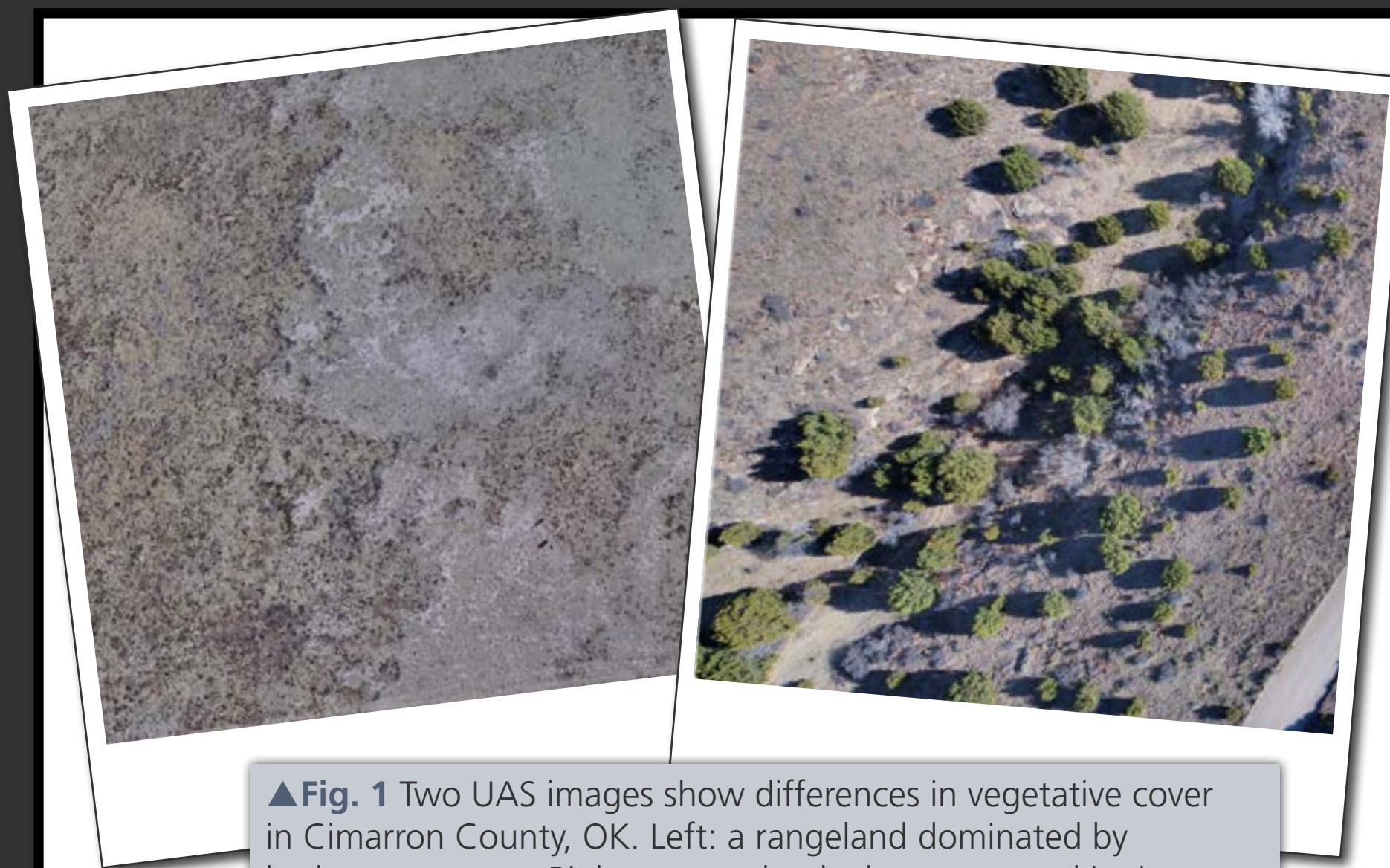




Climatic and Environmental Factors Influencing Parcel-Scale Woody Plant Encroachment in Cimarron County, Oklahoma

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▲ Fig. 1 Two UAS images show differences in vegetative cover in Cimarron County, OK. Left: a rangeland dominated by herbaceous cover. Right: a rangeland where one-seed juniper (*Juniperus monosperma*) has become established.

INTRODUCTION

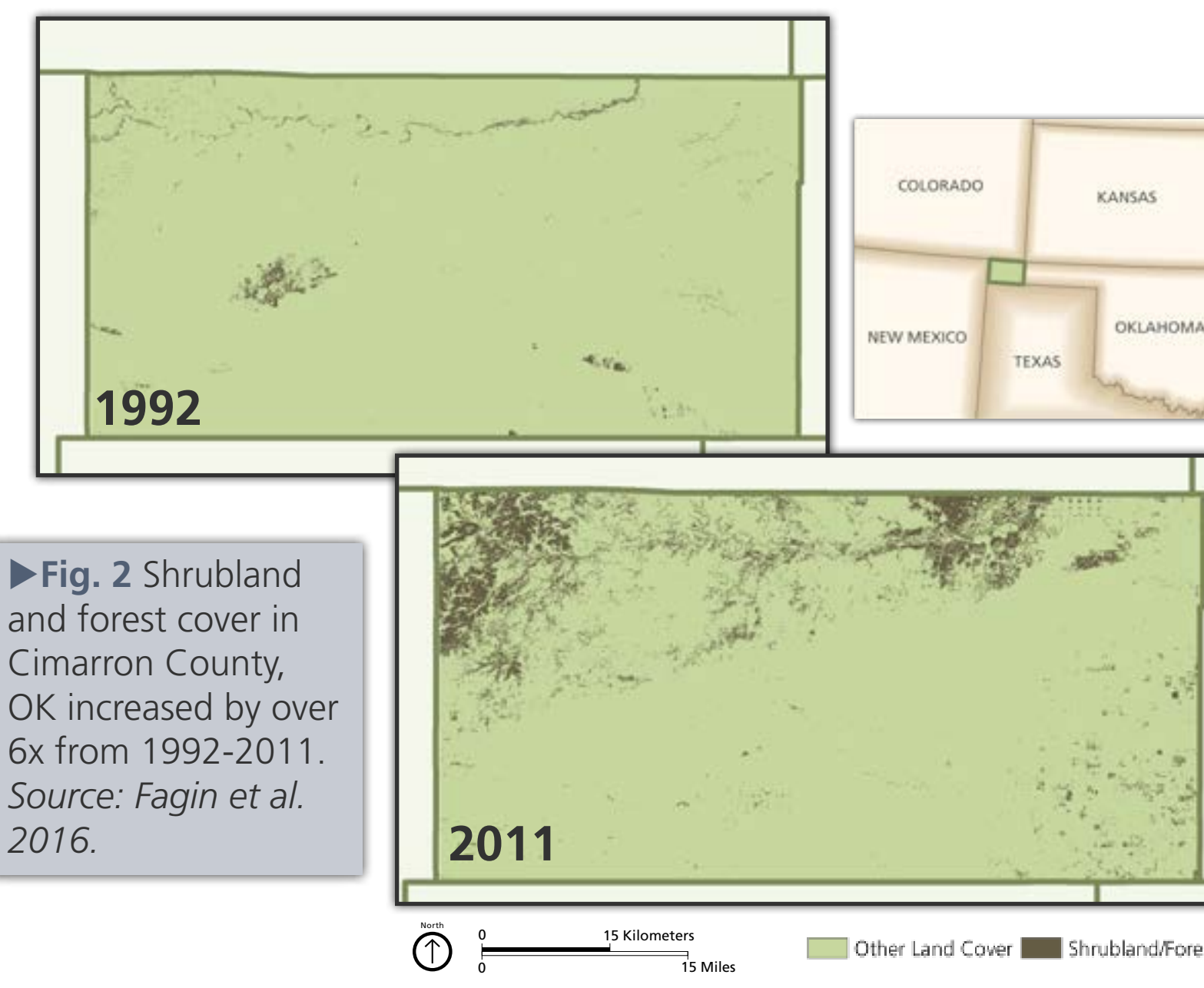
Woody vegetation in Cimarron County, OK has increased by more than 600% since 1992, presenting challenges for ranchers who rely on intact grasslands to graze cattle¹. While land tenure has been studied as a factor affecting woody plant encroachment (WPE) in the county, there has been less investigation of the role of environmental factors such as climate, soil, and topography. **Here, we ask to what extent environmental factors affect WPE in Cimarron County as a means of assessing landowner vulnerability.**

Cimarron County ranks in the top 1% of U.S. cattle producing counties² with an economy driven primarily by agriculture³. In light of cyclical droughts that have persisted since the historic Dust Bowl of the 1930s,

WPE serves as an additional environmental hazard (Fig. 2). The phenomenon has been associated with decreased cattle forage⁴, increased fire severity⁵, reduced stream flows⁶, and loss of groundwater resources through transpiration⁷. Thus, the issue afflicts both farmers and ranchers alike.

WPE has been observed globally⁸ and may be exacerbated by overgrazing⁹, fire suppression¹⁰, decreased biodiversity¹¹, and climate change¹². Notably, all of these processes are ultimately associated with anthropogenic change. Additionally, Fagin et al.¹ found WPE in Cimarron County was more severe on state leased lands, presumably because short-term leasing policies do not incentivize control or removal of trees and shrubs. While land

management practices certainly play a role, environmental characteristics such as climate and soils also place constraints on the where certain plants may grow¹³. Past research in other systems has found a relationship between WPE and drier climates¹³ and terrain ruggedness¹⁴. Additionally, drier sandy soils have been associated with greater shrub cover¹⁵. With a complex array of synergistic factors potentially influencing WPE severity, implementation of a spatial error regression can help elucidate the extent to which climate, soil, and terrain variables affect vegetation change in Cimarron County. These results have great relevance to landowners who may wish to assess their potential risk to WPE and make mitigating land use decisions.



► Fig. 2 Shrubland and forest cover in Cimarron County, OK increased by over 6x from 1992-2011. Source: Fagin et al. 2016.

METHODS

We sourced NLCD data from 1992 and 2011¹⁶, reclassified using methods described in Fagin et al.¹. We used raster algebra to find pixels where herbaceous cover converted to forest or shrubland, then used a square root transformation to obtain a normal distribution. We also obtained raster datasets at 30-second resolution from the WorldClim Climate Database¹⁷ for five climate variables:

- Annual Temp (μ)
- Annual Precip
- Temperature Seasonality (SD of temp)
- Precipitation Seasonality (CV of temp)
- Vapor Pressure (μ)

Additionally, we sourced soil data from the USDA SSURGO database¹⁸ to obtain the following soil variables:

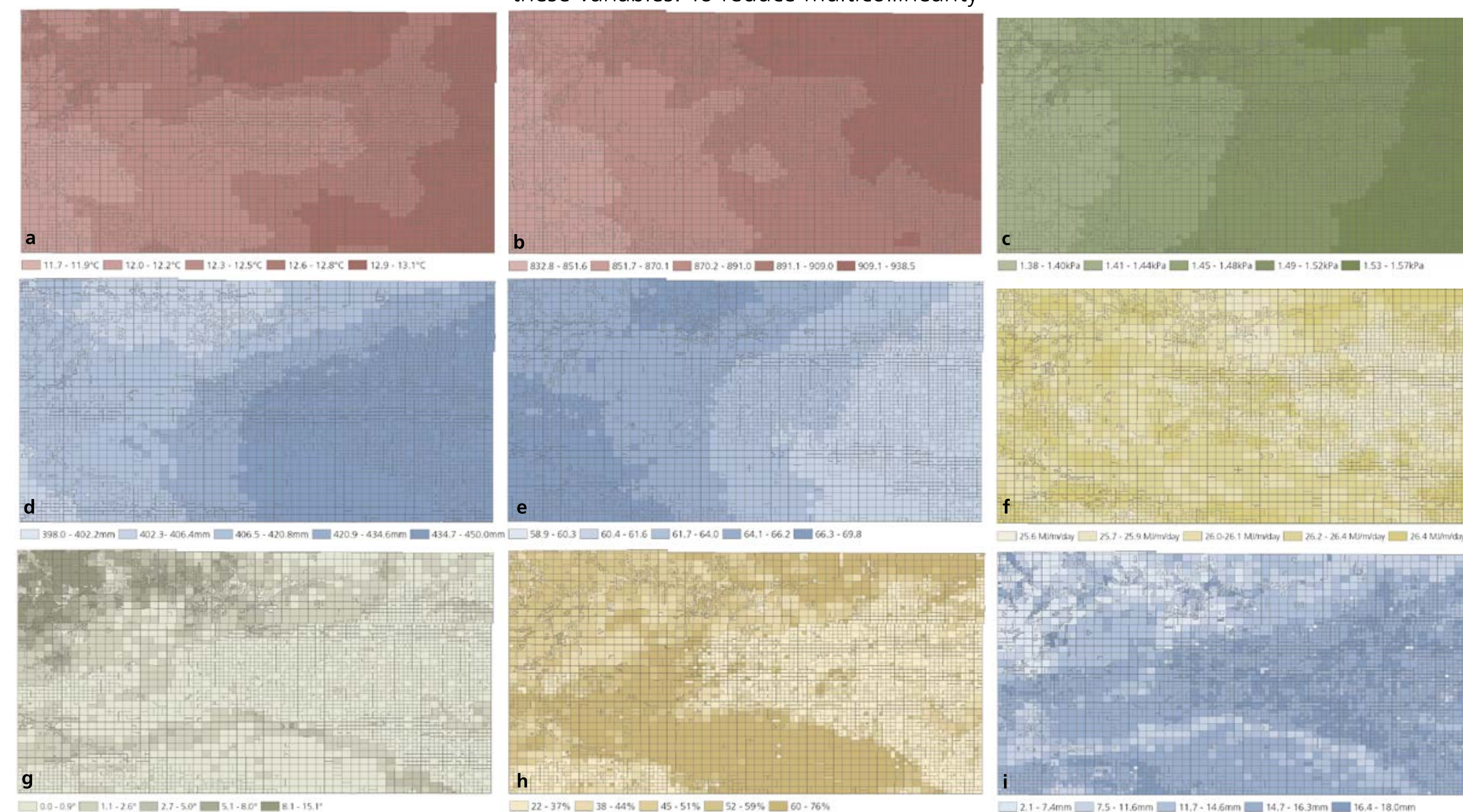
- Sand/Clay (%)
- Dominant Soil Order
- Available Water Storage (AWS)

We also used the USGS NED at 1/3 second resolution¹⁹ to create a slope map using the Slope tool in ArcGIS 10.4. Implementing Cimarron County land parcels (n=4,363) as our unit of study, we used the Zonal Statistics tool in ArcGIS 10.4 to aggregate values. Parcels are a logical unit, since land management practices affecting WPE can vary dramatically between neighbors, but environmental traits are generally consistent within such a small area. For each parcel, we calculated:

- Pixels changed to forest/shrubland (%)
- μ for climate variables
- μ % for soil components and available water supply
- Binary for presence of each soil order
- SD for slope (terrain ruggedness)

Climate variables tended to occupy very similar gradients across the county extent, resulting in ambiguity in the effects of these variables. To reduce multicollinearity

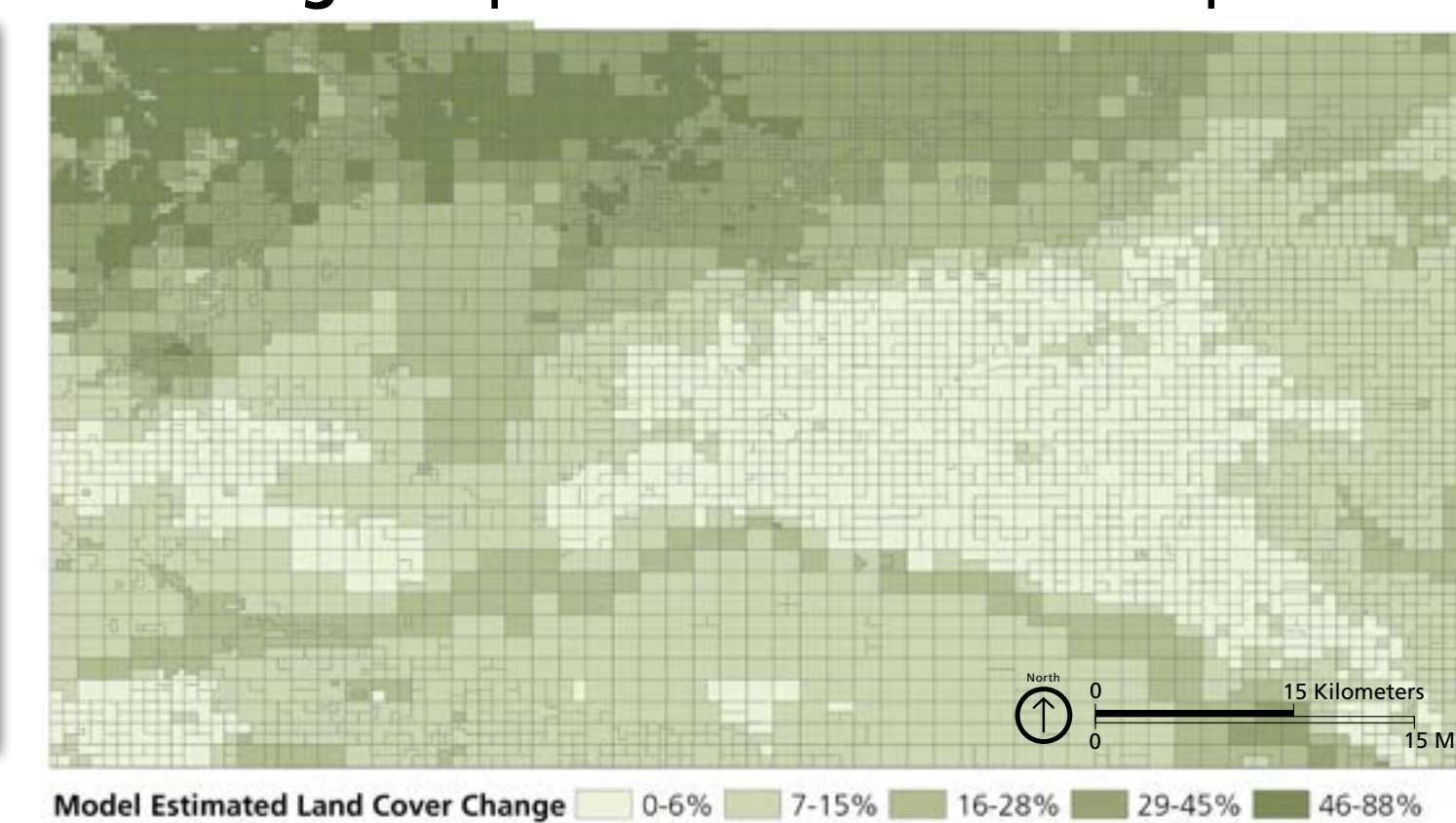
and increase parsimony, we implemented principal components analysis (PCA) in SPSS v25 to collapse climate variables into fewer components, using a varimax rotation to optimize component loadings. We selected components for our model that cumulatively accounted for at least 95% of variation in the data. We then created a linear regression special error model in Geoda 1.12 to explore the relationship between our environmental variables and the severity of WPE. The spatial error component, λ , accounts for spatial autocorrelation in the dependent variable and corrects for effects of unknown variables. Variables were added using a stepwise approach, with a significance threshold of $\alpha=.05$ and VIF>3 to control collinearity particularly in soils data. We selected the model that maximized R^2 , while minimizing standard error.



▲ Fig. 3 Environmental variables were aggregated within each parcel of land in the county. While there was typically very little variation within parcels, all variables exhibited a gradient of change at county scale. a) annual mean temperature, b) temperature seasonality (S.D. of temp), c) vapor pressure, d) annual mean precipitation, e) precipitation seasonality (C.V. of precip), f) solar radiation, g) terrain ruggedness (S.D. of slope), h) soil sand content, i) soil available water storage. Source: (a-f) WorldClim Global Climate Database (Hijmans et al. 2005), (g) USGS NED (2015), (h-i) USDA SSURGO.

RESULTS

Fig. 4: Spatial Error Model Output



► Fig. 4 The model accurately identified parcels in the northern extent of the county as the most vulnerable to woody plant encroachment, while cultivated areas in central/eastern portions of the county exhibited almost no WPE ($R^2 = .758$, $SE = 0.115$).

Table 1: Model Variables and Statistics

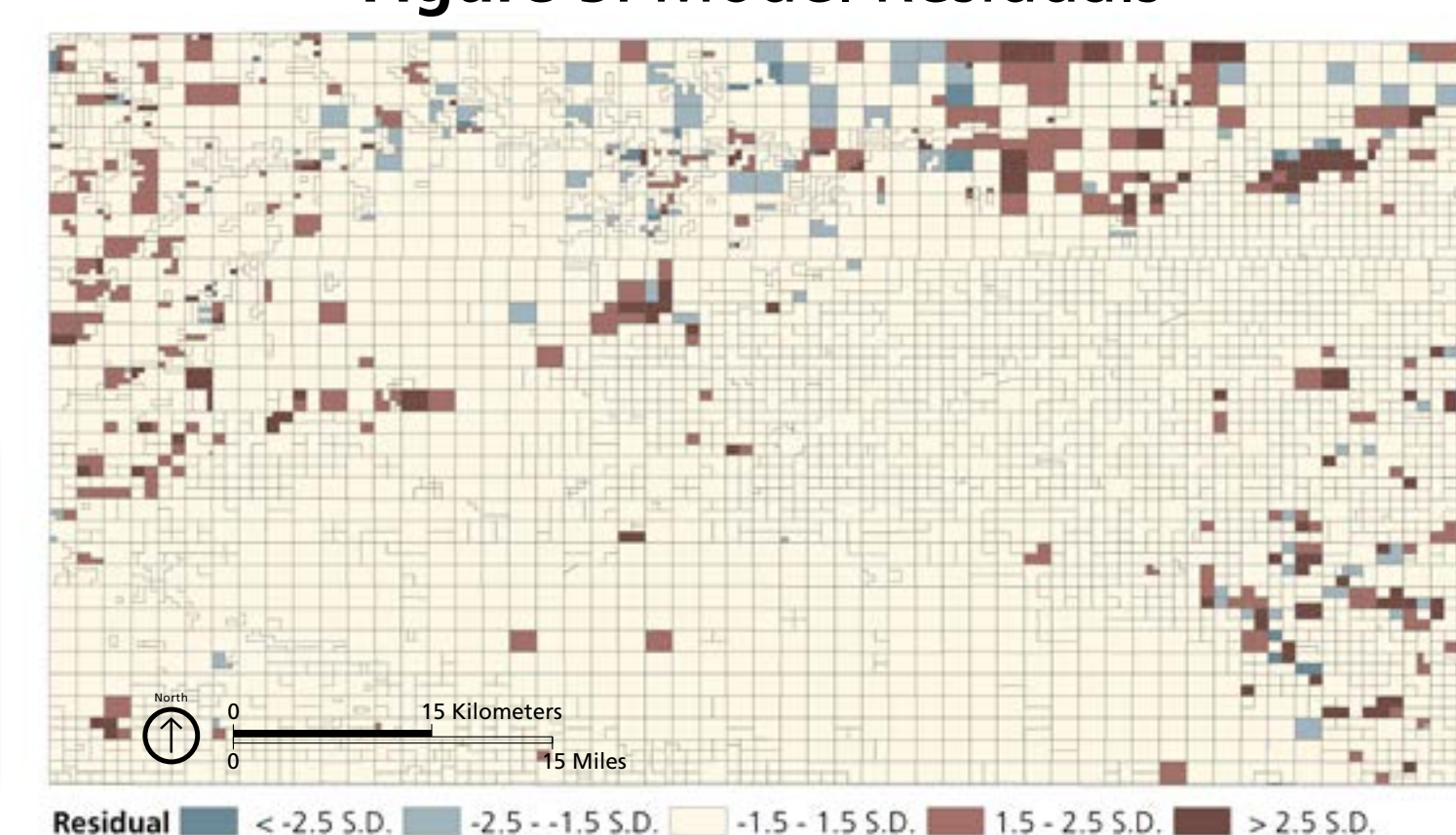
Variable	Coefficient	Std. Error
Constant	-8.38*	3.09
Percent Sand	0.06	0.03
Available Water Storage	-0.31**	0.09
PC1 (Temperature)	5.20**	0.46
PC2 (Precipitation)	-5.91**	5.20
Solar Radiation	0.01**	0.00
Slope Std. Deviation	4.14**	0.17
Lambda (Spatial Error)	67.84**	1.07

*p<.01, **p<.001. All variables were significant at p<.05

Table 2: PCA Variables and Loadings

Variable	Component Loadings		Extraction Communities
	1	2	
Annual Mean Temp	0.971	0.110	0.954
Annual Mean Precip	0.140	0.983	0.986
Temp Seasonality	0.888	0.374	0.927
Precip Seasonality	-0.507	-0.845	0.971
Mean Vapor Pressure	0.798	0.556	0.946

Figure 5: Model Residuals



► Fig. 5 The majority of the model's significant residuals occurred along the Dry Cimarron River Corridor. The presence of state leased lands in the area could be a factor; Fagin et al. (2016) demonstrated that land tenure significantly effects WPE severity even when accounting for topographic wetness index (TWI).

DISCUSSION & CONCLUSION

Environmental factors clearly were important influences of the spatial distribution of woody plant encroachment from 1992-2011. Areas exhibiting the most severe WPE were in warmer, drier, and more seasonally variable climates, and in well-draining sandier soils and rugged terrain. The findings are logical, given that most of Cimarron County's species of concern are chiefly plants adapted to dry, hot climates. Cholla (*Cylindropuntia imbricata*) yucca (*Yucca glauca*), for example, have thick, waxy skins to prevent water loss. One-seed juniper (*Juniperus monosperma*) is drought adapted and performs well in high-slope areas, with an extensive root structure that serves as an anchor in marginal, dry soils.

Of course, the model is limited by potential covariation between the environmental variables and the distribution of land use practices. Cultivated lands in Cimarron County tend to be distributed across the central and southeastern extents due to the higher quality soils. Conversely, rangeland dominates areas to the north and west. As a result, cultivated lands tend to be more heavily manipulated and therefore less prone to establishment of trees and shrubs. Therefore, we cannot say with certainty that soil and terrain are direct drivers of WPE, but rather they may be associated with agricultural practices that facilitate or impede tree and shrub growth. However, past research in areas with less land use variability have found similar results^{13, 15}.

Land ownership is also likely a confounding variable, as state-owned lands are mostly concentrated in the drier, more rugged northwestern corner of the county. Previous research¹ found greater WPE severity in state leased lands than privately owned lands, even when controlling for environmental variability through use of a topographic wetness index (TWI). Their analysis used randomly distributed points as analysis units, rather than parcels, and therefore may have captured the effects of finer-scale patterns. By contrast, land ownership did not contribute significantly to any versions of our model when experimentally added.

SCOPE & LIMITATIONS

Given the threats WPE poses to agriculturalists in the region, land managers should interpret the model results with moderation. Although environmental factors do explain a sizeable portion of WPE patterns, changes in land management practices can also have dramatic effects on reducing trees and shrubs on the landscape. These results may help landowners assess their vulnerability to potential WPE, while sustainable grazing practices, controlled burning, and occasional manual removal of trees and shrubs are necessary to ensure continued rangeland health.

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