Testing the Establishment of Eight Forbs in Mowed Lawns of Hard Fescue (Festuca brevipila) for Use in Pollinator Conservation

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Additional index words. bee lawn, flowering lawn, reconciliation ecology, urban diversity

Abstract. Public concern for the conservation of pollinating insect communities, such as bees, has created demand for more florally diverse landscapes. In urban environments, lawns form a large portion of cultivated land, and are typically managed to exclude flowering species richness. In this study, we investigated the establishment of eight flowering plants with pollutant value (plants that provide floral nectar and pollen for visiting insects) when coseeded with the turfgrass hard fescue (Festuca brevipila Tracey). The study was established as a dormant seeding at two locations in central Minnesota with substantially different soil types. Plots were maintained at either a 6- or 9-cm mowing height. We monitored these as a dormant seeding at two locations in central Minnesota with substantially different soil types. Plots were maintained at either a 6- or 9-cm mowing height. We monitored these as a dormant seeding at two locations in central Minnesota with substantially different soil types. Plots were maintained at either a 6- or 9-cm mowing height. We monitored these as a dormant seeding at two locations in central Minnesota with substantially different soil types.
plants to tolerate repeated defoliation (Leffel and Gibson, 1973).

Repeated defoliation, in the form of mowing, seems to frequently impact the floral diversity of lawns, but in mixed ways. For lawns in Paris, there was no effect of mowing frequency on floral diversity, but higher mowing heights benefited floral richness in smaller home lawns, although not in large park lawns (Shwartz et al., 2013). In both the turfless floral lawns and conventional turf in Reading, United Kingdom, more intense mowing frequencies negatively impacted floral visitors, but floral richness was favored by intermediate mowing frequencies (Smith and Fellowes, 2014) where lawns were mowed to 4 cm when they attained 6 cm in height. One observational study in Paris found that mowing frequency, among other factors, negatively impacted plant diversity (Bertoncini et al., 2012). Conversely, another observational study of lawns in Sheffield, England, found that mowing frequency had little effect on plant richness (Thompson et al., 2004). In Saltdean, England, where mowing frequencies were experimentally controlled, an increase in both floral abundance and floral visitor abundance was observed under less intense mowing regimens (Garbuzov et al., 2014). In the United States, less frequent mowing was found to improve both floral resources and pollinator abundance and richness in suburban areas (Lerman et al., 2018). It seems clear that any effort to enhance lawns for biodiversity must consider how mowing affects the establishment and maintenance of forbs within lawns.

To increase the ability of lawns to support biodiversity in North America, we set out with the objective of identifying forb species and mowing practices that could be used during the establishment of a new lawn to achieve greater floral diversity and abundance. We targeted six native forbs with low growth habits and seed availability from commercial sources, and two non-native species that were commercially available, have a known value to bees, and are relatively noninvasive in natural areas. We tested if 1) interseeding these forbs at time of lawn establishment would result in establishment and bloom of target forbs, and 2) if mowing height would affect the ability of target forbs to establish and bloom in these same lawn plantings. Because native plants with low growing habits come from a variety of both moist and dry habitats, we chose two different locations for our study with different soil environments. One location was a “xeric site,” with a well-drained sandy soil with limited organic matter, and the other a “mesic site” with loamy soil and high organic matter. We predicted that study locations would favor different species, and that higher mowing heights would generally aid the establishment and bloom of targeted forbs in both locations.

Materials and Methods

Site characteristics. Two study sites were established by dormant seeding in November of 2013 (late fall in Minnesota): one at the Turfgrass Research Outreach and Education Center (TROE) at the University of Minnesota St. Paul campus and the other at the University of Minnesota Sand Plains Research Farm (SPRF) located in Becker, MN. Both soil types are commonly found in the seven-county metro area of Minneapolis-Saint Paul. Aggregate soil samples were taken over the entire study area at each site. The TROE site was a silty clay loam (7.5% sand, 61.3% silt, 31.3% clay) with an organic matter content of 4.3% (Supplemental Table 1), with a soil profile designation of Kingsley sandy loam with a 2% to 6% slope. The SPRF site was a sandy clay loam (68.8% sand, 8.2% silt, and 22.5% clay) with an organic matter content of 1.7% (Supplemental Table 1) and a soil profile designation of Hubbard-Mosford complex with 0% to 3% slope. Sites were prepared for planting through an application of glyphosate, rototilling, and soil leveling to create an adequate soil bed.

Site climatic conditions varied slightly between sites during the April to September growing season. The TROE location averaged slightly higher monthly temperatures in 2014 through 2016 (Supplemental Table 2), being on average 0.9 °C warmer than the SPRF. Average monthly precipitation was higher at the SPRF in 2014 and 2015, averaging 2.1 cm and 1.1 cm more rain fall than TROE, respectively, but was higher at TROE in 2016 with an average of 3 cm more rain fall than the SPRF (Supplemental Table 2).

Species selection. Eight forb species were selected (Table 1) for coestablishment with turfgrass based on recommendations from local nursery growers, growth height characteristics, and perceived value as a forage plant for bees; that is, a flower that provides floral nectar or pollen for bee pollinators. Hard fescue (Festuca brevifolia) was chosen as the companion turf species for its slow growth habit and low water and fertilizer input needs along with results from an earlier study showing its utility in a flowering lawn (Lane et al., 2019). Forb seed lots for each species were tested for germination in 2015 (Supplemental Table 3).

Site establishment. Dormant seeding was used due to multiple flower species having a cold stratification requirement for germination. Seeding of experimental plots occurred in November of 2013, and proceeded as follows: a broadcast seeding hard fescue at a cold stratification requirement for germination. Seeding of experimental plots occurred in November of 2013, and proceeded as follows: a broadcast seeding hard fescue at

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Table 1. List of forb species used and their properties extracted from online databases.

| Species                      | Common name | Ht (cm) | Habitat       | Bloom time     |
|------------------------------|-------------|---------|---------------|----------------|
| *Anemone patens* (L.) Mill.  | Pasque flower | 7.6–45.7 | Dry–sunny     | April–May      |
| *Claytonia virginica* L.     | Spring blue  | 7.6–12.7 | Moist–sunny   | April–June     |
| *Oxypetalum lammersii* Pursh | Purple locoweed | 10.2–40.6 | Dry–sunny     | April–June     |
| *Astragalus gramineus* Nutt. | Ground plum  | 10.2–61  | Dry–sunny     | May–June       |
| *Erigeron compositus* Pursh  | Cutleaf daisy| 15.2     | Dry–sunny     | May–July       |
| *Trifolium repens* L.        | Dutch white clover | 20.3     | Moist–sunny   | June–October   |
| *Prunella vulgaris* sp.      | Lanceleaf selfheal | 7.6–30.5  | Moist–sunny   | June–August    |
| *Thymus serpyllum* L.        | Creeping thyme | 20.32    | Dry–sunny     | July–September |

Table 2. Type III analysis of variance results from the linear mixed-effects model for each forb’s leafing and blooming units with interactions.

| Factor                              | Degrees of freedom | $\chi^2$ | $P$ value |
|-------------------------------------|--------------------|----------|-----------|
| **Trifolium repens**                |                    |          |           |
| Mowing height                        | 1                  | 0.16     | 0.68      |
| Location                            | 1                  | 4.38     | 0.036*    |
| Mowing height $\times$ Location     | 1                  | 0.5      | 0.48      |
| **Blooms**                          |                    |          |           |
| Location                            | 1                  | 0.25     | 0.6       |
| Mowing height                        | 1                  | 0.51     | 0.48      |
| Location $\times$ Mowing height     | 1                  | 1.1      | 0.31      |

| **Prunella vulgaris**               |                    |          |           |
| Basal rosettes                      |                    |          |           |
| Mowing height                        | 1                  | 0.16     | 0.68      |
| Location                            | 1                  | 44       | <0.001†   |
| Mowing height $\times$ Location     | 1                  | 0.1      | 0.78      |
| **Blooms at Turf Research, Outreach, and Extension center** | | | |
| Year                                | 2                  | 10.4     | <0.001†   |
| Mowing height                        | 1                  | 6.3      | 0.01*     |
| Year $\times$ Mowing height          | 2                  | 2.3      | 0.33      |
| **Blooms at Sand Plains Research Farm** | | | |
| Mowing height                        | 1                  | 2.5      | 0.12      |

| **Thymus serpyllum**                |                    |          |           |
| Stems                               |                    |          |           |
| Mowing height                        | 1                  | 1.8      | 0.2       |
| Location                            | 1                  | 6.1      | 0.01†     |
| Mowing height $\times$ Location     | 1                  | 1.9      | 0.17      |
| **Blooms 2016**                     |                    |          |           |
| Mowing height                        | 1                  | 0.46     | 0.5       |

| **Astragalus crassicarpus**          |                    |          |           |
| Stems                               |                    |          |           |
| Mowing height                        | 1                  | 0.01     | 0.9       |

*Denotes significant result.

month, which resulted in three mowing events at SPRF and two mowing events at TROE. Although the timing of mowing events in 2016 differed from what was seen in 2014 and 2015, the assignment mowing heights to each block (6 cm vs. 9 cm) was consistent for each year of data collection.

Vegetation data collection. To assess establishment, we collected vegetative data from all plots for all species in September of 2014 and 2015. The number of plants establishing in plots can be difficult to determine for species with spreading vegetation, so aboveground vegetative units appropriate for the species were quantified on the premise it would correlate to the number of individuals establishing in a plot. This method has been most commonly applied for *T. repens* in the form of trilobate leaves (McCurdy et al., 2013; Sparks et al., 2015), and was adopted here for additional species. Vegetative units were considered any structure that arose from the ground and could be reasonably counted over the entire plot. In addition to trilobate leaves, these structures included basal rosettes (*P. vulgaris*) and stems (*T. serpyllum* and *A. crassicarpus*). These data were collected before a final mowing event in September to avoid introducing a cutting bias in the data. Vegetative structures were not considered separately during analysis, and only once blooming had begun at that location. A bloom was counted only if it contained at least one unopened bud. In 2016, bloom data were collected differentially, with plots receiving overall less management. The first data collection point at SPRF occurred in May to measure the bloom of *A. crassicarpus*, a species that was able to establish only under the sandy soil conditions at SPRF. After this collection point, blooms were measured once per month at each location culminating in a final data collection in late July/early August. Data collection ended in early August based on the phenology of the flowers established in the plots.

Analysis. All analyses were conducted in the R statistical environment (R Core Team, 2019). First, a mixed-effects model was specified using the “lme” package (Pinheiro et al., 2018) with either vegetative units or blooms for each species as a response variable and location $\times$ treatment as a fixed effect. Plot number was specified as a random effect to account for repeated measures of plots over the growing season (in the case of blooms) and year. Model assumptions of homoscedasticity and normality were evaluated by inspection of residual plots. If assumptions were violated, square root transformations were applied and residual plots reevaluated. If assumptions were still not met through square root transformations, a log transformation was applied and residual plots were reevaluated. In all cases, transformations were sufficient to accommodate model assumptions. All figures represent the untransformed data. We then specified a type III analysis of variance (ANOVA) using the “car” package (Fox and Weisberg, 2011) for each mixed-effects model to determine if fixed effects and their interaction were significant. Analyses were conducted only for species with sufficient data across locations and/or treatments. Although our model accounted for variation through time, we chose to use year as a fixed effect for blooms of *P. vulgaris*. We did this because it was one of the few species we had bloom data for in all 3 years for a location, and also to highlight a significant trend over time for this species. We also evaluated bloom for *P. vulgaris* separately for both locations, as the TROE location had 3 years of bloom data, whereas SPRF achieved bloom only in the final year.

In cases in which there were significant effects were found, a “Tukey” means separation protocol for pairwise comparisons using the “multcomp” package (Hothorn et al., 2008) was used to assess differences between treatments or locations.

Results

Forb establishment. Of the eight species investigated in our trials, we saw establishment and bloom for four species: *T. repens*, *P. vulgaris*, *T. serpyllum*, and *A. crassicarpus*. Both *T. repens* and *P. vulgaris* bloomed
during the first growing season, with *T. serpyllum* achieving bloom at both sites by the third year. Although *A. crassicarpus* established only at the SPRF location, it achieved bloom in some plots by the third year as well. We saw no evidence of vegetative establishment or blooms of the remaining four species: *Claytonia virginica*, *Anemone patens*, *Oxytropis lamberti*, or *Erigeron compositus*.

Vegetation response to mowing height and location. Results from ANOVA of mixed-effects models indicated that none of the observed forb vegetation showed a significant interaction between mowing treatment and location, or between mowing treatments within location, indicating that mowing did not seem to affect the growth/development of vegetative structures of forbs species we observed (Table 2).

Location, however, was significant for three of the observed forbs. Trifoliate leaf counts of *T. repens* were significantly higher at SPRF (385 mean trifoliates per plot) compared with the TROE location (208 mean trifoliates per plot) (Fig. 1A). The reverse was true for counts of *P. vulgaris* basal rosettes, which were significantly higher at TROE (76 mean rosettes per plot) compared with the SPRF location (20 mean rosettes per plot) (Fig. 2B). Similar to *T. repens*, *T. serpyllum* had significantly higher vegetative growth at the SPRF with 105.8 mean stems per plot compared with TROE with 70 mean stems per plot (Fig. 1C). Leafing units of *A. crassicarpus* were found only at the SPRF location (20.9 mean rosettes per plot), and were not significantly different between mowing height treatments (Table 2).

**Bloom response to mowing height and location.** Of the four species found blooming in our trials, *T. repens* was the only species to bloom at both locations in every year. Analysis indicated there were no differences in mean blooms per plot in either location or mowing treatment (Table 2). *P. vulgaris* blooms were found only at the TROE site in 2014 and 2015, but were found at both sites in 2016. As such, we analyzed these data separately for both TROE and SPRF due to unequal sampling across years. We found a significant effect of mowing height at the TROE location ($F_{(1,18)} = 6.2, P = 0.02$) with low mowing heights having lower mean rosettes per plot (4.6 mean blooms per plot, $P = 0.01$) than in high mowing height plots (10.6 mean blooms per plot, Fig. 2A). Because of a noticeable decline in *P. vulgaris* blooms after the first year, we tested for a mowing height × year interaction at the TROE location. We found a significant effect of year ($F_{(2,26)} = 10.4, P \leq 0.001$), but we found no evidence of an interaction ($F_{(2,26)} = 1.1, P = 0.34$). Means comparisons for blooms over years revealed an initial burst of flowering in 2014, averaginng 17.4 mean blooms per plot, followed by a steep decline in 2015 that was sustained in 2016 (averaging 5.8 and 4.4 mean blooms per plot, respectively, Fig. 3). This initial bloom was significantly higher than in both 2015 and 2016 ($P \leq 0.01$ for both years), but 2015 and 2016 did not differ from each other ($P = 0.7$).

*T. serpyllum* blooms were found only at the SPRF location in 2015 in 3 of 10 plots during the course of its bloom season, and only in plots mowed at the 9-cm mowing height. As a result, means comparisons for location and mowing height were not appropriate. Conversely, in 2016, the TROE location had a significant amount of *T. serpyllum* bloom (every plot had blooms), whereas the SPRF location had only a single plot with blooms. Because of the negligible bloom at SPRF, mowing height comparisons for this species were done only for the TROE location. Bloom counts were 10.6 per plot in the high mowing height treatment compared with four per plot in the low mowing height treatment; this relationship was not significant [$F_{(1,8)} = 0.5, P = 0.54$, Fig. 2B].

Two *A. crassicarpus* blooms were observed in one plot at the SPRF location in 2015, and in 2016 three plots at SPRF were found to have blooms, with 2, 12, and 25 blooms for each plot. The small number of plots in which blooms occurred made statistical analysis inappropriate, but these results show that this species has the potential to establish and bloom in lawns, if only sporadically.

**Discussion**

This study represents an important first step in identifying forbs and management practices that could be applied in the diversification of lawns for the purpose of pollinator conservation. Of the eight forbs we investigated, four of them established and bloomed, with location and mowing height treatments playing a mixed role for each species.

Location played a prominent role in the vegetative establishment of all species observed, with *T. repens*, *P. vulgaris*, *T. serpyllum*, and *A. crassicarpus* all showing differences in vegetative growth between locations. The location with high soil sand content (SPRF) favored *T. repens*, *T. serpyllum*, and *A. crassicarpus*. *T. repens* established well at both sites and is well known for its adaption to a wide range of soil conditions (Turkington and Burdon, 1983). Its increased vegetative growth at the SPRF may be due to nitrogen limitation (as evidenced by yellowing of grass leaves) imparting a competitive advantage for the species over its companion grass due to the ability of *T. repens* to fix nitrogen. To our knowledge, no studies on the optimal establishment and site conditions for *P. vulgaris* or *T. serpyllum* have been conducted, although reports of optimal growing conditions exist. The U.S. Natural Resource Conservation Service reports that *P. vulgaris* prefers moist and disturbed conditions across a wide range of habitats (Young-Mathews, 2012), suggesting that the low moisture retention of sandy soils may not favor its growth. Studies on the distribution of *T. serpyllum* suggest that it is most commonly found in dry and human disturbed areas,
we have conducted with establishment was delayed. From other studies during this time, or if the TROE location became less favorable (such as water and nutrients) at the SPRF, a 15 trend for higher stem counts at the SPRF. bloom in 2016 at TROE, counter to the 2014–2154 HORTSCIENCE VOL. 54(12) D ECEMBER 2019 year.

achieved 7.6 mean blooms per plot in the same species. 

P. vulgaris

although it can tolerate mesic conditions as well (Eriksson, 1998). This preference for drier conditions may have played a part in its success at the SPRF location. Location also affected the bloom of some species. P. vulgaris blooming was delayed at the SPRF until 2016, and then achieved only a relatively low level of one mean bloom per plot compared with the TROE location, which achieved 7.6 mean blooms per plot in the same year. T. serpyllum achieved its highest level of bloom in 2016 at TROE, counter to the 2014–15 trend for higher stem counts at the SPRF. Because we ceased any supplemental inputs (such as water and nutrients) at the SPRF location that year, it is difficult to determine if the SPRF location became less favorable during this time, or if the TROE location establishment was delayed. From other studies we have conducted with T. serpyllum, we have observed that, although T. serpyllum seems slow to establish, it does well in mesic lawn environments, such as at TROE. This is also supported by other observations of lawn environments (Eriksson, 1998; Stalter et al., 1993). Mowing height had a negligible role on vegetative establishment at both sites and had no impact on the flowering of observed species except for a consistent negative effect on P. vulgaris in the low mowing height treatment at TROE. This is somewhat supported by previous work that investigated mowing frequency effects on turfless lawn, where P. vulgaris coverage was affected by mowing frequency (Smith and Fellows, 2014). The lack of negative effect of mowing height was surprising given previous studies finding negative effects of mowing frequency and height on lawn forbs (Bertocnini et al., 2012; Garbuzov et al., 2014; Lerman et al., 2018). One possible explanation is due to the relatively low frequency with which our cutting treatments were applied. Because we used a height-based mowing criterion combined with the slow-growing grass F. brevipilla, the number of mowing events was much lower compared with other studies. This is somewhat encouraging, as our results suggest combining slow-growing turfgrass with height-based mowing regimens reduces mowing pressure on turf swards and thus the potential negative effects of mowing on forbs. Previous research has shown that turf species can affect forb flowering (Lane et al., 2019), regardless of mowing regimen, and is an important consideration in crafting floral lawns. Regardless of low mowing frequency, P. vulgaris still saw negative impacts on bloom at the low mowing height, highlighting that some species may be more sensitive than others to mowing regimen during bloom.

Four of the eight species, C. virginica, A. patens, O. lamberti, and E. compositus, did not establish in our research plots. Their failure to establish in plots could be for a number of reasons, such as germination challenges and environmental mismatches. When we conducted germination tests in a growth chamber for the selected species, the nonestablishing species either did not germinate at all (E. compositus) or only sparsely (C. virginica, A. patens, O. lamberti) (S2). This lack of germination indicates that there may be additional dormancy mechanisms, such as persistent dormancy breaking requirements, or planting strategies needed beyond cold stratification. C. virginica, for example, has been known to establish in lawns (Schemske et al., 1978), but is typically found in more shaded environments where its seeds are stored underground by ants. This may indicate an important biotic interaction our research plots were unable to re-create. A. patens also has been found in association with close grazing and mowing (Wildeman and Stevens, 1982), but previously documented low germination rates (Greene and Curtis, 1950) indicate other dormancy breaking requirements may have been poorly met by our study design. These challenges could be overcome through additional seed treatments, or transplanting individuals directly into lawns. Previous work has seen some success in the transplanting of C. virginica, and other species, directly into warm-season lawns (Wisdom, 2018).

Another possible explanation for why these species failed to establish is that our growing sites were poor matches for their environmental needs. O. lamberti is a low-growing forb but is more characteristic in dry environments (Wheeler et al., 1992; Whitman and Stevens, 1952). E. compositus, although a native to the central United States, is more characteristic of rocky sites in montane habitats very different from our planting sites. We believed that the low growth habit and a well-drained soil (such as at SPRF) would allow these species to germinate and persist given the slow-growing turf companion species, but the increased inputs and mowing may have excluded them.

Overall, these results are encouraging and indicate that forbs can establish and bloom, especially T. repens, P. vulgaris, T. serpyllum, and A. crassicalcarpus, when seeded concurrently with F. brevipilla. Future efforts to diversify lawns would benefit from expanded species exploration using both seed and transplanted individuals. One of the largest barriers to implementing flowering lawns with native forbs is a lack of seed stock available from local nurseries. Many native plants have low-growing traits that are desirable for forbs in turfgrass plantings, such as low and competitive growth habits, but seeds are not available in appreciable quantities. This lack of seed stock is potentially due to the difficulty in harvesting plant seeds from low-growing plants, as well as a lack of demand from the public for plants with these qualities. Future directions with flowering lawns using native plants should seek partners in the native plant seed industry to facilitate the exploration and production of candidate plant seeds for use in research and by the public.

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Supplemental Table 1. Soil fertility and texture results from the Turf Research, Outreach, and Extension Center (TROE) and the Sand Plains Research Farm (SPRF).

| Name   | Bray P (ppm) | NH₄OAc-K (ppm) | Organic matter (%) | Water pH | Sand (%) | Silt (%) | Clay (%) |
|--------|--------------|----------------|-------------------|----------|----------|----------|----------|
| TROE   | 61           | 149            | 4.3               | 6.1      | 7.4      | 61.3     | 31.3     |
| SPRF   | 39           | 53             | 1.7               | 6.6      | 68.8     | 8.7      | 22.5     |

Supplemental Table 2. Mean temperature and precipitation for each month of the growing season, at the Turf Research, Outreach, and Extension center (TROE) and the Sand Plains Research Farm (SPRF).

| Month | Location | Yr  | Mean temp (°C) | Mean precipitation (cm) |
|-------|----------|-----|----------------|--------------------------|
| April | SPRF     | 2014 | 4.5           | 13.97                    |
| April | SPRF     | 2015 | 8.4           | 4.7                      |
| April | SPRF     | 2016 | 7.3           | 5                        |
| April | TROE     | 2014 | 4.6           | 17.6                     |
| April | TROE     | 2015 | 8.5           | 5.3                      |
| April | TROE     | 2016 | 7.7           | 9.3                      |
| May   | SPRF     | 2014 | 13.6          | 22                       |
| May   | SPRF     | 2015 | 13.6          | 14.5                     |
| May   | SPRF     | 2016 | 14.5          | 6.7                      |
| May   | TROE     | 2014 | 13.8          | 9                        |
| May   | TROE     | 2015 | 13.8          | 12.5                     |
| May   | TROE     | 2016 | 14.8          | 5.2                      |
| June  | SPRF     | 2014 | 19.1          | 21.6                     |
| June  | SPRF     | 2015 | 18.9          | 8.7                      |
| June  | SPRF     | 2016 | 19.3          | 6.4                      |
| June  | TROE     | 2014 | 21.1          | 23.4                     |
| June  | TROE     | 2015 | 19.8          | 8.4                      |
| June  | TROE     | 2016 | 20.4          | 9.3                      |
| July  | SPRF     | 2014 | 19.9          | 5.3                      |
| July  | SPRF     | 2015 | 21.1          | 18.6                     |
| July  | SPRF     | 2016 | 21            | 16.5                     |
| July  | TROE     | 2014 | 21.8          | 6.9                      |
| July  | TROE     | 2015 | 21.9          | 15.7                     |
| July  | TROE     | 2016 | 22.5          | 15.2                     |
| August| SPRF     | 2014 | 20.3          | 10.6                     |
| August| SPRF     | 2015 | 19.5          | 14.8                     |
| August| SPRF     | 2016 | 20.6          | 11.7                     |
| August| TROE     | 2014 | 22.2          | 7.9                      |
| August| TROE     | 2015 | 20.1          | 7.1                      |
| August| TROE     | 2016 | 21.4          | 25.1                     |
| September| SPRF | 2014 | 15.4          | 9.8                      |
| September| SPRF | 2015 | 18.2          | 4.1                      |
| September| SPRF | 2016 | 16.4          | 12.9                     |
| September| TROE | 2014 | 16.1          | 5.6                      |
| September| TROE | 2015 | 18.8          | 9.7                      |
| September| TROE | 2016 | 17.5          | 13.2                     |

Supplemental Table 3. Seed germination testing seeds for each species were separated into three replicates of 30 seeds. Seeds were subjected to 60 d of 1.5 °C for cold stratification, then placed in a growth chamber in petri dishes with germination paper. Petri dishes were checked daily to ensure adequate moisture. After 14 d, initial germination was checked (7 Nov.), and germination was recorded. Germinated seeds were removed, and remaining seeds were checked on 25 Nov. Data were averaged for each species.

| Species                | Germination (%) |
|------------------------|-----------------|
| Trifolium repens       | 89              |
| Thymus serpyllum       | 61              |
| Anemone patens         | 2               |
| Prunella vulgaris      | 72              |
| Erigeron compositus    | 0               |
| Astragalus crassicarpus| 4               |
| Oxytropis lambertii    | 3               |
| Claytonia virginica    | 3               |