Invasive Plant Science and Management 2012 5:164–169

Effects of Aminopyralid on Ponderosa Pine (*Pinus ponderosa*)

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Invasive weed control within cleared, forested sites in the inland Northwest is complicated by the susceptibility of ponderosa pine to synthetic auxin herbicide injury, used to control broadleaf weeds. Herbicide injury may lead to decreased canopy volume and variable growth patterns of ponderosa pine, which is a commercially important tree species. Herbicide injury to ponderosa pine can be decreased with dormant-season applications, a timing suited to control many weeds that may occur within ponderosa pine sites. However, spring-timed herbicide applications are needed to control other weeds, such as meadow hawkweed, and that application timing coincides with active ponderosa pine growth. In this study, we determined the level of injury to ponderosa pine resulting from spring-timed aminopyralid, clopyralid, and picloram applications beneath ponderosa pine canopies. Herbicide injury to leader and lateral candles and needle elongation was evaluated 1 and 12 mo after treatment (MAT). Low rates of aminopyralid alone (0.05 kg ae ha^{-1} [3 fl oz ac^{-1}]) and aminopyralid + clopyralid (0.05 + 0.10 kg ae ha^{-1}) resulted in herbicide injury ratings that did not differ from untreated trees. The high rate of aminopyralid (0.12 kg ae ha^{-1}) resulted in leader candle injury on 75% of treated trees, 5% of which were necrotic at 12 MAT. Herbicide injury was observed on 30% of lateral candles. In comparison, picloram (0.28 kg ae ha^{-1}) treatments resulted in necrosis or mortality of leader and lateral candles on 65% and 40% of trees, respectively, at 12 MAT. Results suggest that use of low rates of aminopyralid alone or in combination with low rates of clopyralid minimizes the risk of nontarget injury to ponderosa pine (> 5 yr old) while controlling hawkweed with a spring application.

Nomenclature: Aminopyralid; clopyralid; picloram; meadow hawkweed, *Hieracium caespitosum* Dumort; ponderosa pine; *Pinus ponderosa* Lawson & C. Lawson.

Key words: Nontarget effects, integrated weed management.

Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) is a commercially important tree species in the western United States, ranking second in value and third in volume harvested (Western Wood Products Association 2010). In the inland Northwest, ponderosa pine occupies a narrow environmental range between steppe vegetation in the loessal soils of the Palouse region and more-mesic Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] forests of the Northern Rocky Mountains province at elevations below 1,220 m (4,003 ft) (Cooper et al. 1991). Ponderosa pine is the climax overstory species in the driest forested zones and is seral to Douglas-fir in more-mesic forests. Plant associations range from a shrub- and forb-rich understory to a drier bunchgrass-dominated understory. Douglas-fir and ponderosa pine stands are often harvested and subsequently maintained for pasture, or grazed after trees have been replanted. Disturbance, including tree harvesting and livestock grazing, results in increased susceptibility to weed invasions. Invasive weeds associated with forested sites that may include ponderosa pine are meadow hawkweed (*Hieracium caespitosum* Dumort.) and orange hawkweed (*Hieracium aurantiacum* L.), spotted knapweed (*Centaurea stoebe* L.) and diffuse knapweed (*Centaurea diffusa* Lam.), Dalmatian toadflax [*Linaria dalmatica* (L.) P. Mill.] and yellow toadflax (*Linaria vulgaris* P. Mill.), and Canada thistle [*Cirsium arvense* (L.) Scop.] (Duncan and Clark 2005).

Chemical weed control within cleared forest sites is complicated by the susceptibility of ponderosa pine to synthetic auxin herbicides, which are commonly used to control broadleaf weeds. Synthetic auxin herbicides have, however, been used in newly planted ponderosa pine stands to release tree seedlings from shrub competition. Selectivity is achieved by applying those herbicides during fall and winter tree dormancy to reduce absorption and translocation of the herbicide to the site of action (Paley and Radosevich 1984). The greatest injury to ponderosa pine

DOI: 10.1614/IPSM-D-11-00052.1

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Interpretive Summary

Broadleaf weeds under ponderosa pine canopies are often controlled in the fall when trees are dormant but the weeds are susceptible to treatment. Meadow hawkweed, however, is not susceptible to fall herbicide treatments. Managing broadleaf weeds in the spring risks injury to ponderosa pine, thus herbicide application rates were tested to determine whether injury could be minimized. Spring applications of low rates of aminopyralid (0.05 kg ae ha^{-1}) with or without low rates of clopyralid (0.10 kg ae ha^{-1}) did minimize the risk of injury to ponderosa pine when applied below the canopy. Our results suggest that use of high aminopyralid label rates (0.12 kg ae ha^{-1}) or picloram (0.28 kg ae ha^{-1}) should be avoided when targeting invasive weeds in the spring because of likely negative effects to ponderosa pine. In particular, the results of this study should improve meadow hawkweed management decisions in the Pacific Northwest, which requires spring-timed applications but are effective at low use rates.

trees from synthetic auxin herbicide applications occur when plants are actively growing, the xylem sap tension is low, and the rate of photosynthesis is high (Radosevich et al. 1980). Synthetic auxin injury symptoms may include necrosis or epinasty of new needle growth and leader candle epinasty, which may lead to decreased canopy volume and variable growth patterns. Therefore, development of integrated weed management programs should select herbicides and application timings that minimize injury to ponderosa pine.

Synthetic auxin herbicides that are frequently used for invasive broadleaf weed control in rangeland, pastures, and noncrop areas include the pyridine carboxylic acids: aminopyralid, clopyralid, and picloram. Given the effectiveness of these herbicides, the use of a particular product can be based on other factors aiding management objectives, such as selecting the product that controls other weedy species or minimizes nontarget effects on desirable species at the site. Among these herbicides, aminopyralid has become an attractive option for land managers. Aminopyralid controls many broadleaf species in the Asteraceae family at low use rates (Carrithers et al. 2005), and favorable ecotoxicological and environmental fate properties allow for its use where picloram or clopyralid is not recommended (Jachetta et al. 2005). However, little is known about the effect of aminopyralid on ponderosa pine.

Recent research has focused on the development of integrated management programs for meadow hawkweed control in cleared, forest zones and abandoned farmland, where the long-term management objective may be to harvest ponderosa pine. Wallace et al. (2010) demonstrated that use of selective herbicides that provide multiyear control of meadow hawkweed was a critical factor for successful revegetation of invaded sites. Effective herbicides include aminopyralid, clopyralid, and picloram, whose use results in high levels of meadow hawkweed control (> 90% at 2 mo after treatment [MAT]) when targeting the rosette to bolting stage in northern Idaho (Wilson et al. 2006a, 2006b). Research has shown that the most effective application timing for meadow hawkweed is late spring to early summer, coinciding with the rosette-to-bolting phenological stages, which overlap with periods of active ponderosa pine growth. Wallace and Prather (2011) demonstrated that fall aminopyralid applications, even at the high label rate (0.12 kg ae ha^{-1} [7 fl oz ac^{-1}]), result in undesirable meadow hawkweed control (< 75%), whereas aminopyralid applications timed to the spring rosette through bolting stages using the low label rate (0.05 kg ae ha^{-1}) result in high levels (> 95%) of control. These results differ from other common invasive broadleaf weeds in ponderosa pine habitat. Targeted applications of aminopyralid to actively growing plants in the fall provides good control of Canada thistle (Enloe et al. 2007) and spotted knapweed (Duncan 2011). Fall application timings may be used for control of these weeds to minimize potential nontarget effects to ponderosa pine.

The objective of this study was to determine the level of injury to ponderosa pine resulting from spring-timed aminopyralid applications. A greater understanding of nontarget effects to ponderosa pine following aminopyralid applications in comparison to commercial standards will allow land managers to select the appropriate product and application timing to achieve system-specific management objectives.

Materials and Methods

Study Sites. Field studies took place within a 7 km (4.35 mi) radius of Santa, ID (47°08′36″N, 116°26′51″W) located within the St. Joe River Valley in the northern panhandle of Idaho. Soils of the study region are in the Reggear silt loam series, consisting of moderately well-drained soils formed by volcanic ash and loess. The study area is characterized by ponderosa pine–common snowberry (*Symphoricarpos albus* L.) habitat, and these species range in elevation from 762 to 1,036 m. Annual precipitation averages 87.3 cm (34.4 in; Table 1). Precipitation occurring between April and September is on average 33% of total annual precipitation.

The study was conducted in 2007 and repeated in 2008. In May 2007, the field experiment was established on private forest land that had been converted to pasture and used for grass hay production and intermittent cattle grazing. The site had not been grazed for at least 15 yr and was infested with meadow hawkweed. Ponderosa pine ranging in age from 5 to 10 yr that were undergoing natural encroachment at the interface of the pasture and forest stand were targeted for treatments. In May 2008, the study was repeated at a site approximately 6 km west of the

https://doi.org/10.1614/IPSM-D-11-00052.1 Published online by Cambridge University Press

Table 1. Annual precipitation during 2007–2009 and the 30-yr average (avg.), at Santa, ID.

Year [a]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
	mm												
2007	110	110	89	39	41	50	4	13	14	76	101	203	850
2008	158	101	122	57	47	78	7	58	39	26	141	158	987
2009	130	64	137	58	75	57	31	45	9	92	70	74	842
30-yr avg.	112	91	81	67	74	54	35	33	40	57	112	117	873

[a] Data source for presented precipitation records: PRISM Climate Group, Oregon State University, Corvallis, OR. http://www.prismclimategroup.org, accessed January 10, 2011. The 30-yr avg. is averaged over 1971–2000.

2007 site. This study was located on meadow hawkweed–infested private forest land that had been harvested and replanted to ponderosa pine approximately 8 yr before. Ponderosa pine trees were 7 yr old and planted with approximately 5-m spacing.

Experimental Treatments. Herbicides tested were aminopyralid, clopyralid, and picloram, all of which are labeled for use in forest sites, pastureland, or noncrop areas, and each herbicide provides a high level of meadow hawkweed control. The experiment consisted of four herbicide treatments and an untreated control. Treatments included aminopyralid (Milestone, Dow AgroSciences, Indianapolis, IN) at a low (0.05 kg ae ha^{-1}) and high (0.12 kg ae ha^{-1}) label rate, aminopyralid + clopyralid (Transline, Dow AgroSciences) (0.05 + 0.10 kg ae ha^{-1}) at low label rates and picloram (Tordon 22K, Dow AgroSciences) (0.28 kg ae ha^{-1}) at a low label rate. Treatments were applied with a nonionic surfactant (R-11, Wilbur Ellis Company, San Fransisco, CA) (0.25% v/v).

A single ponderosa pine tree was located at the center of a 7.2 by 4.8 m (35.4 m^2) plot. Treatments were applied in a swath on each side of the tree, targeting below the tree canopy, using a CO_2 backpack sprayer calibrated to deliver 112 L ha^{-1} (12 gal ac^{-1}) using a single off-center nozzle (OC-06, TeeJet Technologies, Wheaton, IL). Lower branches were pulled back when necessary to prevent spraying the tree foliage. Each treatment was replicated 10 times in a randomized complete-block design, resulting in 50 ponderosa pine trees per study site. In 2007, distribution and age of ponderosa pine trees were not uniform because they arose from natural encroachment from the pasture margins. Ponderosa pine trees ranging from 5 to 10 yr old and 2 to 4 m high were targeted for treatments and blocked by tree age. In 2008, the study site had ponderosa pine trees that were the same age. Consequently, treatments were blocked by spatial distribution to create a randomized complete-block design. Plots were located at least 5 m apart. Treatment dates were May 24, 2007, and June 2, 2008. Ponderosa pine trees had broken dormancy at the dates of treatment, and the dates were within the time frame to effectively control meadow hawkweed and other broadleaf weed species.

Treatment Evaluation. Previous studies have evaluated synthetic auxin herbicide injury to ponderosa pine by estimating the percentage of trees showing missing needles or needle epinasty and by assessing leader- and lateral-candle epinasty (Paley and Radosevich 1984, Radosevich et. al. 1980). *Candles* are the new, annual growth on pine trees consisting of a flexible stem and a developing bundle of needles. Our methodology for evaluating herbicide injury approximates those studies. Two measurements were taken per tree at 1 and 12 MAT.

First, leader and lateral candles were evaluated for epinasty using an ordinal ranking of injury severity in comparison to normal growth. Candles were assessed for nonvertical candle orientation (candle epinasty) and for needle epinasty or inhibited elongation of needles (needle injury). The ordinal ranking of injury was 1, normal growth; 2, needle injury or nonvertical candle orientation present; 3, needle injury + candle epinasty, resulting in nonvertical candle orientation; 4, needle injury + candle epinasty, resulting in candle oriented horizontal or toward ground; and 5, needle injury + candle epinasty, resulting in necrosis or mortality of candle. Leader and lateral candles were evaluated separately; lateral candles were given the rank of the most severely injured lateral candle present on the treated tree. Deviations from vertical candle growth were observed on untreated trees. Evaluations of candle orientation included untreated trees to control for natural variation in candle growth.

In addition, the proportion of the total number of lateral candles per tree that showed needle epinasty and the proportion of candles showing inhibited needle elongation were counted to assess the severity of herbicide injury. Inhibited needle elongation precluded quantification of needle epinasty. Consequently, needle inhibition data were used for statistical analysis.

Data Analysis. Ordinal rankings of herbicide injury to candles were transformed into generalized logit response functions for analyses and are presented in tables as frequency distributions. It was necessary to collapse injury rankings into three categories (no injury, injury present, necrosis to mortality) for analyses resulting in two response functions:

https://doi.org/10.1614/IPSM-D-11-00052.1 Published online by Cambridge University Press

Table 2. Effect of herbicide treatments on epinastic symptoms of ponderosa pine leader and lateral candles 1 mo after treatment (MAT). The effect of treatments on leader and lateral candles were nonsignificant ($P < 0.05$).

Response variable × treatment	Rate	Treatment injury level		
		No injury	Injury present[a]	Necrosis to mortality
	kg ae ha^{-1}	% Frequency		
Leader candle 1 MAT				
Aminopyralid	0.05	65	35	0
Aminopyralid + clopyralid	0.05 + 0.10	65	35	0
Aminopyralid	0.12	55	45	0
Picloram	0.28	20	80	0
Untreated check	—	80	20	0
Lateral candle 1 MAT				
Aminopyralid	0.05	55	45	0
Aminopyralid + clopyralid	0.05 + 0.10	70	30	0
Aminopyralid	0.12	55	45	0
Picloram	0.28	35	65	0
Untreated check	—	95	0	0

[a] Deviations from vertical candle growth observed on untreated trees were included in category to control for natural variation in leader candle growth.

$$\log(p_2) - \log(p_1) \quad [1]$$

$$\log(p_3) - \log(p_1) \quad [2]$$

where p_1 is the probability of the no-injury category, p_2 is the probability of the injury present category, and p_3 is the probability of the necrosis to mortality category. Data were analyzed by evaluation date (1 and 12 MAT) and candle type (leader and lateral) as linear models using maximum-likelihood estimates, resulting in four total model evaluations. Design effects included treatment and site main effects and their interaction. Linear contrasts (2 degrees of freedom [DF]) were conducted to determine differences between treatments in significant ($P < 0.05$) main-effect models. Evaluations of the proportion of candles showing inhibited elongation of needles per tree were arcsine square root–transformed before analysis to achieve normality. Data were analyzed using ANOVA. Treatment and site and their interaction were included in the model. The LSD (5%) was used to separate treatment means. Data are presented as untransformed means.

Results and Discussion

The effects of year and its interactions with herbicide treatments were not significant ($P < 0.05$) in each model evaluation of candle injury. The frequency distributions of leader and lateral candle injury of treated ponderosa pines were not significantly different from untreated ponderosa pine at 1 MAT. General trends in the data showed that herbicide injury was present on 30 to 45% of leader and lateral candles on aminopyralid- or aminopyralid + clopyralid–treated trees, compared with 80 and 65% injury to leader and lateral candles, respectively, on picloram-treated trees (Table 2). Observed herbicide injury symptoms were predominantly leader candle epinasty and needle epinasty on leader and lateral candles across all treatments. No necrosis or mortality of individual candles was observed at this evaluation date.

Epinasty was more pronounced at 12 MAT, and significant differences ($P < 0.05$) between treatments were detected in leader candles (Table 3). Herbicide injury trends were similar on lateral candles, but there was limited evidence ($P = 0.22$) for treatment differences. The frequency of injury on leader candles from the low rate of aminopyralid treatment alone or in combination with clopyralid did not differ from the untreated check. At 12 MAT, 60 to 85% of trees showed no injury symptoms following the aminopyralid + clopyralid and low aminopyralid treatment, respectively. Conversely, the frequency of herbicide injury on leader candles for picloram or the high rate of aminopyralid exceeded injury in the untreated check. At 12 MAT, herbicide injury had become more severe, ranging from nonvertical orientation of candles and needle epinasty to mortality of individual candle stems. Picloram treatments resulted in a high frequency (65%) of leader candle necrosis or mortality and would reduce productivity of the tree. In these cases, needle formation or elongation did not occur and candles were oriented parallel to the ground surface before mortality. Herbicide injury symptoms were variable across ponderosa pine treated with

Table 3. Effect of herbicide treatments on epinastic symptoms of ponderosa pine leader and lateral candles 12 mo after treatment (MAT). Bolded response profiles are significantly different ($P < 0.05$) from the untreated check within categories.

Response variable × treatment	Rate	Treatment injury level		
		No injury	Injury present[a]	Necrosis to mortality
	kg ae ha^{-1}	% frequency		
Leader candle 12 MAT				
Aminopyralid	0.05	85	15	0
Aminopyralid + clopyralid	0.05 + 0.10	60	40	0
Aminopyralid	0.12	**25**	**70**	**5**
Picloram	0.28	**10**	**25**	**65**
Untreated check	—	95	5	0
Lateral candle 12 MAT				
Aminopyralid	0.05	90	10	0
Aminopyralid + clopyralid	0.05 + 0.10	80	20	0
Aminopyralid	0.12	70	30	0
Picloram	0.28	5	55	40
Untreated check	—	100	0	0

[a] Deviations from vertical candle growth observed on untreated trees were included in category to control for natural variation in leader candle growth.

the high rate of aminopyralid, ranging from needle epinasty and nonvertical candle orientation to prevention of needle elongation and severe necrosis.

There was no difference in leader candle injury between the low rate of aminopyralid alone and in combination with clopyralid (Table 4). The low rate of aminopyralid resulted in a frequency distribution of herbicide injury that was significantly less severe than the high rate of aminopyralid and picloram treatments. Evidence of differences between the low rate of aminopyralid plus clopyralid and picloram ($P = 0.05$) or the high rate of aminopyralid ($P = 0.09$) was marginal. There was also marginal evidence ($P = 0.06$) that picloram treatments resulted in more severe injury symptoms than the high rate of aminopyralid.

Although no evidence for treatment differences of lateral candle epinasty was observed, significant treatment differences were observed in analysis of the percentage of total candles per tree in which inhibited needle elongation was observed (Table 5). Inhibited elongation occurred on less than 1% of candles per tree in both the untreated check and the low rate of aminopyralid. The percentage of candles affected increased from low aminopyralid + clopyralid (15%) to the high rate of aminopyralid (46%) and from the high rate of aminopyralid to picloram (90%).

In this study, vegetation at the study sites and annual precipitation in 2007 (850 mm [33.5 in]) and 2008 (987 mm) were characteristic of mesic ponderosa pine sites that are seral to Douglas-fir in the inland Northwest. Annual precipitation at mesic ponderosa pine sites range

Table 4. Contrasts of maximum-likelihood estimates to test for significant differences between herbicide treatments on the response profile of leader candles 12 mo after treatment.

Pairwise comparison[a]	df	χ^2	Pr > χ^2
Aminopyralid (low) × aminopyralid (low) + clopyralid	2	3.0	0.2240
Aminopyralid (low) × aminopyralid (high)	2	11.4	0.0033
Aminopyralid (low) × picloram	2	6.9	0.0312
Aminopyralid (high) × aminopyralid (low) + clopyralid	2	4.7	0.0934
Aminopyralid (high) × picloram	2	5.4	0.0657
Picloram × aminopyralid (low) + clopyralid	2	5.9	0.0533

[a] Treatment rates: aminopyralid (low), 0.05 kg ae ha^{-1}; aminopyralid (high), 0.12 kg ae ha^{-1}; aminopyralid (low) + clopyralid, 0.05 + 0.10 kg ae ha^{-1}; picloram, 0.28 kg ae ha^{-1}.

Table 5. Effect of herbicide treatments on the percentage of candles per ponderosa pine tree in which inhibited needle elongation was observed 12 months after treatment.

Treatment	Rate	Delayed needle elongation[a]
	kg ae ha^{-1}	% total candles
Aminopyralid	0.05	< 1 a
Aminopyralid + clopyralid	0.05 + 0.10	15 b
Aminopyralid	0.12	46 c
Picloram	0.28	90 d
Untreated check	—	< 1 a
LSD		6

[a] Means followed by the same letter are not significantly different (LSD, 5%).

from 760 mm to 1,140 mm in the Pacific Northwest (Atzet et al. 1992; Uchytil 1991), whereas climax stands of ponderosa pine bordering grasslands are drier, ranging from 280 to 430 mm (Habeck 1992). Previous studies have demonstrated that sensitivity of ponderosa pine to synthetic auxin herbicide applications is greatly influenced by water stress. Paley and Radosevich (1984) showed that the date of the highest daytime water stress, measured by xylem potential, coincided with the minimum herbicide damage in ponderosa pine plantations. Ponderosa pine trees during the period of herbicide application in our study were not water stressed so injury was not minimized.

The results of our study indicate that there are differences between aminopyralid and picloram in the level of ponderosa pine injury at a spring-timed application. Significant herbicide injury levels, which would likely result in detrimental economic and ecological effects, were observed using low rates of picloram. Herbicide injury of ponderosa pine was also observed at high frequencies (70%) using the high rate (0.12 kg ae ha^{-1}) of aminopyralid, but epinastic symptoms were generally less severe compared with picloram treatments. Low levels of injury were observed across treated trees and within trees using aminopyralid (0.05 kg ae ha^{-1}) with and without clopyralid (0.10 kg ae ha^{-1}). These treatments would likely enable a land manager to minimize herbicide injury when spraying below ponderosa pine canopies while still achieving the meadow hawkweed control objective. Land managers are, however, likely to encounter a range of ponderosa pine tree ages in cleared forest sites, including saplings, and would benefit from greater study on the effects of broadcast aminopyralid applications over the top of saplings.

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Received July 15, 2011, and approved January 3, 2012.