” cut and sold juniper wood—first for charcoal and later for fence posts as barbed wire became popular (Cartwright 1966; Patoski 1997; Ferguson 2019). Conversion of wooded areas to cropland was less likely to occur in these counties, as there was a rapid decline in total cropland area during the same period (Ramankutty and Foley 1999; Berg et al. 2016), so the removal of brush was likely for grazing land management and wood harvesting.

Between 1958 and 1975, woody plant cover loss begins to stabilize and woody cover begins to slowly increase in most watersheds. This is consistent with changing attitudes toward the economics of “one-size-fits-all” land management practices (Allison and Rechenthin 1956), growing interest in managing rangelands for wildlife habitat (Hamilton et al. 2004), the shift from predominantly browsing animals (sheep and goats) to cattle (Brown and Carter 1998), a reduction in harvesting juniper for fence posts, and fragmentation of private property (Kjelland et al. 2007; Sorice et al. 2014; Berg et al. 2015).

From a patch dynamics perspective, there are some interesting points to consider (see Figs. 3 and 4). In the 2000s, there is a noticeable increase in the total number of patches (NUMPAT) and patch density (DENS), with little change to the total woody cover (PLAND). This is most likely indicative of landscape fragmentation as land ownership demographics, management strategies, and priorities are shifting. As land ownership is fragmented, new woody plant patches are carved from cross-fencing and other anthropogenic activities, so the expansion of some patches is mitigated by the dissection of others. This is also reflected in the contagion (CONTAG) index. As an overall metric of raster cell dispersion and aggregation, all values of CONTAG ranged from 40.5 to 67.7, demonstrating that the landscape was predominately made up of moderately sized patches. Area-weighted mean patch size has declined in the Bennett Creek watersheds, where total woody cover has decreased, but increased in the Sulphur Creek watershed, where total cover has had a net increase over time. Interestingly, the fractal index (AWFRAC) has remained relatively stable throughout the dataset, suggesting that the overall patch shape complexity has remained consistent through various management paradigms, though the number and sizes of patches has fluctuated.

Stabilization of woody plant cover in recent years may also be attributable to climatic shifts, where warmer, drier climates favor fewer shrubs. In southern Arizona, Huang et al. (2018) found that woody plant cover on long-term transects has stabilized at around 25% total cover. They were able to identify three distinct phases of woody plant cover; an expansion period from 1961 to 1991, a decline from 1992 to 1997, and finally stabilization from 1998 to 2012. Broad-scale woody plant stabilization was confirmed from assessing 28 yr of Landsat data spanning 1984—2011. This pattern of decline, regrowth, and stabilization is suggestive in the woody cover trends from the Bennett Creek watersheds, though not in the Sulfur Creek watersheds.

Differences in woody plant trends between the Bennett and Sulphur Creek watersheds may be attributable to the demographic variances between the two areas (Berg et al. 2016). Bennett Creek in Mills County is more rural, has a much lower human population, and a larger average farm size than Sulphur Creek in Lampasas and Burnet Counties. In the neighboring Cowhouse Creek watershed, Sorice et al. (2012) found that 39% of landowners owned their property solely for lifestyle reasons and only 24% of landowners used the land as their main source of income. Lifestyle landowners may be less likely to employ land management measures due to lack of knowledge or skillsets needed to appropriately implement them (Sorice et al. 2014). Factors impacting long-time agricultural operations include livestock market stability, cultural factors relating to land use, and the availability of labor (Hurst et al. 2017).

Total animal unit decline over time may be attributed to a few factors. Total AU climbed in each county as the average farm size also climbed and woody cover initially dwindled, suggesting that larger landowners may have been clearing newly acquired land to maintain larger herds. As the average farm size began to decline after 1978, the newer-lifestyle landowners likely kept fewer or no animals at all. In many cases, there may be instances where a small landowner would only have the minimum number of animals needed to maintain local agricultural property tax exemptions (Rowan 1994; Machen and Lyons 2000).

Woody plant cover attrition from 1938 to 1940 to 2018 has been substantive (see Table 3, Fig. 5). Across all five watersheds, 90–97% of the woody plant cover that was present in 1938 to 1940 has been lost or replaced. This is an important dynamic to consider in the context of woody plant encroachment, as nearly all of the woody plant cover present in 2018 is $<$ 80 yr old. Recent analysis of old growth juniper stands on protected areas in Texas state parks 90 km northeast of Goldthwaite (Bennett Creek) and 136 km southwest of Lampasas (Sulphur Creek) showed a mean age of 84 yr, with a handful trees reaching $>$ 147 yr old (McLemore et al. 2004). Archer and Bratton (2010) found that escarpment live oak trees in an old growth stand near Waco, Texas ranged from 27 to 171 yr old. Clearly, these woodlands could reach ages surpassing 100 yr or more given the opportunity; however, due to a combination of the aforementioned anthropogenic, environmental, and climatic variables, woody plant cover has been in a constant state of flux. Cover gained on one front has often been negated on another, presumably due to a combination of management actions and natural decline.

A potential issue when using historical aerial imagery is that the image capture technology of the time may have limitations on rendering detail. The ability of lenses to resolve detail has dramatically increased over time, and modern aircraft are equipped with forward-motion compensation systems (FCM) to reduce blurring of images while the camera shutter is open (Bozek et al. 2019). The dynamic range (the lightest lights and darkest darks) that can be recorded on early film is much narrower than that of modern digital sensors. Any part of a scene that is outside of this range will not be rendered properly and may lack textural detail (Robertson et al. 2003). Additional error may be introduced due to the decay of film negatives in storage or during the scanning of images. Our intent with converting modern images to grayscale was an attempt to equalize modern imagery and provide consistency temporally; however, it appears that even when converted to single-band imagery, modern imagery still generally performed better in image classification. The overall classification accuracy of historic and modern imagery was comparable, but modern imagery tended to have a higher woody class accuracy. All classifications were above the commonly cited benchmark of 85% for overall accuracy and 70% in-class accuracy (Thomlinson et al. 1999; Wulder et al. 2006), though this metric is more of a guideline that may not be applicable universally (Foody 2008; Stehman and Foody 2019). Nonetheless, the classification accuracy of historical aerial imagery performed quite well, likely due to having only two classes (Shao et al. 2019).

The nature of the raster algebra approach to calculating attrition may be prone to some error, as a single misclassified image could have implications for subsequent temporal iterations. However, we believe that this has been kept to a minimum due to the high overall and in-group classification accuracy of the imagery. Almost all classification errors identified were errors of commission within the woody classification. This would have the effect of slowing the observed rate of attrition in some cases, rather than accelerating it, since misclassified cells would be given a value of "1" in the raster multiplication process outlined in Figure 2. Nevertheless, this is a criterion that is worthy of more investigation.

Implications

This research underscores the importance of long-term datasets in the application and interpretation of land management trends over time. In this study, we found that past documented trends and paradigms in rangeland woody plant management are consistent with woody plant cover trends in this central Texas study area. Following drastic anthropogenic reductions of woody plant cover post World War II, many concurrent, more nuanced variables seem to be at play in the current state of woody plant dynamics. These range from private land fragmentation, changing human and livestock demographics, and climatic factors contributing to a relatively stable plant community over the past few decades. Studies that rely solely on change in total cover over time or that do not use multiple temporal stages may be missing important stand age and patch characteristics.

Some of the management measures used to remove woody plant cover may be easier to infer than others. For example, large-scale removal between 1938 and 1958 is most likely attributed to widespread availability and technological advances in heavy machinery during this period. However, as time goes on, discerning the exact type of management measure taken may prove difficult, as the management options have grown substantially to include not only mechanical ones but also herbicides, prescribed burning, and biological control. In the future, studies of this nature will benefit from an excess of multispectral imagery options with high temporal frequency, making inference of management treatments more readily available, potentially even in near real-time.

Given these lessons learned from the past, how will future management paradigms affect the decline or spread of woody plant cover? In addition, how can this information be used to better anticipate the long-term effects of management choices being made today, especially in the face of changing climate and demographics? Pairing remote sensing analysis with ground truthing of age structure will help verify measurements of attrition and provide indications of emerging trends. Finally, future research and development should include decision support tools and forecasting models to anticipate woody plant cover trends based on the influence of cultural, environmental, technological, economic, and climatic drivers on management perspectives.

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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