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

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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.),

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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