Rangeland Ecology & Management 69 (2016) 199–205

Contents lists available at ScienceDirect

Rangeland Ecology & Management

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

Impacts of Imazapyr and Triclopyr Soil Residues on the Growth of Several Restoration Species☆,☆☆

Cameron H. Douglass [a,*], Scott J. Nissen [b], Paul J. Meiman [c], Andrew R. Kniss [d]

[a] Postdoctoral Fellow, Environmental Sciences Program, Trinity College, Hartford, CT 06106, USA
[b] Professor, Bio-agricultural Sciences and Pest Management Department, Colorado State University, Fort Collins, CO 80523, USA
[c] Associate Professor, Forest and Rangeland Stewardship Department, Colorado State University, Fort Collins, CO 80523, USA
[d] Assistant Professor, Plant Sciences Department, University of Wyoming, Laramie, WY 82071, USA

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 15 January 2016
Accepted 18 January 2016
Available online 7 April 2016

Key Words:
active restoration seeding
herbicide degradation
herbicide dose response
minimum plant back intervals
tamarisk

ABSTRACT

Herbicides are frequently used in natural systems to control invasive plants, but nontarget impacts from persistent soil residues can result in unintended ecosystem effects. Imazapyr and triclopyr are herbicides that are widely used in noncrop areas such as rangelands to manage perennial weeds, especially woody species such as tamarisk (saltcedar). Due to widespread environmental and anthropogenic changes in the American southwest, tamarisk, which is commonly thought to co-occur only with riparian plants, is increasingly being found in communities of upland rangeland species. Using an in vitro study combined with high-performance liquid chromatography (HPLC) analyses, imazapyr and triclopyr degradation rates were determined in six Colorado soils. In addition, the relative sensitivity of desirable species to the two herbicides was determined in a field dose response study. Exponential decay models estimated that triclopyr degradation (half-lives of 5 − 16 days) was 20 times more rapid than imazapyr degradation (half-lives of 82 − 268 days). All species tested were sensitive to imazapyr residues, but the degree of sensitivity was strongly dependent on soil properties. Sensitive species (alkali sacaton and western wheatgrass) were tolerant of imazapyr residues in some soils 20 − 23 months after applications. Relatively insensitive species (slender wheatgrass) were tolerant of imazapyr residues in the same soils 10 months after applications. American licorice was sensitive to triclopyr residues up to 89 days after applications, and several grasses (including sideoats grama) showed minor sensitivity. Our study indicates that there is an interaction between the spatial variability in herbicide degradation driven by edaphic properties and the sensitivity of plants to a herbicide, which could be exploited by management practitioners to aid in site rehabilitation. Specifically, managers could stagger planting of species temporally on the basis of their sensitivity to herbicide residues or could target areas of treated sites for planting that are known to have soil types facilitating relatively rapid herbicide degradation.

Introduction

Herbicides are useful tools for managing invasive exotic plants in natural areas, but their use may result in unintended nontarget impacts. In particular, when herbicides are used to control invasive plants where seeding will occur, the herbicide residues can negatively affect seeded plants (Pearson and Ortega 2009; Sher et al. 2010). In this study, we examined nontarget plant species impacts of imazapyr and triclopyr, two herbicides widely used in natural areas to control woody invasive plants, such as tamarisk (*Tamarix* spp. L.) (Nissen et al. 2010).

Tamarisk is now one of the most common woody species in many portions of the arid and semiarid western United States and therefore is a frequent target for management (Ringold et al. 2008; Douglass et al. 2013). Tamarisk is generally considered a facultative phreatophyte, but numerous environmental changes have taken place in the species' introduced range that result in tamarisk commonly co-occurring with understory species thought to be restricted to upland habitats (Merritt and Poff 2010; Reynolds and Cooper 2011; Perry et al. 2012). For example, in the Arkansas River watershed of southeastern Colorado, tamarisk is found frequently in communities with an understory composed of alkali sacaton (*Sporobolus airoides* [Torr.] Torr.),

☆ Research was funded by Colorado Water Conservation Board Grant OE PDA 10000000059 to C.H.D. and S.J.N. and a Colorado State University Agricultural Experiment Station grant to S.J.N.
☆☆ At the time of research, Douglass was a graduate research assistant, Bio-agricultural Sciences and Pest Management Dept, Colorado State University, Fort Collins, CO 80523, USA.
* Correspondence: Cameron H. Douglass, Environmental Sciences Program, Trinity College, Hartford, CT 06106, USA.
E-mail address: cameron.douglass@trincoll.edu (C.H. Douglass).

http://dx.doi.org/10.1016/j.rama.2016.01.006
1550-7424/

sand dropseed (*S. cryptandrus* [Torr.] A. Gray), western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Love), fourwing saltbush (*Atriplex canescens* [Pursh] Nutt.), and rubber rabbitbrush (*Ericameria nauseosa* [Pall. Ex Pursh] G.L. Nesom & Baird) (Lindauer 1983; Douglass 2013; USDA-NRCS, 2014).

Imazapyr is a broad-spectrum herbicide, and products containing this compound can be applied using several different methods and timings (Senseman 2007). Imazapyr is used frequently to control invasive plants in wetter habitats because it rapidly photodegrades when applied to water, but not soils (Mallipudi et al. 1991). Imazapyr residues can be long-lived in the soil, with reported soil half-lives (t_{50}) between 25 d and 142 d, depending on edaphic and environmental conditions (Senseman 2007). Triclopyr is generally only phytotoxic to dicotyledonous plants and degrades rapidly in soil ($t_{50} = 10 - 46$ d) (Senseman 2007). Soil degradation of both herbicides is known to occur primarily via microbial activity. Therefore, environmental parameters that promote soil biological activity (e.g., soil moisture levels) generally increase degradation rates of both herbicides (Skopp et al. 1990; Johnson et al. 1995b; McDowell et al. 1997; Conant et al. 2004; Newton et al. 2008).

Given the choice among several herbicides with similar efficacy against the target weed, the herbicide with the least potential for nontarget environmental effects is generally recommended (Masters and Nissen 1998). However, there are circumstances where the herbicide that is known to have nontarget impacts is more appropriate given project objectives and the landscape-scale of treatments. This is the case with large-scale aerial applications to manage tamarisk, where imazapyr is most commonly used in spite of its broad spectrum of activity and relatively long-lived soil residues (Duncan and McDaniel 1998; Nissen et al. 2010). Understanding the relative sensitivity of desirable native species to herbicide residues could allow for more reliable plant establishment when seeding is used to restore native species following such herbicide applications. For instance, plants that are relatively more tolerant of imazapyr residues could be seeded first, and then species that are more susceptible could be seeded later after imazapyr degrades.

However, few studies have empirically tied imazapyr or triclopyr degradation in field soils to the sensitivity of plant species endemic to regions where tamarisk has proliferated (Kaeser and Kirkman 2010; Ortega and Pearson 2011). Therefore, the objectives of our study were to 1) determine imazapyr and triclopyr degradation rates in several soils from tamarisk-dominated sites in southeastern Colorado and 2) determine the sensitivity of nine important restoration plant species to the herbicides in the field.

Methods

Four tamarisk-infested sites (CC, FL, LJ, and OR) in the Arkansas River watershed near Pueblo, Colorado (Table 1) were used solely as soil sources for herbicide degradation experiments (Fig. 1). Two other sites (AR and HO) located in north-central Colorado were used for both herbicide degradation and field dose response experiments. NRCS site descriptions do not exist for the precise locations of the study at the CC and FL sites. Both sites had fine-textured soils and plant communities dominated by alkali sacaton, western wheatgrass, fourwing saltbush, and twoscale saltbush (*Atriplex micrantha* Ledeb.). The LJ and OR sites are categorized as “salt meadows” by NRCS, with slightly coarser soils, and plant communities dominated by alkali sacaton, sand dropseed, western wheatgrass, and inland saltgrass (*Distichlis spicata* [L.] Greene) (Soil Survey Staff, 2015). The AR and HO sites are on research farms operated by the Colorado State University Agricultural Experiment Station, and these sites are characterized by fine-textured clay loam soils.

Table 1
Soil type, pH, cation exchange capacity (CEC), organic matter (OM), and texture for sites sampled in this study. Sites marked with an asterisk (*) were those at which the plant species sensitivity studies were conducted. All results from private laboratory analysis.

Site	Latitude	Longitude	Soil subgroup	Soil series	Soil type
AR*	40°38′51″	−105°0′1″	Aridic Haplustalfs	Fort Collins	Clay loam
CC	38°29′27″	−105°12′7″	Ustic Torriorthents	Shingle	Loamy sand
FL	38°22′47″	−105°2′16″	Aquic Ustifluvents	N/A	Sandy loam
HO*	40°36′42″	−104°59′38″	Aridic Argiustolls	Nunn	Clay loam
LJ	37°59′34″	−103°33′0″	Ustic Torrifluvents	Glenberg	Sandy loam
OR	38°10′57″	−103°44′52″	Vertic Fluvaquents	Apishapa	Loam

	pH	CEC (meq 100 g^{-1})	OM (%)	Sand (%)	Silt (%)	Clay (%)
AR*	8.10	26.60	1.90	39.2	32.0	28.8
CC	7.78	16.30	1.70	85.2	11.6	3.2
FL	7.90	19.75	1.75	61.2	30.6	8.2
HO*	7.90	31.10	3.00	30.8	30.0	39.2
LJ	8.00	20.65	1.75	68.2	28.6	3.2
OR	7.80	25.00	3.10	46.2	35.4	18.4

Laboratory Herbicide Degradation Experiments

We collected soil from the upper 10 cm of untreated areas at each of the six sites 16 − 27 May 2011. Moist soils were spread out in 1- to 2-cm layers on butcher paper and air-dried for 72 h. Air-dry soils were sieved (2 mm), and a subsample was removed for chemical and textural analyses (AgSource Laboratories, Lincoln, NE). A second subsample was treated with 1 mg active ingredient (ai) kg soil^{-1} of imazapyr and triclopyr using a handheld spray bottle containing the herbicide solution. Treatment solutions were made with 99.8% pure analytical standards of the two herbicides. The imazapyr concentration was roughly equivalent to the typical field application rate (1.12 kg ai ha^{-1}), while the triclopyr concentration was 57% of the typical field rate (1.96 kg ai ha^{-1}). The aqueous volume of the treatment solutions was adjusted to bring each soil to 75% of field capacity. Treated soils were homogenized in a soil tumbler for 30 minutes.

Twenty-seven subsamples (20 gm) of each herbicide-treated soil were weighed into 50 mL polypropylene centrifuge tubes and held in a dark incubator at 23 − 25°C and 65 − 70% relative humidity. At 0, 3.5, 7, 14, 28, 56, 112, and 160 days after treatment (DAT), three tubes containing soil from each site were removed and stored at −20°C until analysis. Every other week during the experiment, tubes were vigorously shaken and the lid was removed momentarily to allow air exchange. Water was added periodically to maintain soils at 75% of field capacity. The laboratory herbicide degradation experiment was repeated, and each soil sample was extracted and analyzed in triplicate using the HPLC methodology described in Appendix S1 (available online at http://dx.doi.org/10.1016/j.rama.2016.01.006).

Field Plant Species Sensitivity (Dose-Response) Experiments

The following serial dilutions of imazapyr (Habitat, 28.7% isopropylamine salt [BASF Corp., Florham Park, NJ]) and triclopyr (Garlon 4 Ultra, 60.45% butoxyethyl ester [Dow Agro Sciences LLC, Indianapolis, IN]) herbicides were applied to plots: 1×, 0.5×, 0.25×, 0.125×, 0.0625×, 0.0313×, 0.0156×, and 0× (**Table S1** available online at http://dx.doi.org/10.1016/j.rama.2016.01.006). The highest (“1×”) imazapyr rate was 0.28 kg ai ha^{-1}, which corresponds to 25% of the typical field application rate (and of the concentration used in degradation studies). The highest triclopyr rate was 3.92 kg ai ha^{-1}, which corresponds to twice the typical field application rate and 350% of the triclopyr concentration used in degradation studies. We selected these imazapyr and triclopyr ranges based on previous experience to allow for a range of responses from mortality to survival. Herbicide applications were made on 1 June (HO) and 6 June (AR) 2011, using a CO_2-pressurized backpack sprayer calibrated to deliver spray solutions at 141 l ha^{-1}. Herbicide applications were made to bare soil, and plants were seeded within 24 hours of applications. Untreated control plots (the “0×” dose earlier) were also included in the experimental design, and the entire experimental area was hand-weeded to reduce weed competition.

Two forbs, one shrub, and six grasses were selected for use in the field dose response experiment because of their common occurrence

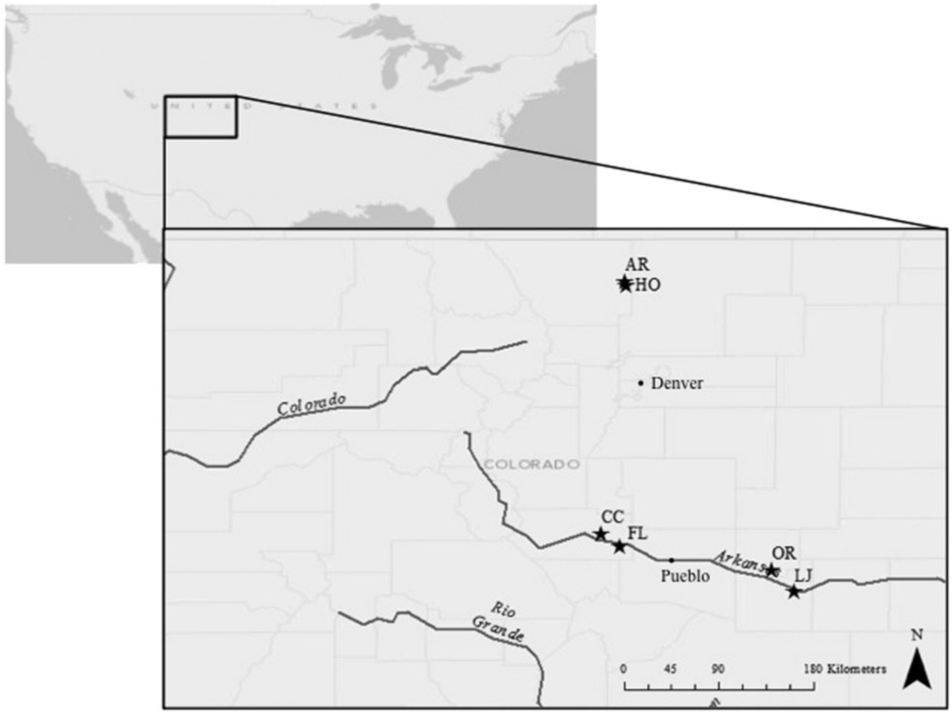

Figure 1. Location of tamarisk soil sampling sites in eastern Colorado, United States. Sites "AR" (CSU Agricultural Research, Development and Education Center) and "HO" (CSU Horticultural Research Center) were also used for field herbicide sensitivity studies. Sites "CC" (Canon City), "FL" (Florence), "LJ" (La Junta), and "OR" (Ordway) were sites in the Arkansas River Watershed used for a simultaneously occurring large-scale tamarisk management study (Douglass et al. 2013).

at sites in the Arkansas River watershed where tamarisk occurs (**Table S2**, available online at http://dx.doi.org/10.1016/j.rama.2016.01.006) (Lindauer 1983; Douglass 2013). A split-split plot experimental design was replicated at the two sites (AR and HO). Herbicides were applied within 3 × 23 m plots, and plant species were seeded perpendicular to the herbicide treatment plots. A modified seed drill was used to plant seeds 1 cm deep in two rows. Forbs and grasses were seeded at densities of 0.39 and 1.18 seeds cm^{-1} of row, respectively. Each plant species × herbicide rate treatment was replicated four times at each of the two sites. Total water from June to October 2011 was 44.0 cm and 49.0 cm, respectively, at AR and HO.

Aboveground biomass for all species was collected from a randomly selected 0.25 m^2 portion of each plot 24−25 October (HO) and 1 November (AR), with the exception of common sunflower (*Helianthus annuus* L.) biomass, which was collected 2 weeks earlier. All plants were clipped at the soil surface, and biomass was oven-dried at 70°C for 7 d and then weighed. We collected additional data on species growth (stem density, plant height, and frequency) and fecundity dose responses to imazapyr and triclopyr, but their presentation and discussion were determined to be outside the scope of this manuscript. Information detailing methods for these other measured responses are reported in Appendix S2 (available online at http://dx.doi.org/10.1016/j.rama.2016.01.006).

Statistical Analyses

Herbicide degradation rates were estimated separately for imazapyr and triclopyr in soils from the six sites using the following exponential decay equation that relates the response y (herbicide concentration expressed as mg kg^{-1}) to time t (days after treatment):

$$y = d^{*}\left(exp^{-t/e}\right) \qquad (1)$$

where d = estimated herbicide concentration immediately after application, and e = shape parameter related to the steepness of the decay curve. The e parameter was constrained to values > 0.8 to aid model convergence. These regression models were used to calculate the soil half-life (t_{50} value, or the number of days to reach a 50% reduction in herbicide concentration) for imazapyr and triclopyr in soil from the six sites. Relationships between degradation rates of the two herbicides and soil chemical (pH, CEC) and physical (organic matter and texture) characteristics were analyzed using principal components analysis. The number of principal components axes to retain for analysis was determined using scree plots of eigenvalues because interpretable components were easily identified for our data (Jackson 1993). Extracted components were rotated using varimax rotation (Gotelli and Ellison 2013).

The herbicide rate that caused a 20% reduction in plant species biomass (GR_{20}) was estimated using modified log-logistic dose response models (Seefeldt et al. 1995; Knezevic et al. 2007):

$$z = c + (d - c)/\left(1 + exp^{[b(\log[x] - \log[GR20])]}\right) \qquad (2)$$

where c = lower limit, d = upper limit, x = herbicide rate (kg ai ha^{-1}), and b = relative slope at the GR_{20} value. Twenty percent was established as the response point of interest because this level of reduction in growth of seeded plant species could be considered tolerable by restoration practioners. Model reduction was conducted by setting the c-parameter equal to zero, then comparing AIC values for the 3- and 4-parameter models. In all cases, this analysis indicated that the 3-parameter model provided a better fit to the data, so the 3-parameter log-logistic model is presented. Log-logistic dose response models were fit separately for the two experiment sites ("AR" and "HO").

The amount of time (I_{20}) required for each herbicide to degrade to the rate estimated to cause a 20% reduction in plant biomass (GR_{20}) was then estimated for each species from herbicide degradation curves (Eq. 1). Compared with more commonly used GR_{50} and I_{50} estimates, the GR_{20} and I_{20} estimates we used deliberately provide a relatively conservative safe plant back interval. The "drc" package in R (ver. 2.15.2) was used for analyses of variance (ANOVA), exponential decay, and logistic dose response modeling (Ritz and Streibig 2005; R Development

Core Team 2014). JMP (ver. 10.0.1, SAS Institute, Cary, NC) software was used for all other statistical analyses.

Results

Herbicide Degradation

Mean retention time using the described HPLC methodology was 7.45 minutes (coefficient of variation [CV] = 4.6%) for imazapyr and 11.50 minutes (CV = 0.6%) for triclopyr. Recovery of imazapyr in fortified, quality control soil samples averaged 91.3% (CV = 21.5%), and mean triclopyr recovery was 86.5% (CV = 13.5%). The limit of quantification (LOQ) was 0.01 mg kg^{-1} in the soils tested, and the limit of detection (LOD) was 0.005 mg kg^{-1}. Details on our HPLC methodology are available in Appendix S1 (available online at http://dx.doi.org/10.1016/j.rama.2016.01.006).

Similarities among the six sites in their soil herbicide degradation profiles allowed us to construct generalized models on the basis of relative rates (slow, moderate, and fast) of imazapyr and triclopyr degradation in our study soils. Site pairs that shared imazapyr degradation profiles were slow (AR & LJ), moderate (CC & FL), and fast (HO & OR). Sites that shared triclopyr degradation profiles were slow (FL & LJ), moderate (CC & AR), and fast (HO & OR). Imazapyr degradation occurred most rapidly in soils from OR (t_{50} = 82 d [Fig. 2]) and most slowly in soils from AR and LJ (mean t_{50} = 259 d). Soil half-lives in soils from the remaining sites were 122 d (HO) to 165 d (CC and FL). Triclopyr degradation occurred most rapidly in soils from OR and HO (mean t_{50} = 5 d) and most slowly ($P < 0.05$) in soils from FL (t_{50} = 12 d) and LJ (t_{50} = 16 d). Average triclopyr degradation occurred 19 times faster (mean t_{50} = 9 d) than average imazapyr degradation (mean t_{50} = 175 d).

Two principal components accounted for 86% of the variation in soil herbicide degradation rates (Fig. 3). The first principal component (43% of the variation) indicated that degradation of both herbicides occurred more rapidly in finer-textured soils with higher organic matter and CEC. The second principal component (an additional 43% of the variation) suggested that triclopyr degradation in particular occurred more slowly in coarser-textured soils.

Plant Species Sensitivity

Results presented in this section are based solely on biomass data. Results for other plant dose responses (morphology, abundance, and fecundity data) to herbicide treatments are reported in **Tables S3** (imazapyr) and **S4** (triclopyr) (available online at http://dx.doi.org/10.1016/j.rama.2016.01.006). Some species were highly tolerant of all applied concentrations of triclopyr (fourwing saltbush, slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Shinner], and bottlebrush squirreltail [*Elymus elymoides* (Raf.) Swezey]) and imazapyr (bottlebrush squirreltail) and showed no dose response in the study. Common sunflower did not establish sufficiently at either site, so sensitivity data are not presented for this species.

Fourwing saltbush was sensitive to imazapyr residues (Table 2). Consequently, in soils with fast to moderate degradation profiles, 14.9 − 28.9 months would need to pass before imazapyr residues reached the GR_{20} rate for the species (Table 3). Alkali sacaton was the grass most sensitive to imazapyr residues, and I_{20} values for the species in soils with fast to moderate degradation profiles were 20.6 − 32.7 months. Western wheatgrass was less sensitive to imazapyr, and the predicted I_{20} (22.7 − 30.9 months) varied relatively little across soils with different degradation profiles. Sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.) and Canada wildrye (*Elymus canadensis* L.) were similarly sensitive to imazapyr. Predicted I_{20} values in soils with fast to moderate degradation profiles were 15.0 − 28.1 months for the two species. For soils with slow degradation profiles, I_{20} values for these species were 42.5 − 53.5 months. Slender wheatgrass was the most tolerant grass species to imazapyr, with an I_{20} value of 18.9 months in soils with moderate degradation profiles. In soils with slower degradation profiles, the predicted imazapyr I_{20} for slender wheatgrass was 37.4 months.

American licorice (*Glycyrrhiza lepidota* Pursh) was relatively sensitive to triclopyr (Table 2). Models predicted American licorice I_{20} values between 10.3 d (fast degradation profiles) and 89.1 d (slow degradation profiles). Grass sensitivity to triclopyr was highest for sideoats grama, with I_{20} values of 28.3 − 58.9 d in soils with moderate to slow degradation profiles. Alkali sacaton and Canada wildrye were also sensitive to triclopyr, with predicted I_{20} values of 2.1 − 3.6 d for soils with fast to moderate degradation profiles. Western wheatgrass was highly tolerant of triclopyr and was only negatively affected by residue levels found in study soils for a few hours after applications.

Discussion

Herbicide Degradation

Overall, we found that triclopyr residues degrade much more rapidly than imazapyr residues, confirming what is known about the two herbicides (Senseman 2007). Imazapyr degradation occurred relatively quickly in soils from Ordway (t_{50} = 82 d) and also in soils from HO, FL, and CC (mean t_{50} = 150 d). These results corroborate previous studies that reported soil imazapyr half-lives of 25 − 144 d (McDowell et al.

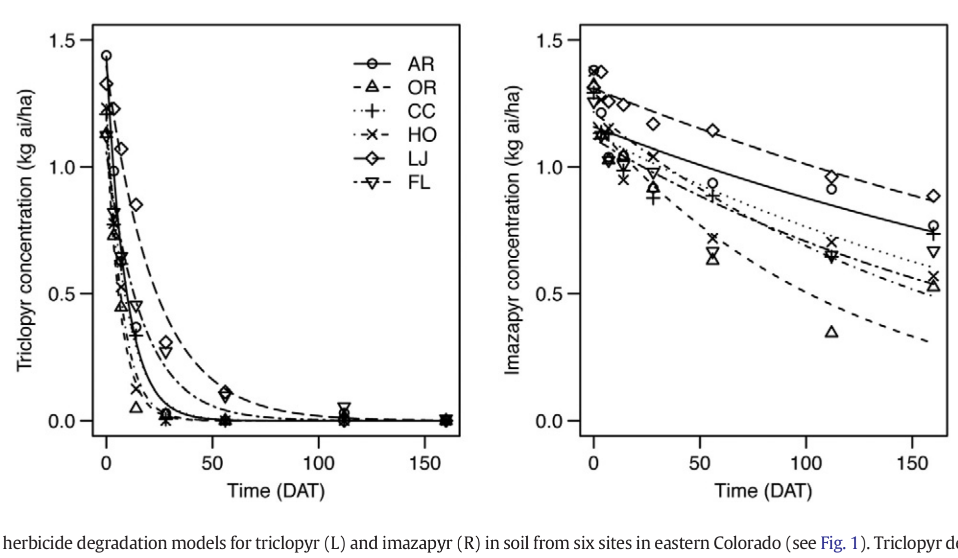

Figure 2. Exponential decay herbicide degradation models for triclopyr (L) and imazapyr (R) in soil from six sites in eastern Colorado (see Fig. 1). Triclopyr decay model residual standard error = 0.09 (df = 276), and imazapyr decay model residual standard error = 0.18 (df = 276).

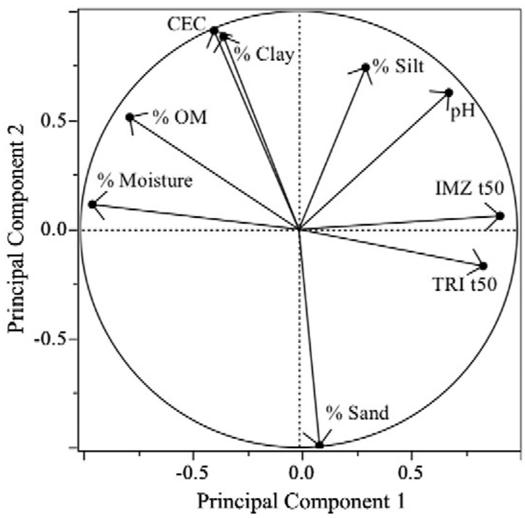

Figure 3. Factor loading plot of standardized and rotated variables from principal components analysis of relationship between imazapyr and triclopyr soil degradation rates (analyzed as t_{50} values) and physical (organic matter [%] and texture [% sand, silt, clay]) and chemical (pH, CEC [meq 100 g^{-1}]) characteristics of the Colorado soil used in this study. Principal component 1 explained 43.3% of the variance between the variables, and principal component 2 an additional 42.7% of the variance.

1997; Borjesson et al. 2004). However, imazapyr degradation in two of our soils (AR and LJ) occurred 80% slower (mean $t_{50} = 259$ d) than was expected. On the other hand, triclopyr degradation occurred in $4-7$ d for all sites except FL ($t_{50} = 12$ d), and LJ ($t_{50} = 16$ d). These degradation rates are mostly faster than what has been reported ($t_{50} = 10-46$ d), but other studies have found soil half-lives as short as 5 d for some soils (Johnson et al. 1995a; Senseman 2007).

On the basis of previous work with both herbicides, we expected that differences between soils in texture and organic matter would determine varying soil water holding capacity and herbicide adsorption and consequently affect degradation rates (Pusino et al. 1994; McDowell et al. 1997; Wang and Liu 1999; Thompson et al. 2000). Reduced soil moisture levels are known to directly inhibit aerobic microbial activity that is critical for the degradation of both herbicides (Conant et al. 2004). Edaphic predictions largely held true for soils in our study. Degradation of both herbicides occurred more rapidly in fine-textured soils with relatively high organic matter. Degradation rates were slowed in soils with lower organic matter, particularly in coarser-textured soils.

Plant Species Sensitivity

Triclopyr was so short-lived in the specific soils tested that overall productivity of most plant species was unaffected by applications at even twice the normal field rate (1.96 kg ai ha^{-1}). American licorice and sideoats grama were exceptions to this trend, with triclopyr residues affecting these species persisting for $2-3$ mo in soils with slow degradation profiles. Triclopyr is not normally considered to be injurious to grasses, but Huffman and Jacoby (1984) reported that high rates of triclopyr (roughly equivalent to the highest rate we used) decreased germination of sideoats grama by 50%. In another study, 1.09 kg ai ha^{-1} of a slightly different triclopyr formulation (Garlon 3A, 44.4% TEA salt) applied before planting reduced biomass $67-92$% in several species (Kaeser and Kirkman 2010). Neither of these studies was carried out under field conditions. Together with our results, though, they indicate there may be greater potential for injury to sensitive grasses from triclopyr residues than is generally assumed, which is worthy of further study.

Sensitivity of many plants to imazapyr is well documented (Kaeser and Kirkman 2010). What is surprising about our results is that species tolerance to imazapyr, while still relatively low overall, was variable. Western and and slender wheatgrass were sensitive to imazapyr residues equivalent to $10-18$% of the typical imazapyr field application rate (1.12 kg ai ha^{-1}). Fourwing saltbush and Canada wildrye were sensitive to imazapyr residues equivalent to $2-3$% of the typical imazapyr field application rate. While knowledge of species' relative sensitivity to imazapyr is by itself valuable, our study also found a strong interaction between plant species' sensitivity to imazapyr and spatially variable edaphic factors affecting the herbicide's soil persistence. Productivity of some species in our study was negatively affected by imazapyr residues expected 10 months after applications in some soils. Productivity

Table 2
Imazapyr and triclopyr rates at which restoration plant species biomass was reduced 20% (GR_{20}) as estimated from log-logistic dose response models of the form $y = c + (d - c)/(1 + exp^{[b(log[x] - log[GR20])]})$. Data are from companion field dose response studies carried out at two sites (AR and HO) in northern Colorado.

	Species	AR		HO	
		GR_{20} (kg ai ha^{-1})	SE	GR_{20} (kg ai ha^{-1})	SE
IMAZAPYR	Alkali sacaton	PE [1]		0.017	0.010
	Fourwing saltbush	< .000	< .000	0.055	0.030
	Canada wildrye	0.016	0.020	0.052	0.020
	Sideoats grama	0.039	0.100	0.056	0.020
	Western wheatgrass	0.103	0.100	0.011	0.020
	Slender wheatgrass	0.059	0.040	0.138	0.090
	Bottlebrush squirreltail	PE [1]		NR [2]	
	American licorice	PE [1]		PE [1]	
TRICLOPYR	American licorice	0.015	< .000	0.281	0.580
	Sideoats grama	0.067	0.130	1.540	0.520
	Alkali sacaton	PE [1]		0.891	0.960
	Canada wildrye	1.606	0.770	0.825	0.530
	Western wheatgrass	1.370	1.090	NR [2]	
	Fourwing saltbush	NR [2]		NR [2]	
	Bottlebrush squirreltail	PE [1]		NR [2]	
	Slender wheatgrass	NR [2]		NR [2]	

[1] PE, the given species did not establish sufficiently for biomass samples to be collected.
[2] NR, the given species demonstrated no measurable response to imazapyr at any rates used in the study.

Table 3
Time until herbicide soil residue levels fell below concentrations at which dose response models predicted that seeded restoration species biomass would be reduced 20%. Time predictions (I_{20}) were estimated from exponential decay models (see Fig. 2) using species specific growth response data (GR_{20}) derived from log-logistic dose response models (see Table 2). Data were calculated separately for site pairs that shared fast, moderate or slow degradation profiles[1].

	Species	FAST		MODERATE		SLOW	
		I_{20} (d)	SE	I_{20} (d)	SE	I_{20} (d)	SE
IMAZAPYR	Alkali sacaton	626	83	994	167	PE [2]	
	Western wheatgrass	690	62	714	120	940	186
	Fourwing saltbush	453	60	879	148	3,305	655
	Canada wildrye	462	61	830	139	1,626	322
	Sideoats grama	451	60	751	126	1,293	256
	Slender wheatgrass	316	42	575	97	1,138	226
	Bottlebrush squirreltail	NR [3]		NR [3]		PE [2]	
	American licorice	PE [2]		PE [2]		PE [2]	
TRICLOPYR	American licorice	10.3	0.6	42.6	2.6	89.1	6.2
	Sideoats grama	PE [2]		28.3	1.7	58.9	4.1
	Canada wildrye	2.6	0.2	PE [2]		PE [2]	
	Alkali sacaton	2.1	0.1	3.6	0.2	PE [2]	
	Western wheatgrass	NR [3]		<1	<1	<1	<1
	Fourwing saltbush	NR [3]		NR [3]		NR [3]	
	Bottlebrush squirreltail	NR [3]		NR [3]		PE [2]	
	Slender wheatgrass	NR [3]		NR [3]		NR [3]	

[1] Site pairs that shared degradation profile were as follows: imazapyr – fast (HO/OR), moderate(CC/FL), slow (AR/LJ); triclopyr – fast (HO/OR), moderate (AR, CC), slow (FL, LJ).
[2] PE, the given species did not establish sufficiently for biomass samples to be collected.
[3] NR, the given species demonstrated no measurable response to triclopyr at any rates used in the study.

of other species was still impacted by residues expected as long as 4 years after applications, depending on a given soil's degradation profile.

Species sensitivity results for soils in which imazapyr degraded slowly should be thought of as worst-case scenarios because our experimental design involved planting seeds into recently (within 24 hours) sprayed soils. This design likely concentrated imazapyr in the top soil layer into which seeds were planted. In many scenarios time would pass between imazapyr applications and seeding, and imazapyr would be more fully distributed throughout the soil profile. Under certain soil conditions (neutral-high pH levels, low organic matter, and clay content), and with precipitation, imazapyr can move up to 25 cm downwards in the soil profile within months of application (Vizantinopoulos and Lolos 1994; McDowell et al. 1997; Borjesson et al. 2004). Data presented for restoration species sensitivity in soil with moderate to fast imazapyr degradation profiles are more likely to be representative of applicable real-world management scenarios.

The persistence, mobility, and ultimate biological availability and activity of herbicides in soils is very site specific (Ogle and Warren 1954; Gevao et al. 2000). This study provides evidence for the important implications of herbicide degradation rates and resulting soil persistence on the establishment and growth of desirable plants. Herbicides such as imazapyr and triclopyr are commonly used in natural areas to control unwanted plant species and can serve beneficial roles in such efforts when properly used. Appropriate and informed herbicide use can favor the establishment of valuable native species, as Masters and Nissen (1998) demonstrated in their work on *Euphorbia esula* L. (leafy spurge) management in the Great Plains. Chemical weed management can also result in unintended negative outcomes, including the facilitation of secondary invasions following the removal of targeted species (Rinella et al. 2009; Ortega and Pearson 2011). In a companion study we found that large-scale aerial imazapyr treatments of tamarisk led to early successional dominance by the ruderal species kochia (*Bassia scoparia* [L.] A.J. Scott), which then inhibited understory plant community recovery (Douglass 2013).

There are often multiple approaches to controlling target weeds such as tamarisk. The use of integrated strategies incorporating mechanical or biological control methods can minimize negative environmental impacts to sites from invasive species management (Masters and Sheley 2001; Shafroth et al. 2008; Flory and Clay 2009). Also, application methods targeting individual plants rather than large areas can reduce the amount of a herbicide applied and minimize potential nontarget impacts (Rinella et al. 2009). It is critical that natural resource managers carefully consider treatment options for a given target species and, in particular, take into account possible environmental fates of herbicides, as well as how their persistence may affect revegetation. Finally, further study is necessary to develop imazapyr and triclopyr degradation models for a wider range of soil types and dose response models for a larger variety of relevant species. Such information would allow land managers to better predict herbicide soil residue levels through time and potential environmental impacts following common herbicide applications.

Implications

Rangeland managers using herbicides to control perennial weeds and invasive plants may understand that persistent herbicide residues can affect subsequently seeded species. It may not be as commonly known, though, that environmental and soil properties largely determine soil residue persistence. As a consequence, herbicides applied over a large area may vary spatially in their degradation rates. Small differences between adjacent soil types in texture and organic matter content, along with other properties, may result in the same plant species having variable sensitivities to the same herbicide across a large treated area. Data from our study will allow managers to be able to better plan for restoration seeding efforts following imazapyr or triclopyr applications by providing species and soil-specific minimum plant back intervals.

Acknowledgement

This article is dedicated to Galen R. Brunk, a consummate scientist and friend whose laboratory assistance on this research was invaluable.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rama.2016.01.006.

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