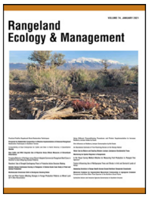
Rangeland Ecology & Management 88 (2023) 129–134

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: www.elsevier.com/locate/rama



Original Research

Prosopis velutina Response to Aerial Herbicide Application[☆]

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ARTICLE INFO

Article history:
Received 8 October 2022
Revised 13 February 2023
Accepted 27 February 2023

Key Words:
aminopyralid
clopyralid
eddy covariance
herbicide efficacy
triclopyr
velvet mesquite

ABSTRACT

Herbicides have been widely used to manage woody vegetation, but quantification of their effects is often lacking. We documented the impacts of a commonly used clopyralid + aminopyralid + triclopyr herbicide blend on *Prosopis velutina* Woot. in grazed Sonoran Desert grasslands in southern Arizona. Similar to other applications of comparable herbicide blends in the region, we recorded only modest and short-term impacts. *P. velutina* mortality was 7%. Foliar cover declined to 9.2% ± 0.80% the month following treatment and was comparable across size classes. Cover reductions persisted for ~2 yr, by which time it was comparable on treated and control plants (66.9% and 69.3%, respectively). On the basis of eddy covariance tower monitoring of carbon and water flux, soil temperature, and soil moisture, we suggest how knowledge of diurnal and seasonal changes in physiological activity (e.g., evapotranspiration, gross primary production) and environmental conditions may help identify more optimal times to apply herbicides to improve their efficacy. Future research should explore *P. velutina* response to herbicides at various levels of photosynthetic activity in response to soil temperature and soil moisture in the subtropical North American Monsoon climate system of the Sonoran Desert. From a broader ecosystems trophic perspective, our results also suggest a need to ascertain how herbicide-induced reductions in *P. velutina* pod and seed production may impact native herbivore communities.

Introduction

The ratio between woody and herbaceous vegetation has shifted in favor of unpalatable shrubs and woody weeds in recent decades in rangelands around the globe with myriad consequences for ecosystem function (Eldridge et al. 2011). The widespread conversion of grasslands and savannas to shrublands or woodlands has long been of concern to the ranching industry from a livestock production standpoint, but the realization that this land cover change has implications for other ecosystem services challenges us to adopt a broader perspective on this global phenomenon (Archer and Predick 2014). Management focused on reducing the abundance of woody vegetation is commonly known in the United States as brush management (Hamilton et al. 2004).

Prosopis spp. shrubs are among the world's most notorious woody invasive plant taxa (Shackleton et al. 2014). Accordingly, there is global interest in managing this genus. Aerially applied herbicides are widely used in brush management owing to their ability to readily reach remote areas and to cover extensive areas of rugged topography. Most herbicide research on *Prosopis* in the United States has been conducted on *Prosopis glandulosa* Torr. in the Southern Great Plains and Chihuahuan Desert ecoregions (Bovey 2001). *Prosopis velutina* Woot. dominates many landscapes in the Sonoran Desert ecoregion, where its abundance has increased markedly in semidesert grasslands since the early 1900s (McClaran 2003). Private landowners and public land managers in the Sonoran Desert have used herbicide formulations developed for *P. glandulosa* to manage *P. velutina*; however, there is little quantitative documentation of herbicide impacts on *P. velutina* mortality and recovery. Here, we report the effects of a commonly used herbicide blend on *P. velutina* with respect to foliar cover, seed pod production, basal sprouting, and mortality. To enhance interpretation of these response variables, we also present detailed flux

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[☆] This project was supported by the US Dept of Agriculture (USDA) NIFA 2015-67019-23314, Arizona Agricultural Experiment Station ARZT-3013240-G12-517, and USDA Long-Term Agroecosystem Research network. Mention of trade names/commercial products is solely for providing specific information and does not imply recommendation/endorsement by the USDA.

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https://doi.org/10.1016/j.rama.2023.02.014

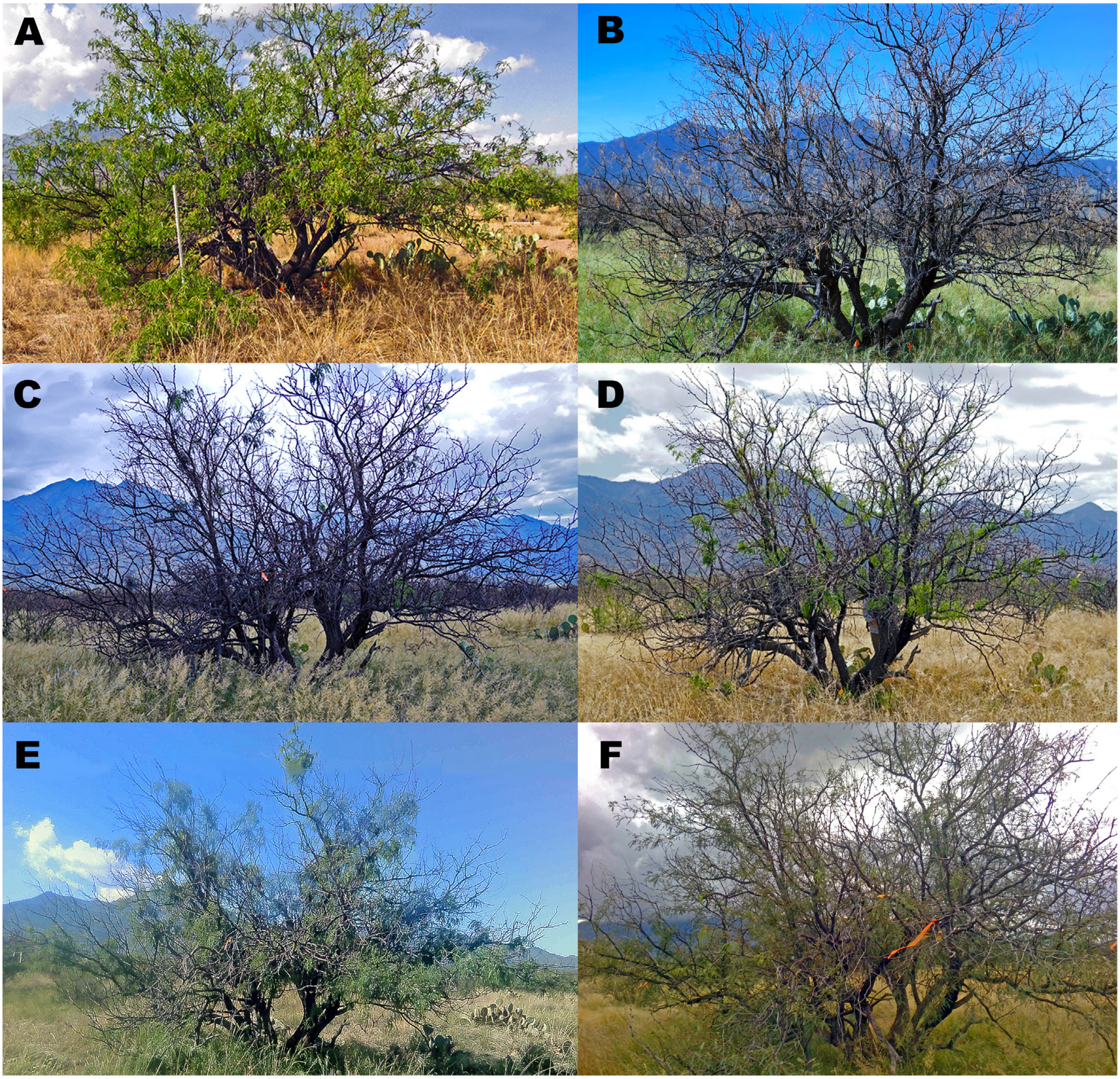

Figure 1. Repeat photos of the north-facing canopy of a large *Prosopis velutina* individual in the treated area with **A,** intact foliage in May 2016 (1 mo before treatment), herbicide-induced reductions in foliage **B,** 1 mo (July 2016) and **C,** 3 mo (September 2016) after treatment, and foliar recovery **D,** 9 mo (March 2017), **E,** 16 mo (Oct 2017), and **F,** 28 mo (Oct 2018) following treatment.

tower data documenting the environmental conditions preceding and following the herbicide application. This information is part of a broader project to be addressed in future publications, aimed at quantifying the effects and cost-effectiveness of brush management on a portfolio of ecosystem services, evaluating trade-offs between them, and enabling a more comprehensive analysis of the cost-effectiveness of brush management. This was not an efficacy study, but rather an exploratory study quantifying the impacts of an herbicide formulation widely in use in the region.

Study Site

The Santa Rita Experimental Range (SRER; 210 km^2, elevations from 900 m to 1 400 m), created in 1903, is on the western alluvial fans of the Santa Rita Mountains 45 km south of Tucson, Arizona. The climate is subtropical semiarid with precipitation (PPT) dominated by the North American Monsoon (Adams and Comrie 1997). Mean annual PPT and temperature ranges from 330 mm/18.9°C at low elevations (978 m) to 430 mm/17.2°C at higher (1 293 m) elevations (Wheeler et al. 2007). Vegetation is dominated by velvet mesquite *(P. velutina)* and a ground layer predominantly of lovegrass (*Eragrostis lehmanniana* Nees.) The primary land use has been cattle grazing (McClaran et al. 2003).

Our study was conducted on two 1.1-ha instrumented watersheds maintained by the US Department of Agriculture—Agricultural Research Service (ARS; Polyakov et al. 2010; Pierini et al. 2014). The watersheds occur on pastures managed with rotational cattle grazing. Our site was on a sandy

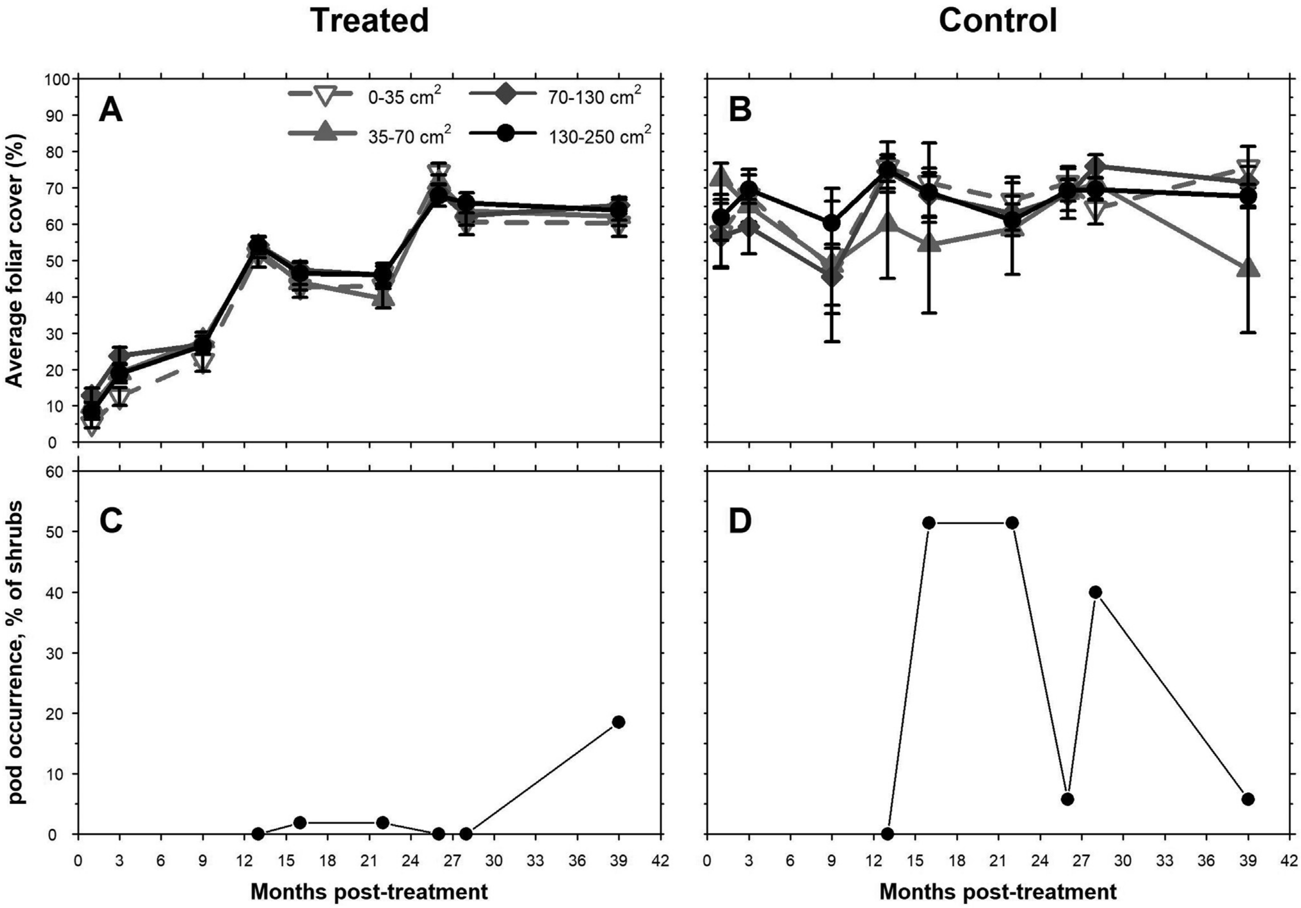

Figure 2. Upper panel: **A,** Mean (±SE) *Prosopis velutina* foliar cover in $n = 211$ treated plants from 1 to 39 mo (June 2016–October 2018) following treatment across four basal area size classes, and **B,** $n = 33$ untreated *P. velutina* plants over the same time span. Lower panel: percentage of *P. velutina* plants producing seed pods on **C,** treated and **D,** control areas.

clay/sandy clay-loam Sasabe-Baboquivari soil complex at 1 150–1 180 m elevation with a long-term (1975–2021; ARS Rain Gauge 8) mean annual PPT of 418 mm. *P. velutina* plants in the area managed with our herbicide treatment were multistemmed, owing to a brush management treatment (basal application of diesel) in the 1970s. Individuals on the nontreated control area were predominantly single stemmed.

Methods

Our herbicide application followed Dow, Inc. recommendations and mimicked applications typical of those conducted on private and public lands in the region. A helicopter application (Crop Protection Services, Chandler, AZ and Tri-Rotor AG, LLC, Somerton, AZ) was conducted on an 18-ha area on June 19, 2016 using a 170.3 L tank filled five times at an estimated total cost of $366/ha. The herbicide was a blend of clopyralid, aminopyralid, and triclopyr (*Transline, Milestone,* and *Garlon 4 Ultra;* Dow Inc.) delivered at rates of 473-, 108-, and 707-mL ha^{-1}, respectively, with an added surfactant-adjuvant (*Herbimax;* 1162 mL ha^{-1}) to facilitate leaf absorption.

Environmental conditions before, during, and after aerial herbicide application were recorded at an eddy covariance (EC) flux tower situated on the treated area. Quantified variables included evapotranspiration and net carbon flux along with air (1.5 m height) and soil (2 and 4 cm depth) temperature, ground heat flux, soil moisture (5 cm depth), relative humidity, incoming solar radiation, net radiation, and wind speed and direction (Pierini et al. 2014; Vivoni et al. 2022). The herbicide was applied between 0630 and 0715 h on June 19, when air temperatures *(T)* were 27.8°C and 32.2°C, respectively (ranging from 22.3°C to 42.2°C and averaging 32.9°C over the 23-h period). Flux tower sensors had been deactivated as a protective measure just before the June 19 herbicide application, but soil *T* on June 14 averaged over 5, 15, 30, and 100 cm depths were 31.7°C, 24.2°C, and 41.9°C (mean, min, and max, respectively); soil *T* at 30 cm was 31.1°C, 24.3°C, and 41.0°C (mean, min, and max, respectively).

Herbicide-induced defoliation and mortality of *P. velutina* plants was quantified along four equally spaced, parallel 450-m transects spanning the treated area. Point-centered quadrants were established at 50-m intervals along each transect. The *P. velutina* plant nearest the point in each quadrant was assessed and generated a sample of $n = 160$ individuals. Assessments were also conducted on an additional, randomly selected individuals ($n = 52$) occurring within the EC flux tower footprint. A separate set of $n = 34$ untreated *P. velutina* individuals within a 5-ha area adjoining the treated area served as controls. Data collected for each plant included basal diameter, height, canopy dimensions (major and minor axes), and crown foliar cover (%; ocular estimates), number of basal stems, and seed pod abundance. Stem basal diameter measures were used to calculate basal area as a metric for plant size. Plants were classified as dead on the basis of visual inspection of the cambium of stems near ground level, and presence or absence of basal sprouting was recorded. Measurements were repeated for each *P. velutina* individual at 1, 3, 9, 13, 16, 22, 26, 28, and 39 mo post treatment.

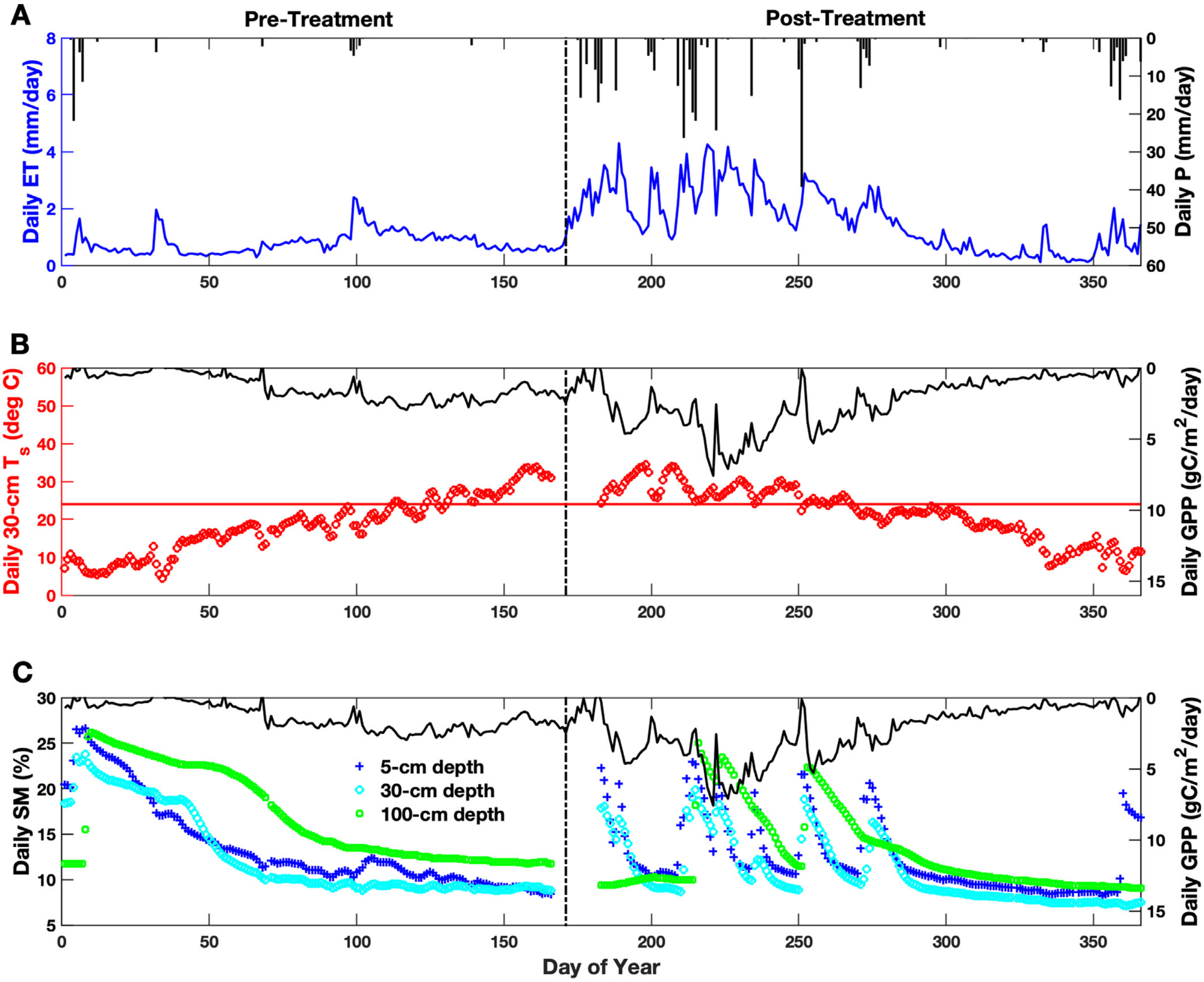

Figure 3. Environmental conditions and gross primary productivity in the days before and after herbicide application on June 19, 2016 (Julian d 170; *dashed vertical line*) (extracted from Vivoni et al. 2022). **A,** Daily precipitation *(bars)* and evapotranspiration *(lines)*. **B,** Daily gross primary productivity *(black line)* and soil temperature at 30 cm depth (*red circles; red line* denotes the 24°C threshold for soil temperatures above which herbicide application is thought to be effective for *P. glandulosa* (Sosebee and Dahl 1991). **C,** Daily gross primary productivity *(black line)* and soil moisture (SM) at depths of 5, 30, and 100 cm. Data 7 d before and 14 d after treatment are missing (sensors covered to prevent potential damage by chemicals in the aerially applied herbicide formulation).

The study was not replicated (i.e., Hurlbert 1984), and the design was such that options for statistical comparisons were confined to Kruskal-Wallis chi-square tests (Kruskal and Wallis 1952) to examine whether differences in foliar cover as a function of plant size existed between treated and control areas at each measurement date. Statistical analyses were carried out using R 3.6.3 (R Core Team 2020).

Results

Before herbicide application, *P. velutina* individuals in the treated and control areas averaged (± standard error, SE) 2.1 ± 0.1 and 1.3 ± 0.2 stems plant^{-1} with a basal area of 99.1 ± 6.2 cm^2 and 95.6 ± 9.5 cm^2, respectively. Canopies were well foliated the month before herbicide application (Fig. 1A). As we did not quantify foliar cover at that time, statistics are reported for the post-treatment period.

Mean (± SE) *P. velutina* plant foliar cover in the treated area was 9.2% ± 1.44% the first month following treatment, at which time foliar cover of plants on the control site averaged 60.7% ± 4.01% (see Fig. 1A and B, Fig. 2A and B). The size class × treatment interaction for foliar cover was significant at 1, 3, 9, 13, 16, and 22 mo post treatment (Kruskal Wallis $\chi^2 = 78.6$, 85.0, 32.4, 39.3, 33.3, and 29.9, respectively; $P < 0.0002$ in all cases). While foliar cover of all size classes on the treated site generally increased following herbicide applications (see Fig. 2A), that of control plants fluctuated (see Fig. 2B). By 26 mo post treatment, foliar cover was statistically comparable in treated and control plants (66.9% and 69.3%, respectively; $P > 0.05$) (see Fig. 1E and F, Fig. 2A and B). Herbicide application did not stimulate basal sprouting, as no new basal stems appeared during the 39-mo assessment period. Plant mortality was 7%, and there was no relationship between mortality and size (Kruskal-Wallis $\chi^2 = 2.34$, $P = 0.50$). Less than 1% of the *P. velutina* plants on the treated site produced seed pods during the 12–28 mo following treatment (see Fig. 2c), whereas ~50% of the plants on the control site produced seed pods during that same timeframe (see Fig. 2D).

The months preceding herbicide application were characterized by low evapotranspiration (ET; < 1 mm/d), low gross primary productivity (GPP; < 3 g C/m^2/d), low soil moisture, and no measurable PPT (Fig. 3). Soil temperatures at 30-cm depth consistently exceeded the 24°C threshold recommended for herbicide application (B. Wallace, personal communication, 8 April 2016). Monsoon PPT received subsequent to herbicide application elevated soil moisture content and ET. Grass growth stimulated by monsoon rains initially elevated GPP during the 14 d following herbicide application, but herbicide-induced reductions in *P. velutina* foliar cover offset the grass response and subsequently caused a persistent net reduction of GPP until *P. velutina* leaf area was reestablished.

Discussion

This exploratory work represents the first examination of herbicide impacts on *P. velutina* on the SRER in more than 60 yr (e.g., Reynolds and Tschirley 1957; Tschirley and Hull 1959; Cable and Tschirley 1961). Ours was not a herbicide efficacy study but rather a quantification of the impacts of an herbicide formulation widely in use in the region. Our results constitute another example in a long line of evidence that indicates that the intended outcomes of brush management are often short-lived or not realized (e.g., Archer et al. 2011; Scholtz et al. 2021). The herbicide application had a transient impact on *P. velutina* foliar cover, and mortality rates were low. Herbicide applications comparable to ours produced qualitatively similar outcomes on upland sites in Cochise County, Arizona (Kim McReynolds, personal communication, April 4, 2022). Unexpectedly, mortality was not a function of plant size. Pod production was substantially reduced in plants treated with herbicides, but the ramifications of this for future *P. velutina* recruitment and for the dynamics of herbivores dependent on *P. velutina* pods and seeds (e.g., ants, kangaroo rats [*Dipodomys* spp.], javelina [*Tayassu tajacu*]) are open to speculation. The temporary loss of *P. velutina* foliage also appears to have unexpectedly stimulated recruitment of the non-native, invasive grass *E. lehmanniana* beneath *P. velutina* canopies (data not shown).

Efficacy studies on *P. velutina* response to herbicide application are generally lacking. Research on *P. glandulosa* in the Southern Great Plains and Chihuahuan Desert suggest treatments are most effective when photosynthetic rates are high, so herbicides are translocated with carbohydrates to kill basal buds and induce whole-plant mortality (Bovey 2001, 2016). This led to the recommendation to wait until the soil temperatures were > 24°C at 0.3 m (12") depth and between 42 and 63 (Texas) and 72 and 84 (New Mexico) d after bud break (B. Wallace, personal communication, April 8, 2016; Sosebee and Dahl 1991). Bud break for *P. velutina* in Arizona typically occurs in April (Turner 1963) before the recommended 24°C soil temperature threshold (see Fig. 3) occurs, and the 24°C soil temperature threshold occurs well before the onset of the monsoon. The effectiveness of our herbicide treatment, had it occurred in late April/early May, closer to *P. velutina* bud break, or just after the onset of the summer monsoon, is open to speculation. The below-average winter PPT in the months preceding our herbicide application (see Fig. 3A) may have further limited its potential effectiveness because spring *P. velutina* GPP response is low following dry winters (Scott et al. 2009). Although the date of our June 19 herbicide application was dictated by logistical considerations, qualitative observations from sites in the region receiving May applications of a comparable herbicide formulation also indicated little impact on *P. velutina* (K. McDaniel, personal communication, May 5, 2016). This regional observation suggests low winter PPT in 2015/2016 may have been a factor. Efficacy may have improved had our herbicide application been made in a year with average/above-average winter PPT or postponed until the summer monsoon season. Field efficacy studies are needed to address these possibilities. Direct measurements of shrub physiological status (e.g., predawn xylem water potential, net photosynthesis, chlorophyll fluorescence) using portable field equipment, coupled with data from flux tower networks (e.g., evapotranspiration and gross primary production; Ameriflux 2022), could also help inform the timing of herbicide application. However, forecasting protocols for the timing of herbicide application need to be robust enough to accommodate the substantial advance coordination and planning logistics associated with aerial applications.

Declaration of Competing Interest

None.

Acknowledgments

Kirk McDaniel and Charles Hart provided valuable advice and guidance; Barry Wallace (Crop Protection Services, Chandler, AZ) and Matt Fieldgrove (Tri-Rotor AG Services, Somerton, AZ) handled herbicide application logistics.

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