Rangeland Ecology & Management 108 (2026) 184–189

Contents lists available at ScienceDirect

Rangeland Ecology & Management

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

Evaluating Herbicide Combinations and Application Rates on Texas Pricklypear

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ARTICLE INFO

Article history:
Received 7 April 2025
Revised 19 June 2026
Accepted 20 June 2026

Key Words:
Herbicide
Picloram
Fluroxypyr
Aminopyralid
Individual plant treatment
Ground broadcast

ABSTRACT

Pricklypear (*Opuntia* spp.) occurs on about 28% of rangelands (10.3 million ha) in Texas and coverage is expanding due to overgrazing and mechanical disturbance. Although a native species to Texas rangelands, pricklypear can become so dense that it outcompetes other native vegetation, suppresses forage production, inhibits biodiversity, and limits livestock movement within pastures. Picloram (Pc) and picloram + fluroxypyr (Pc + F) have been effective at managing pricklypear, however, a herbicide combining picloram, fluroxypyr, and aminopyralid (Pc + F + A) has been reported to increase speed of plant mortality and enhance overall efficacy. We examined varying individual plant treatment and ground broadcast application rates consisting of combinations of picloram, fluroxypyr, and aminopyralid compared to standard industry rates of picloram and picloram + fluroxypyr on overall pricklypear mortality using individual plant treatment and ground broadcast applications across 13 sites on Texas rangeland from 2016 to 2018. Individual plant treatment Pc + F + A (1%) achieved the highest mortality rate of 98.0 ± 3.5% two years post-application, significantly outperforming Pc (1%) at 76.4 ± 19.3%, while including aminopyralid at lower rates (0.75% and 0.5%) yielded comparable control at 96.2 ± 8.2% and 89.6 ± 14.5%, respectively. Ground broadcast applications showed no significant differences in mortality between Pc + F + A (2 336 mL/ha), Pc (2 336 mL/ha), and Pc + F (4 672 mL/ha), ranging from 66.8 ± 21.3% to 78.1 ± 20.2%, though lower rates (8 oz/ac and 16 oz/ac) reduced control to 44–59% ± 25%. These findings highlight the efficacy of higher treatment rates for consistent pricklypear management, with some lower rates offering similar outcomes, providing flexible options for rangeland managers.

Introduction

The rugged and distinct beauty of pricklypear cactus (*Opuntia* spp.) with its colorful blooms and fleshy, red fruits make it uniquely qualified to be the official state plant of Texas. Much like the Lone Star state, this succulent is resilient and persistent. Its hardiness allows it to survive drought conditions and makes it a valuable alternative resource to rangeland managers when forage reserves have been exhausted (Hanselka et al. 1993). Aggressively protected with spines, prickly pear's mechanical defenses against prospective herbivores provide added security as a quail nesting site, enhancing bird survivability (Slater et al. 2001). Its competitive nature and adaptability allow the plant to prosper, but this has created a chronic problem for landowners in Texas. In arid and semi-arid climates, like the Edwards Plateau, limited rainfall often precludes the persistence of beneficial grass species. This presents an opportunity for prolific invaders, such as pricklypear, to dominate the landscape. As a result, depleted rangelands retrogress into a degraded resource (Sosa 2019).

Pricklypear can elicit detrimental ecological and economic consequences on rangelands. This problematic cactus species can become so dense that it outcompetes other native vegetation, suppresses forage production, and limits livestock access to pastures. As pricklypear becomes predominate in a pasture, the number of grazable acres available to livestock decreases and negatively impacts stocking rates. Pricklypear cactus can be a serious impediment for sustainable and profitable ranching enterprises.

Contrasting views towards pricklypear cactus as a friend or foe have impacted the scale of control in Texas. A 1981 survey of Texas county agricultural agents revealed that up to 60% of producers believed that cactus benefits their livestock operation, while 80%

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https://doi.org/10.1016/j.rama.2026.06.010
1550-7424/

considered prickly pear a positive asset for wildlife production. The same survey also indicated that a mere 16% of individual landowners chose to control this opportunistic plant (Lundgren et al. 1981; Price et al. 1985). Other barriers prohibiting managers from controlling pricklypear include lower densities of pear and high treatment cost (Hanselka and Paschal 1991).

Common techniques implemented to reduce pricklypear on rangelands include biological, mechanical, cultural (prescribed fire), and chemical control (Hanselka and Falconer 1994). Many herbivores prefer pricklypear, making them a natural enemy of the plant. Although pricklypear's strategically placed spines aid in deterring mammalian predators, numerous insects have also been found to feed primarily on Cactaceae. In the United States, however, no biological control options have been shown to effectively manage pricklypear.

Mechanical options like grubbing, rootplowing, raking, and chaining are commonly employed on rangelands to manage dense stands of brush. Because pricklypear can reproduce from both seed dispersion and by rooting from dislodged pads, mechanical means often compound the problem (Felker and Russell 1988). Dodd (1968) found that rootplowing with or without raking caused prickly pear to rapidly propagate, multiplying the density of cactus by as much as two to three times compared to the untreated control.

In comparison to mechanical and chemical methods, the most economical tool for land management is prescribed fire (Weir 2009). The success of prescribed fire in achieving prickly pear mortality has been linked to season of growth. In north-central Texas, Ansley and Castellano (2007) found that at 3 years post-fire summer fire treatment was much more effective at controlling brownspine pricklypear (80–100% mortality) than high-intensity and low-intensity winter fires (<30%, <10% mortality, respectively) independent of motte size. Likewise, a case study by Taylor (2001) in the Edwards Plateau achieved comparable results for summer fire versus winter fires for reducing pricklypear density (97% vs. 47%). Adoption of this strategy, however, can be limited by lesser amounts of fine fuels. Areas of thick brush or prickly pear prevent accumulation of herbaceous forage, reducing fine fuel loads and the viability of prescribed fire. Mechanical or chemical reduction of brush prior to the implementation of a prescribed fire may increase surrounding forage production and improve the efficacy of fire treatments (Ansley and Taylor 2004). The post-fire application of herbicide may also significantly improve plant mortality by increasing chemical absorption through the already fire stressed plant (Ansley and Castellano 2006).

Using herbicides, either alone or in combination with other methods, is often considered the most efficient approach to pricklypear management (Ferrell et al. 2014). The active herbicide ingredient credited as being the most successful in controlling pricklypear is picloram (Mayeux and Johnson 1989). Corteva Agriscience's (formerly Dow AgroScience) picloram (P) product, called Tordon 22K^{TM} (24.4% picloram), was established in 1964 and is a restricted-use chemical that is widely utilized for pricklypear management by licensed pesticide applicators throughout the state of Texas. The mode of action for picloram is classified by the Weed Science Society of America as a "Group 4-Synthetic Auxin" herbicide. In low concentrations, these auxin-mimicking chemicals stimulate uninhibited cell division and growth that eventually leads to mortality of vascular plant tissue. Contrastingly, the same chemicals impede meristematic division and growth processes at high concentrations, resulting in a similar fate for the plant (Weed Science Society of America [WSSA] 2011). Although the effectiveness of picloram is substantiated, pricklypear death may take up to 2 to 3 years following initial application.

In 2004, Dow AgroScience released an additional option for pricklypear control when they established a patent on a chemical formulated with picloram (13.24%) and fluroxypyr (10.64%) and introduced the product Surmount^{TM}. The addition of fluroxypyr, also a synthetic auxin, was found to expedite pricklypear yellowing and mortality. While the enhanced rate of mortality does increase the appeal of this product to range managers, the recommended rate of application for picloram + fluroxypyr (Pc + F) (2% v/v) is double that of picloram (Pc) (1% v/v) for aerial, ground broadcast (GB), and foliar individual plant treatment (IPT) applications. An increased volume of chemical makes Pc + F formulations a less cost-efficient control option for producers.

The newest Corteva herbicide labeled for pricklypear management (Pc + F + A) received registration by the Environmental Protection Agency (EPA) in 2017. This product is manufactured with three group four synthetic auxins: picloram (10.06%), fluroxypyr (12.53%), and aminopyralid (5.15%). Aminopyralid is considered a "reduced risk pesticide" due to its low toxicity to fish, mammals, and aquatic species (EPA 2018). Aminopyralid also has a greater ability for soil sorption, and therefore reduced risk of off-target mobility, compared to picloram (Fast et al. 2010). The positive chemical attributes obtained by the inclusion of aminopyralid are suspected to make the picloram + fluroxypyr + aminopyralid (Pc + F + A) formulation even quicker and more reliable than its predecessors.

Although Pc+F+A formulation is said to produce quicker mortality, no studies have been executed to validate these claims. Research is necessary to provide land managers appropriate recommendations for treatment methods and rates of chemicals available to improve the control pricklypear on rangelands. The objectives of this study were to determine pricklypear plant mortality following IPT and GB herbicide applications with varying rates and active ingredients; and 2) contrast IPT and GB treatments to existing controls and determine whether picloram + fluroxypyr + aminopyralid (Pc + F + A) is a suitable substitute or replacement for picloram (Pc) and picloram + fluroxypyr (Pc + F) in rangeland. We hypothesized that picloram + fluroxypyr + aminopyralid (Pc + F + A) would (1) yield higher rates of pricklypear plant mortality at 1% IPT and 2.34 $l \cdot ha^{-1}$ GB rates, and (2) Pc + F + A at 1% IPT and 2.34 $l \cdot ha^{-1}$ GB rates would increase pricklypear plant mortality compared to traditional picloram (Pc) formulations.

Methods

A statewide study across 13 sites in West and Central Texas was performed from 2016 to 2018 to compare the effects of herbicide rates and application of three products labeled for pricklypear management that are readily available to licensed pesticide applicators in Texas: picloram (Pc), picloram + fluroxypyr (Pc+F), and picloram + fluroxypyr, and aminopyralid (Pc +F+A). Picloram (often sold as Tordon 22K^{TM} by Corteva Ag Sciences) is a standalone active ingredient product consisting as potassium salt at 24.4% by weight and acid equivalent (ae) of approximately 0.91 kg ae/L (21.1% ae). Surmount^{TM} (also sold by Corteva Agsciences) is a premix containing picloram active ingredients of picloram (triisopropanolamine salt): 13.24% (142.59 g/L; 80.29 g/L) and fluroxypyr (1-methylheptyl ester): 10.64% (115.02 g/L; 80.28 g ae/L). MezaVue^{TM} (also spelled MezaVue sold by Corteva Agsciences) is a three-way premix containing aminopyralid + picloram + fluroxypyr with active ingredients of aminopyralid (potassium salt): 5.15% (58.72 g/L; 50.33 g ae/L); picloram (potassium salt): 10.06% (119.826 g/L; 99.46 g ae/L); and fluroxypyr (1-methylheptyl ester): 12.53% (143.79 g/L; 99.46 g ae/L). Ground broadcast (GB) and IPT field trials (n = 13 and n = 13, respectively) represent various landscape attributes including precipitation, topography, soil type, and vegetation (Table 1). Ground Broadcast and IPT application methods were randomly assigned to location and all treatments were applied during the spring and

Table 1
Location data for the ground broadcast and individual plant treatment applications across Texas from 2016 to 2018.

Ground broadcast		Individual plant treatment	
Location	Application date	Location	Application date
Comanche Co.	April1, 2016	Coke Co.	March 3, 2017
Brown Co.	April 11, 2016	Reagan Co.	May 2, 2017
Menard Co.	August 15, 2016	Hamilton Co.	March 30, 2017
Schleicher Co.	August 15, 2016	Upton Co.	June 21, 2017
Mills Co.	May 16, 2016	Young Co.	April 28, 2017
Eastland Co.	May 6, 2017	Callahan Co.	June 5, 2017
Mills Co.	April 26, 2017	Young Co.	April 17, 2018
Sutton Co.	April 6, 2017	Lampasas Co.	May 24, 2018
McMullen Co.	May 30, 2017	Tom Green Co.	May 31, 2018
Callahan Co.	May 29, 2018	Runnels Co.	June 6, 2018
Palo Pinto Co.	April 2, 2018	Nolan Co.	June 21, 2018
Parker Co.	March 20, 2018	Kent Co.	June 29, 2018
Llano Co.	April 4, 2018	Scurry Co.	July 13, 2018

Table 2
Herbicide mixtures and rates for IPT (individual plant treatment) and GB (ground broadcast) applied directly above pricklypear canopies during 2016–2018, Central and West Texas.

Treatment	Herbicide and rate	
	IPT (1%)	GB (l $\cdot$ha^{-1})
Pc	1	2.34
Pc + F	1	4.69
Pc + F + A	0.25; 0.50; 0.75	0.585; 1.17; 1.76

[1]The Pc and Pc + IPT and GB treatments were applied at the recommended rate (Lyons et al. 2020).
Total spray volume was 93.6 l $\cdot$ha^{-1} (10 gal $\cdot$ac^{-1}) with nonionic surfactant adjuvant. Each replicate plot was 10 × 10-m) and consisted of seven 1-m wide straight-line spray swaths along the long direction. Some plots were shorter in length but wider and remained similar in total size. Texas A&M AgriLife employees supervised the mixing of each treatment load.

summer months. Each plot averaged approximately 40–50 pricklypear individuals and plants within each plot were marked with identification tags and assessed for mortality post-herbicide application. Visual ratings of mortality offer a reliable and efficient approach for assessing herbicide efficacy on pricklypear, allowing non-destructive evaluation under field conditions where quantitative biomass measurements are challenging. Plants qualified as individuals when there was a 20-cm gap between multiple cladodes. If less than 20-cm, the cladodes were marked as the same plant. Untreated controls consisted of 100% live, healthy pricklypear showing no insect or frost damage and was included in the data as an initial comparison to ensure no natural mortality that may have occurred in the two years between treatment and visual assessment.

Individual plant sites

Six treatments were applied at each of the 13 IPT study site locations. Each 10 × 10-m plot was designated with rebar stakes and included a 5-m buffer in between treatments. The following treatments were applied at each IPT site: (1) Pc + F + A at a rate of 0.25% total volume, (2) Pc + F + A at a rate of 0.50% total volume, (3) Pc + F + A at a rate of 0.75% total volume, (4) Pc + F + A at a rate of 1% total volume, (5) P + F at a rate of 1% total volume, (6) Pc at a rate of 1% total volume (Table 2). Individual Plant Treatment applications were applied using a hand-sprayer at 2-gallons total volume with a X8 nozzle on a backpack sprayer. A non-ionic surfactant at 0.25% v/v was included with each treatment. All plots were sprayed approximately from 26 to 32°C ambient air temperature, 24–32°C soil temperature at 30-cm depth, 40–60% relative humidity, and with winds 0–2.24 m $\cdot$sec^{-1}. Treated pricklypear on all IPT sites were healthy, showing no insect and/or disease damage. Mortality rates were determined up to 2 years after treatment. Apparent plant mortality was determined by estimating percentage of visual plant desiccation. Picloram (often sold as Tordon 22K™ by Corteva Ag Sciences) is a standalone active ingredient product consisting as potassium salt at 24.4% by weight and acid equivalent (ae) of approximately 240 g ae/L (21.1% ae). Surmount™ (also sold by Corteva Agsciences) is a premix containing picloram active ingredients of picloram (triisopropanolamine salt): 13.24% (142.59 g/L; 80.28 g ae/L) and fluroxypyr (1-methylheptyl ester): 10.64% (115.04 g/L; 80.29 g ae/L). MezaVue™ (sold by Corteva Agsciences) is a three-way premix containing aminopyralid + picloram + fluroxypyr with active ingredients of aminopyralid (potassium salt): 5.15% (58.71 g/L; 50.33 g/L); picloram (potassium salt): 10.06% (116.23 g/L; 99.46 g/L) and fluroxypyr (1-methylheptyl ester): 12.53% (1.43.79 g/L; 99.46 g ae/L).

Ground broadcast sites

Six plots were established at each of the 13 GB locations. Each 10 × 10-m plot was designated with rebar stakes and included a 5-m buffer in between treatments. The following treatments were used at the GB sites: (1) Pc + F + A at a rate of 0.585 l $\cdot$ha^{-1}, (2) Pc + F + A at a rate of 1.17 l $\cdot$ha^{-1}, (3) Pc + F + A at a rate of 1.76 l $\cdot$ha^{-1}, (4) Pc + F + A at a rate of 2.34 l $\cdot$ha^{-1}, (5) Pc + F at a rate of 4.69 l $\cdot$ha^{-1} (per industry standard), (6) Pc at a rate of 2.34 l $\cdot$ha^{-1} (per industry standard) (Table 2). Ground broadcast treatments were applied at 10 GPA at 35 PSI with six flat fan nozzles on a boom sprayer 30-cm apart approximately 1.5-m from the ground. A non-ionic surfactant at 0.25% v/v was included with each treatment. All plots were sprayed approximately from 26 to 32°C in ambient air temperature, 24–32°C soil temperature at 30-cm depth, 40–60% relative humidity, and with winds 0–2.24 m $\cdot$sec^{-1}. Treated pricklypear on all GB sites were healthy showing no insect and/or disease damage. Mortality rates were determined up to 2 years after treatment. Apparent plant mortality was determined by estimating percentage of visual plant desiccation.

Statistical analysis

Data were analyzed using repeated measures analysis of variance using a randomized block design with location as the block, treatment as the main effect, and time of collection as the repeated measure. Means were separated using Tukey's Protected LSD with $P \leq 0.05$. Data were analyzed using the statistical package JMP (SAS Institute Inc, 2023).

Results

Individual plant treatment

Pricklypear mortality varied across IPT rates and active ingredients ($P < 0.05$). Picloram + F + A (1%) yielded the highest mortality (98 ± 4%) across all 13 sites two years following application (Table 3). While pricklypear control when treated with Pc + F + A (1%) was significantly greater than Pc (1%) ($P < 0.05$; 98 ± 4% vs. 76 ± 19%, respectively), Pc + F + A (1%) was similar in mortality rates compared to Pc + F (1%) ($P = 0.61$). Interestingly, there were no differences in pricklypear mortality between treatments Pc + F (1%) (93 ± 12%) and Pc (1%) (76 ± 19%).

Treatment rate variation also yielded varying responses when even though Pc + F + A (1%) showed the highest rates of plant mortality, Pc + F + A (0.75%) and Pc + F + A (0.5%) treatments afforded comparable pricklypear control ($P = 0.28$; 96 ± 8% and 90 ± 15%) two years post-application on all sites, respectively. However, the

Table 3
Individual plant treatment (IPT) treatment effects on pricklypear as affected by main effects of herbicide treatment.

Treatment	Mortality, %
Pc + F + A 1.0%	98 ± 4 a
Pc + F + A 0.75%	96 ± 8 a
Pc + F + A 0.50%	90 ± 15 a
Pc + F + A 0.25%	74 ± 21 b
Pc + F 1%	93 ± 12 ab
Pc 1%	76 ± 19 b

Pc + F + A, picloram + fluroxypyr + aminopyralid; Pc + F, picloram + fluroxypyr; Pc, picloram.
Means (± least squares standard error) with similar letters within each column are not significantly different at $P \leq 0.05$.

Table 4
Ground broadcast (GB) treatment effects on pricklypear as affected by main effects of herbicide treatment.

Treatment	Mortality, %
Pc + F + A2, 336mL/ha	78 ± 20 a
Pc + F + A1, 752mL/ha	67 ± 21ab
Pc + F + A1, 168mL/ha	59 ± 25 bc
Pc + F + A584mL/ha	45 ± 18c
Pc + F4, 672mL/ha	76 ± 18ab
Pc 2, 336mL/ha	73 ± 19*b*

Pc + F + A, picloram + fluroxypyr + aminopyralid; Pc + F, picloram + fluroxypyr; Pc, picloram.
Means (± least squares standard error) with similar letters within each column are not significantly different at $P \leq 0.05$.

Pc + F + A (0.25%) treatment rate caused less plant mortality and was highly variable, averaging 74 ± 21 %, respectively ($P < 0.0$).

Plant mortality did not differ between Pc + F + A at 0.75% and 1% rates ($P = 0.94$). And increased plant mortality also did not occur between Pc + F + A at 0.75% and Pc + F (1%) ($P = 0.92$). Interestingly, Pc + F + A (0.75%) was 20% greater in plant mortality than Pc (1%) ($P < 0.01$).

A few unexpected comparisons existed between Pc + F + A (0.25%) and Pc (1%), showing no difference between the two treatments even with differing rates ($P = 0.94$). Another interesting treatment and rate showing no differences in plant mortality existed between Pc + F + A (0. 5%) and (1%) (P = 0.08), even though approximately 8.5% more plant mortality was achieved with the full 1% rate. Pc + F + A (0. 5%) generated similar plant mortality responses as Pc + F (1%) showing even less plant mortality gains ($P = 0.87$) compared to Pc + F +A (1%). Untreated controls consisted of 100% live, healthy pricklypear showing no insect or frost damage and applied as benchmark prior to statiscal analyses.

Ground broadcast

Ground broadcast applications generated similar plant mortality trends and patterns as the IPT treatments. No differences were observed at the full rates of Pc + F + A (2 336 mL/ha) vs. Pc (2 336 mL/ha) ($P = 0.90$) or Pc + F + A (1 752 mL/ha) vs. Pc + F (4 672mL/ha) ($P = 1.0$) or Pc + F (4 672 mL/ha) vs. Pc (2 336 mL/ha) ($P = 1.0$) (Table 4).

Surprisingly, there were no differences in plant mortality between Pc + F + A 2 336 mL/ha ($P = 0.23$; 78 ± 20%) and Pc + F + A 1 168 mL/ha ($P = 0.23$; 67 ± 21%). And even more surprising, no differences in plant mortality between Pc + F +A (1 168 mL/ha) vs. Pc + F (4 672 mL/ha) ($P = 0.43$) vs. Pc (2 336 mL/ha) ($P = 0.84$).

Differences in plant mortality only were revealed when the lesser rates of Pc + F + A (1 168 mL/ha and 584 mL/ha) were applied. These treatments yielded 44–59% ± 25% control as compared to the 67–78% ± 17% plant mortality estimates with the 1 168 mL/ha and 1 752 mL/ha rates, respectively. Untreated controls consisted of 100% live, healthy pricklypear showing no insect or frost damage.

Discussion

This study assessed pricklypear plant mortality following the application of IPT and GB herbicide methods, utilizing varying rates and active ingredients. Additionally, this study aimed to compare the efficacy of IPT and GB treatments against untreated "healthy" non-treated controls and evaluate whether the herbicide combination of picloram + fluroxypyr + aminopyralid (Pc +F + A) serves as an effective alternative to the use of picloram (Pc) and picloram + fluroxypyr (Pc + F) formulations in rangeland management.

Data supported the hypotheses, demonstrating that the herbicide combination of picloram + fluroxypyr + aminopyralid (Pc+ F +A) resulted in higher rates of pricklypear plant mortality at both 1% IPT and 2 336 mL/ha GB application rates. Furthermore, Pc + F + A at these specified rates significantly increased pricklypear plant mortality compared to traditional picloram (Pc) formulations.

Our results provide valuable insights into the efficacy of herbicide treatments for pricklypear control, highlighting the influence of active ingredient combinations and application rates on plant mortality across both IPT and GB methods. The Pc + F + A (1%) treatment in IPT applications achieved the highest pricklypear mortality across all 13 sites two years post-application, significantly outperforming Pc (1%) alone, which aligns with previous research demonstrating the synergistic effects of combining picloram, fluroxypyr, and aminopyralid for enhanced control of woody and herbaceous species (DiTomaso et al. 2010). However, the lack of significant differences between Pc + F + A (1%) and Pc + F (1%), as well as between Pc + F + A at 0.75% and 0.5% rates, suggests that lower rates or alternative combinations may offer comparable control, providing cost-effective options for rangeland managers. The high variability observed at the lowest Pc + F + A rate indicates that reduced rates may compromise consistency, likely due to insufficient herbicide uptake under varying environmental conditions, a phenomenon noted in similar studies on herbicide efficacy (Bovey and Meyer 1981).

Ground broadcast applications mirrored IPT trends, with no significant differences in mortality between full rates of Pc + F + A, Pc + F (4 672 mL/ha), and Pc (2 336 mL/ha), suggesting that higher rates do not always translate to improved control in broadcast scenarios, possibly due to uneven coverage or environmental factors such as soil moisture and temperature affecting herbicide absorption (Price et al. 2015). Notably, the reduced rates of Pc + F + A resulted in significantly lower mortality compared to the 584 mL/ha and 2 336 mL/ha rates, underscoring a threshold effect where herbicide concentration becomes limiting for effective pricklypear control. These findings emphasize the importance of tailoring application rates and methods to specific management goals, balancing efficacy with economic and environmental considerations, and suggest that further research into optimizing surfactant use and application timing could enhance outcomes in diverse rangeland conditions.

Managing pricklypear (*Opuntia* spp.) on rangelands should be a priority due to its significant negative impacts on ecosystem health, biodiversity, and livestock productivity. Pc + F + A has emerged as an effective herbicide option for controlling pricklypear, providing several advantages over other management strategies. If left unmanaged, pricklypear invasion can lead to significant shifts in plant community composition, often resulting in reduced biodiversity. Dense pricklypear stands outcompete native grasses and forbs, critical for maintaining diverse and healthy rangeland ecosystems (Archer et al. 2011). The dominance of pricklypear reduces plant diversity and habitat quality for wildlife, negatively affecting the overall ecosystem.

Pricklypear reduces forage availability for livestock. Its thick pads and spines create physical barriers, preventing grazing animals from accessing underlying grasses and other herbaceous plants (Bovey, 1977). This reduction in forage availability directly impacts livestock carrying capacities and can lead to decreased livestock productivity and economic losses for ranchers (Scifres and Brock 1972). Pc + F + A has been shown to provide consistent control of pricklypear compared to other herbicides. This combination of active ingredients including picloram, fluroxypyr, and aminopyralid, works synergistically to improve herbicide uptake and translocation within the plant, resulting in higher mortality rates (Cai et al. 2015) with inevitable implications for forage productivity following initial plant mortality. The combination and synergy of Pc + F + A in controlling pricklypear reduces the competition for resources, thereby promoting the growth of desirable forage species and enhancing overall plant community diversity. This improvement in forage availability directly supports higher livestock carrying capacities and improved grazing outcomes (Scifres and Brock 1972; Fuhlendorf et al. 2012). Without a doubt, picloram adds significant synergy to other actives, and still remains a viable option as a stand-alone herbicide treatment in root-kill and motte canopy reduction (Price et al. 1985; Peterson et al. 1988).

These results indicate the effective and safe use of Pc + F + A that exceeded commonly reported effects of mechanical treatments. Mechanical methods, such as bulldozing or grubbing, can be labor-intensive, costly, and disruptive to the soil and existing vegetation. These approaches often lead to soil erosion, habitat destruction, and unintended damage to non-target plant species (Teague et al. 2001; Archer et al. 2011). In contrast, Pc + F + A can be applied with precision (either IPT or broadcast), minimizing collateral damage and preserving the integrity of the rangeland ecosystem. Its application is less labor-intensive and can cover large areas more efficiently than mechanical techniques (Britton and Dodd 1976) without the severe soil disturbance.

Furthermore, since Pc + F + A contains picloram, it can be effectively used in synergy with prescribed fire to restore rangelands. The combination of herbicide treatment and prescribed burning can enhance the control of pricklypear by targeting different life stages and improving the accessibility of the herbicide to the plant. Prescribed fire can remove the above-ground biomass of pricklypear by making the remaining tissue more susceptible to herbicide penetration and efficacy (Ansley and Castellano 2006). This integrated approach not only improves the management of pricklypear but also promotes the regeneration of native plant species and the restoration of a more diverse and resilient rangeland ecosystem (Davies et al. 2009; Twidwell et al. 2013).

Management implications

Landowners and producers benefit from more control options for invading pricklypear. Here, we offer herbicide results for rangeland managers seeking effective and sustainable strategies to control pricklypear (*Opuntia* spp.), a species that threatens ecosystem health, biodiversity, and livestock productivity by outcompeting native vegetation and reducing forage availability. All herbicides and combinations tested provided a very high level of control. This enhanced efficacy, driven by the various rates tested for synergistic action of the three active ingredients, supports its use as an additional option for restoring forage production and promoting plant community diversity. Managers can expect these rates of specific well-known pricklypear products to achieve consistent control, even though lower rates (e.g., 0.5% or 0.75%) may suffice in some contexts, offering cost-effective alternatives where budget constraints are a concern, albeit with potential trade-offs in consistency under variable environmental conditions. For larger-scale applications, GB treatments at 2.34 l $\cdot ha^{-1}$ provide reliable outcomes, but exceeding this rate may not yield proportional benefits due to factors like uneven coverage or environmental limitations. Compared to mechanical methods, herbicide applications minimize soil disturbance and non-target damage, preserving rangeland integrity while reducing labor and costs. Additionally, integrating any herbicide or combination with prescribed fire can further enhance control by targeting multiple plant life stages, facilitating herbicide uptake, and fostering native species recovery. Managers should tailor application rates and methods to site-specific goals, balancing efficacy with economic and ecological considerations, and consider further exploration of surfactants and timing to optimize results across diverse rangeland conditions.

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.

CRediT authorship contribution statement

Morgan L. Treadwell: Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **James Jackson:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Acknowledgements

The authors dedicate this paper to Dr. Charles R. Hart whom we cherished as a mentor, friend, and colleague.

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