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Seeding Causes Long-Term Increases in Grass Forage Production in Invaded Rangelands☆

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ABSTRACT

Seeding is sometimes used in attempts to increase grass forage production in invaded rangelands, but insufficient long-term data prevent determining if seeded grasses are likely to become and remain productive enough to justify this expensive practice. We quantified long-term seeding outcomes in a widespread Rocky Mountain foothill habitat invaded by leafy spurge (*Euphorbia esula* L.) and several exotic grasses. Fourteen yr after seeding, the most productive grass (bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve]) produced 900 (100, 12 000) kg ha^{-1} [mean (95% CI)], which was about 70% of total plant community biomass. This result was not greatly altered by grazing according to an unreplicated, grazed experiment adjacent to our replicated ungrazed experiment. Regardless of treatment, *E. esula* gradually became less productive and seeded and unseeded plots produced similar *E. esula* biomass 14 yr after seeding. *P. spicata* reduced exotic grasses about 85%. Our results resemble those of another foothills study of another invasive forb (*Centaurea stoebe* L. ssp. *micranthos* [Gugler] Hayek) and a Great Plains study of *E. esula*, so foothills seeding outcomes seem somewhat insensitive to invader composition, and seeding can increase forage across much of *E. esula's* range. While there is always some risk seeded grasses will fail to establish, our study combined with past studies identifies invaded habitats where seeded grasses have a good possibility of forming persistent, productive stands.
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Introduction

Invasive plants with poor forage characteristics have replaced forage grasses on millions of hectares of western US rangelands (Duncan et al. 2004). Examples include leafy spurge (*Euphorbia esula* L.), an invasive forb not typically heavily consumed by cattle, elk, and deer (Trammell and Butler 1995), and downy brome (*Bromus tectorum* L.), an invasive annual grass lacking palatability and protein content beyond early growth stages (Cook and Harris 1952).

Attempts to increase forage quantity and quality sometimes involve seeding. Seeding is considered failure prone, though seeded populations are rarely tracked long enough to conclusively determine their fates. When grasses remain sparse a few years after seeding (e.g., Piper and Pimm 2002; Fansler and Mangold 2011), it is tempting to assume they will remain sparse indefinitely and this assumption is sometimes correct according to a few longer-term studies (Ferrell et al. 1998; see fig. 8 of Rinella et al. 2012; Ott et al. 2019). However, in areas infested with sulfur cinquefoil (*Potentilla recta* L.), seeded grass cover jumped from 8% to 50% between 3 and 6 yr after seeding (Endress et al. 2007; Endress et al. 2012), and in areas invaded by spotted knapweed (*Centaurea stoebe* L. ssp. *micranthos* [Gugler] Hayek), seeded grasses went from sparse to dominant between 2 and 15 yr after seeding (Rinella et al. 2012). Ott et al. (2019), Prodgers (2013), and Copeland et al. (2019) provide further examples of seeded grasses gradually increasing. In short, sparse grass stands are not a good sign a few years after seeding, but it is not assured stands will remain sparse indefinitely.

On the other hand, productive stands are a good sign early after seeding, but it is not assured quickly proliferating stands will remain productive over the long term. After quickly proliferating, seeded grasses sometimes gradually decline and other times remain productive for prolonged monitoring periods (5–12 yr)

(Ferrell et al. 1998; Thacker et al. 2009; Robins et al. 2013; Davies and Boyd 2018; Stonecipher et al. 2019). When grasses gradually decline, it is likely a consequence of invaders recovering from herbicides and/or tillage combined with seeding (e.g., Benz et al. 1999; Metier et al. 2018).

In summary, short-term results are unreliable indicators of long-term seeding outcomes, so more long-term data are needed to determine which seeded grasses can flourish in which invaded environments. The rough fescue (*Festuca altaica* Trin.) habitat we studied is prevalent in northern Rocky Mountain foothills (Taylor 1994). Long-term research indicates seeding can return forage production to foothills invaded by the short-lived, tap-rooted perennial forb spotted knapweed (*C. stoebe* L. ssp. *micranthos* [Gugler] Hayek) (Rinella et al. 2012), and if this is also true for the long-lived, rhizomatous weed of this study *(E. esula),* it will suggest seeding outcomes are somewhat consistent across invader species. Finally, long-term research shows seeded grasses can maintain robust stands in *E. esula*−invaded northern Great Plains habitats (Ferrell et al. 1998), and if this is also true for foothill habitats, it will suggest seeding can reverse forage losses throughout *E. esula's* invasive range.

We seeded five grasses, and previous studies led us to hypothesize one or more of these grasses would be productive 14 yr after seeding (Ferrell et al. 1998; Rinella et al. 2012). We hypothesized the most productive grasses would suppress *E. esula* and exotic grasses. Grasses were sown with and without herbicide, and based on Rinella et al. (2012), we hypothesized seeded biomass would remain greater where herbicide was applied 14 yr earlier.

Methods

Study Area

The study occurred near Lolo, Montana (46°44′7.36″N, 114°1′26.08″W) on level ground with Bigarm gravely-loam (loamy-skeletal, mixed, frigid Typic Haploxerolls) soils and 30-yr (1981−2010) average annual precipitation of 350 mm (Missoula International Airport, https://www.ncdc.noaa.gov/cdo-web/datatools/normals). Forb vegetation was *E. esula* with scattered *C. stoebe* and western salsify (*Tragopogon dubius* Scop). Dominant grasses were downy brome (*Bromus tectorum* L.), Japanese brome (*Bromus arvensis* L.), bulbous bluegrass (*Poa bulbosa* L.), and Canada bluegrass (*Poa compressa* L.), nonnatives considered to have low forage value. Scattered native grasses (purple threeawn [*Aristida purpurea* Nutt.], green needlegrass [*Nassella viridula* (Trin.) Barkworth], and bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve]) and shrubs (*Artemisia* spp.) were present.

Study Design

Six grass seeding treatments (Great Basin wild rye [*Leymus cinereus* (Scribn. & Merr.) Á. Löve], orchardgrass [*Dactylis glomerata* L.], thickspike wheatgrass [*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould], big bluegrass [*Poa secunda* J. Presl], *P. spicata,* no grass) and three herbicide treatments (picloram, imazapic, no herbicide) were randomly arranged in a split-plot design with grass whole-plot (4.3 × 13.5 m) and herbicide subplot (4.3 × 4.5 m) factors. In 2002, treatments were replicated four times inside a 2.4-m tall fence that excluded cattle, goats, and wildlife, and in 2003, treatments were replicated once outside the fence to evaluate sensitivity of results to light grazing.

Seeded forage grasses were perennial and native, except *D. glomerata,* which is nonnative. Pure live seed rates resembled recommended US Department of Agriculture Natural Resources Conservation Service rates and were 9.5 kg ha^{-1}, 3.4 kg ha^{-1}, 9.5 kg ha^{-1}, 3.4 kg ha^{-1}, and 13.5 kg ha^{-1} for *L. cinereus, D. glomerata,*

E. lanceolatus, P. secunda, and *P. spicata,* respectively (Taliga 2011). Picloram (0.56 kg a.e. ha^{-1}) and imazapic (0.03 kg a.i. ha^{-1}) were applied with methylated seed oil (2.3 L ha^{-1}) using a backpack sprayer delivering 130 L ha^{-1}. Herbicides were applied mid-September before killing frost, and grasses were no-till drilled at a soil depth of 0.6 cm in early November.

Plant Measurement

Current-yr biomass was clipped to ground level within one random 1.0 × 1.0 m area per plot in late June of the 2nd, 3rd, and 14th yr after seeding, except for the unreplicated experiment, where clipping occurred the 13th yr. Biomass was sorted into *E. esula,* seeded grass, and other species, dried (72 h, 50°C), and weighed.

Data Analysis

This section concerns the replicated experiment because we present only unanalyzed raw data from the unreplicated experiment. Data from *L. cinereus* plots were not analyzed because 33 of 36 *L. cinereus* values equaled zero. *E. esula* and other species data were natural log-transformed and analyzed with a bivariate mixed effects linear model. Fixed effects were grass species, herbicide, measurement year, replication, and measurement year × herbicide, and random effects were grass species × herbicide, grass species × measurement year, whole plots, and subplots. The seeded grass model had the same terms, except terms for herbicide effects 14 yr after seeding were not significant ($P > 0.3$) and thus excluded. For grasses, we used a Tobit version of the model because 38% of observations equaled zero (Chib 1992). We natural log-transformed non-zeros and assumed zeros represented plots containing < 10.0 kg ha^{-1} of seeded grass. Other cutoff values (2 kg ha^{-1} and 50 kg ha^{-1}) generated similar conclusions. Standard noninformative Bayesian prior distributions were assigned to all model parameters, and the posterior distributions of model parameters were simulated using a Gibbs sampling algorithm implemented in Fortran (Intel Corporation 2013; Gelman et al. 2014). Significance tests were conducted using samples from the posterior distribution.

Results

Seeded Grasses

In yr 2 and 3, *L. cinereus* biomass was 0 in all 12 plots, and in yr 14, it was 0 in 9 plots but nevertheless averaged 780 kg ha^{-1} (data not shown). Herbicides did not affect seeded biomass the 14th yr ($P > 0.1$), though herbicides increased seeded grasses appreciably in yr 2 and 3 (**Fig. 1**). For example, the third yr, *P. spicata* produced about $e^{1.3} = 40$ kg ha^{-1} where no herbicide was applied compared with about 600 kg ha^{-1} where picloram was applied (see Fig. 1). *Poa secunda* was usually the least productive grass (see Fig. 1). The 14th yr, *P. spicata* produced about $e^{4.5} = 900$ kg ha^{-1}, or 70% of total plant community biomass, and *P. spicata* outproduced *D. glomerata* ($P = 0.004$), *P. secunda* ($P = 0.001$), and likely *E. lanceolatus* ($P = 0.06$) (see Fig. 1). In the 13th yr of the unreplicated experiment, *L. cinereus, D. glomerata, E. lanceolatus, P secunda,* and *P. spicata* produced 340 kg ha^{-1}, 0 kg ha^{-1}, 30 kg ha^{-1}, 290 kg ha^{-1}, and 2 030 kg ha^{-1}, respectively.

E. esula

In yr 2 and 3, only *P. spicata* plus herbicide reduced *E. esula* (**Fig. 2**). By yr 14, herbicide and seeding treatments did not affect *E. esula* ($P > 0.14$), although *E. esula* was naturally less abundant:
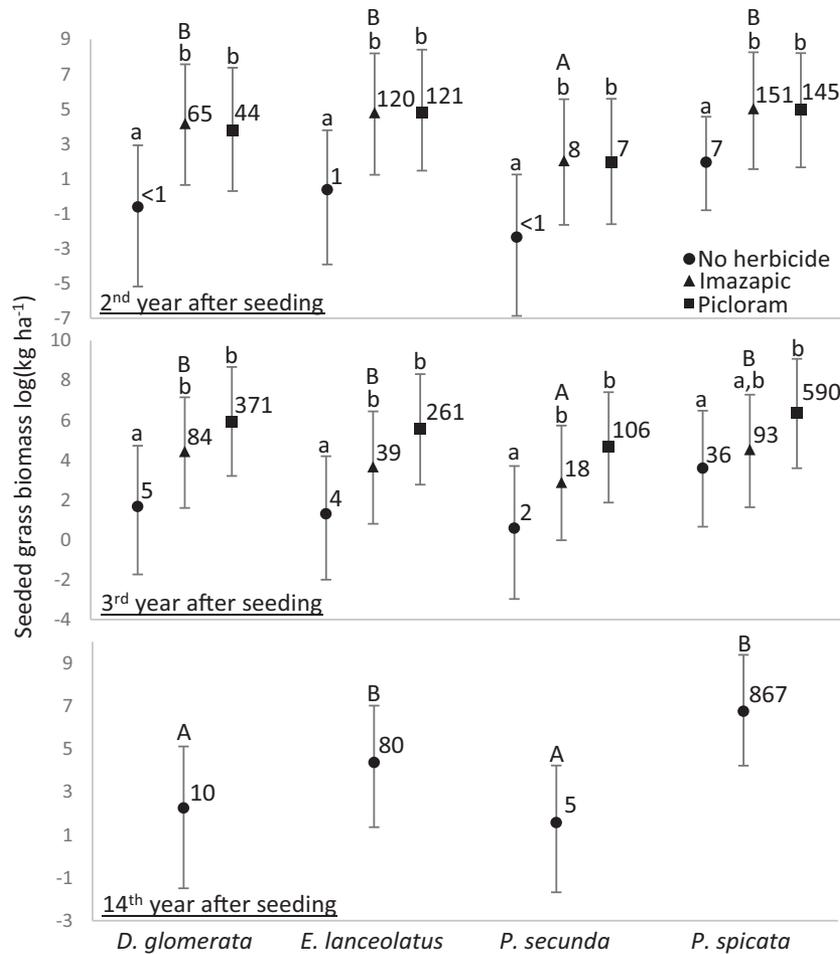
Figure 1. Seeded grass means (symbols) and 95% confidence intervals (bars). There is one estimate per species the 14th yr because herbicides did not significantly impact grasses that yr ($P > 0.30$). Within grass species and years, means with a common lowercase letter do not differ, and averaged over herbicide treatments, grasses with a common uppercase letter do not differ ($P > 0.05$). Numbers next to symbols are back-transformed values.
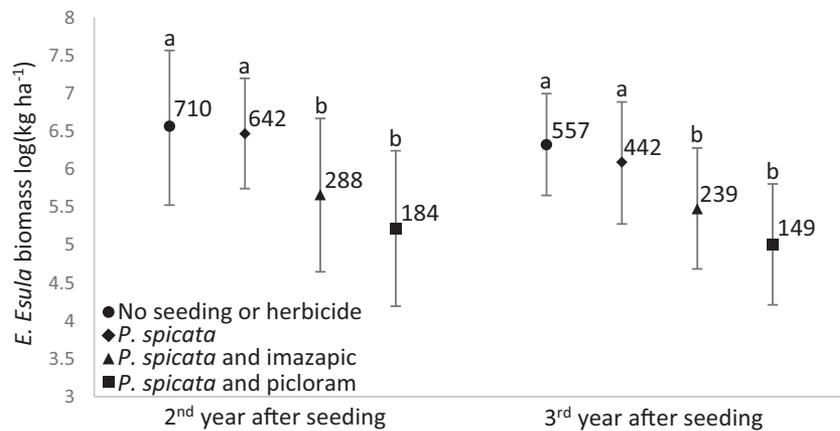
Figure 2. *Euphorbia esula* means (symbols) and 95% CIs (bars). Only *P. spicata*–seeded plots are graphed because other grasses did not reduce *E. esula*. The final study yr is not graphed because there were no significant differences ($P > 0.20$). Means with a common letter do not differ ($P > 0.05$). Numbers next to symbols are back-transformed values.

*E. esula* comprised about 30% of control plot biomass in yr 14, compared with about 55% in yr 2 and 3.

Unseeded Species (excluding E. esula)

Only *P. spicata* reduced unseeded biomass, and it reduced it about 85% (Fig. 3). An exception is yr 2, when *P. secunda* and

E. lanceolatus reduced unseeded biomass in imazapic-treated plots ($P \leq 0.04$, data not shown).

Discussion

After 14 yr, all five seeded grasses persisted and *P. spicata* appeared most productive, comprising about 70% of total plant
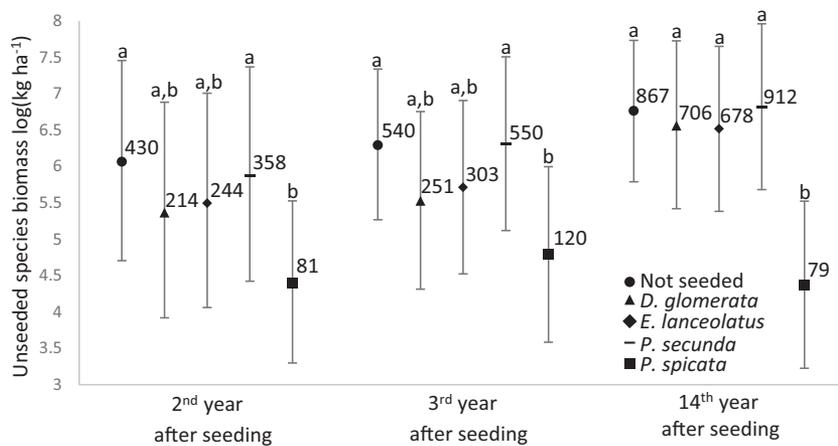
Figure 3. Unseeded biomass (excluding *E. esula*) means (symbols) and 95% confidence intervals (bars). Unseeded species were mostly exotic grasses with low forage value. Within years, means with a common letter do not differ (*P* > 0.05). Numbers next to symbols are back-transformed values.

community biomass. Similarly, in a study of a *C. stoebe*−invaded foothills site, *P. spicata* proved productive 16 yr after seeding (Rinella et al. 2012). Our site and the Rinella et al. (2012) site supported other invaders besides *E. esula* and *C. stoebe,* including *B. tectorum* and *B. arvensis,* so *P. spicata* is capable of boosting forage production in foothills invaded by a range of weed species. Like our *E. esula*−infested foothills site in Montana, *E. esula*−infested Great Plains sites in Wyoming maintained robust grass stands ≥ 10 yr after seeding (Ferrell et al. 1998), so seeding can provide long-term increases in forage production across much of *E. esula*'s invasive range. Though these results are promising, seeding failures are nevertheless possible in invaded foothills. For example, *P. spicata* and other seeded grasses remained rare throughout one of four long-term foothills experiments of Rinella et al. (2012).

Unlike Rinella et al. (2012), we did not observe herbicides benefiting seeded grasses many years after application. Conversely, herbicides have benefited grasses shortly after application in our study and other rangeland seeding studies (e.g., Bakker et al. 2003, but see Wilson et al. 2004). Herbicides likely increase chances grasses establish and grow large enough to persist.

Seeding to increase forage production is useful only if seeded species persist with grazing. Unlike our main experiment, our unreplicated experiment included livestock and wildlife grazing and seeded biomass was roughly similar between experiments. In addition, the productive seeded grass stands of Rinella et al. (2012) and Ferrell et al. (1998) formed with grazing. Seeded grasses can withstand grazing in invaded foothills and *E. esula*−invaded habitats more generally.

P. spicata and other seeded grasses did not suppress *E. esula* over the long term, though *E. esula* naturally became less productive over time. Similarly, in Rinella et al. (2012), *P. spicata* did not suppress *C. stoebe* over the long term, though *T. intermedium* reduced *C. stoebe* biomass about 90%. In our study, unseeded nonnative grasses produced more biomass than *E. esula* and these grasses are undesirable because they lack palatability and protein most of the year (Cook and Harris 1952). *P. spicata* formed productive stands that reduced undesirable grasses about 85%, and that was the biggest benefit of seeding in our study.

Implications

Seeding is an option for trying to increase forage production in invaded rangelands, but it is often unclear if seeded grasses have a reasonable chance of remaining productive enough to justify this expensive practice. Combined with two previous long-term studies, our study shows seeded grasses can boost forage production for prolonged periods in a range of *E. esula*−invaded habitats and Rocky Mountain foothill habitats supporting multiple invaders (Ferrell et al. 1998; Rinella et al. 2012). While there is always a risk seeded grasses will fail to persist, there is a good possibility seeded grasses will form persistent, productive stands in these habitats.

Acknowledgments

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