Survey of non-native species along subalpine and alpine roads

Authors: Ben Murphy, Teal Potter, and Bill Bowman

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PURPOSE

We sought to understand the distribution and abundances of non-native plants at high elevations in Colorado's Front Range. This purpose of the this survey was to inform current research on the mechanisms that allow invasive plant species to expand their ranges upward into high elevation ecosystems as well as to provide Rocky Mountain National Park data on the current status, distribution, and abundances of non-native plants in the park for management uses.

SURVEY METHODS

In order to assess changes in frequency of non-native plant species along an elevation gradient, we chose two different roadways in RMNP with substantial vehicle traffic as our survey sites: Old Fall River Road (OFR) and Trail Ridge Road (TR). At each of these sites we surveyed using five (OFR) or four (TR) transects perpendicular to the road; at OFR these transected ranged from 2,623-3,597 m (8,606-11,801 ft) in elevation, and at TR the transects ranged from 2,837-3,612 m (9,308-11,850 ft) in elevation (Figure 1).

Figure 1. Transect sites along Old Fall River Rd. and Trail Ridge Rd. See Table 1 for transect coordinates.

Transect Methods

We chose transect locations based on the criteria that they were open meadow sites (not conifer understory), and that meadow clearings were open canopy for at least 10 meters away from the road edge (perpendicular to the road), in order to capture the gradient of invasive species abundance away from the road. We chose not to survey in conifer understory because invasive species were rarely observed in these shaded, pine needle-covered soils. After a transect was temporarily established with a meter tape, three 1x5 meter plots were marked along the transect at three different distances from the road: 0.0 m, 2.5 m, and 10.0 m (Figure 2). Each plot was divided into 125 20x20 cm squares. For each plot, we recorded the number of squares in which each non-native species was present and the number in which each was absent.

On each transect, we also recorded the farthest distance from road for species that were established beyond the 10m plot, and additionally looked for and noted any other non-native species present that were not recorded in the plots. While driving along the road traveling between transects, we also recorded the highest elevation occurrence of each observed non-native species. We repeated these methods at three other locations in Colorado's Front Range: Mt. Evans, Guanella Pass, and Niwot Ridge. This survey took place in 2015 between early June and mid-August.

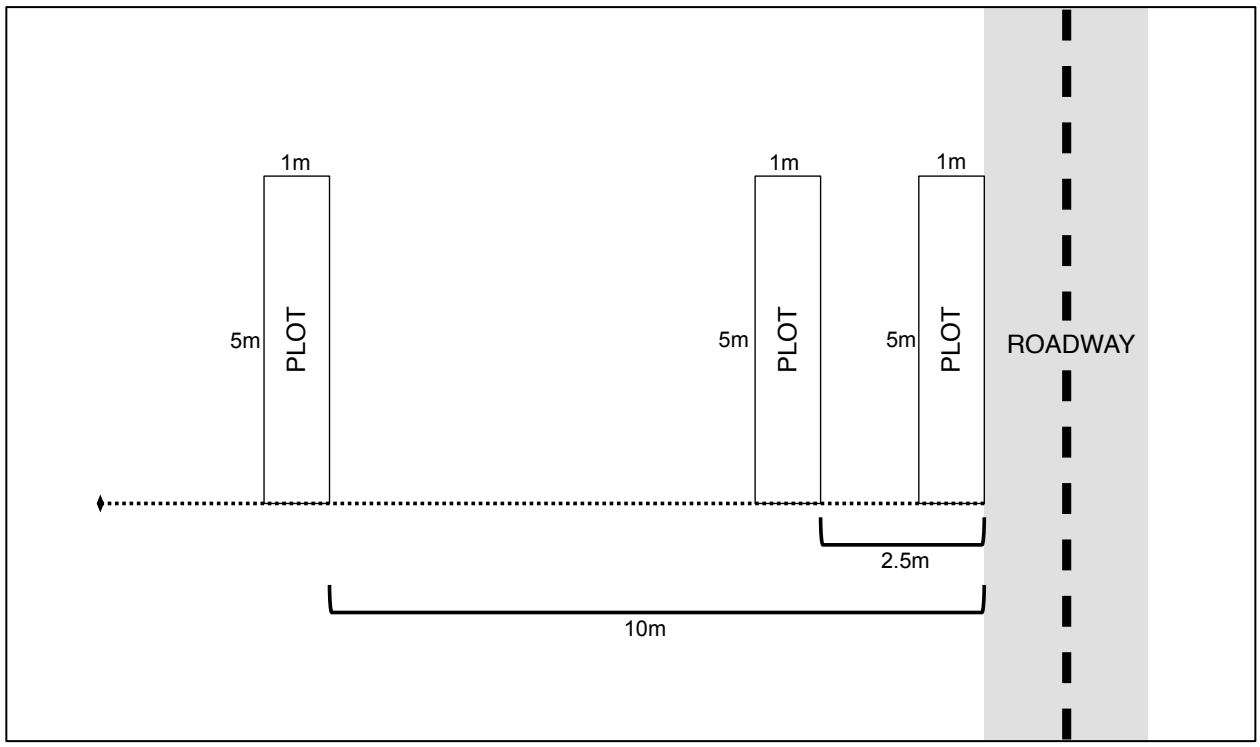

Figure 2. Plot arrangement on a transect perpendicular to the road.

Figure 3. Ben Murphy and undergraduate assistant setting up the transect 3 on Fall River Road.

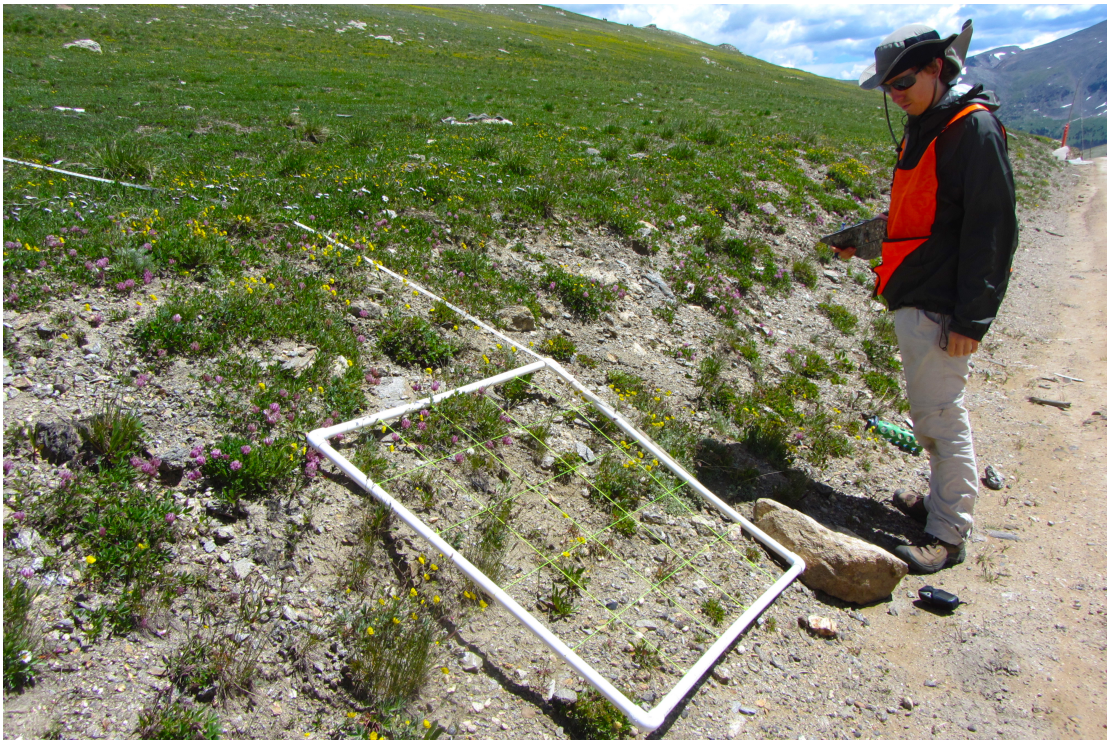

Figure 4. Ben Murphy preparing to search for invasive species in a plot near the Alpine Visitor Center on Fall River Road (transect 5).

SURVEY RESULTS

Highest Elevation Species

On Trail Ridge Rd., the species we found at the highest elevations included *Taraxacum officinale* (common dandelion), *Tragopogon dubius* (salsify), *Bromus inermis* (smooth brome, at Rainbow Curve across road from parking lot), and *Poa pratensis* (Kentucky bluegrass). Also, on Trail Ridge Rd *Bromus tectorum* (cheatgrass) was found at 2930 m (9614 ft). This sighting included 2-4 individuals next to the rock barrier at the small parking area at 40°23'16.41"N 105°37'51.20"W. On Old Fall River Rd (including surrounding the Alpine Visitor Center), the highest elevation species we found were *Rumex crispus* (curly dock), common dandelion, *Plantago major* (common plantain), and smooth brome (present in subalipine-alpine transition zone). Across all sites (including non-RMNP sites), the highest elevation species were common dandelion, curly dock, common plantain, Japanese brome, and smooth brome (Figure 5). Also of note was *Cirsium arvense* (Canada thistle), present up to 3203 m, and three *Trifolium* (clover) species.

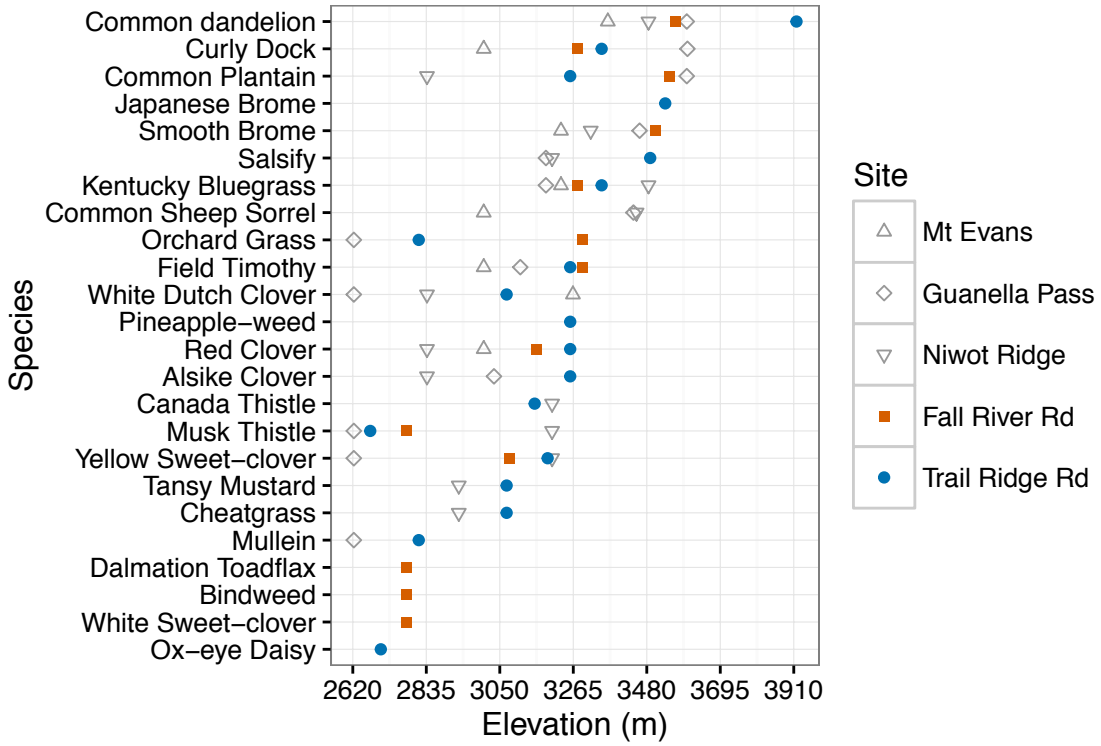

Figure 5. shows the highest elevation at which we observed each species across all survey sites. Species occurrences at Rocky Mountain National Park sites are highlighted in color.

Non-native species frequencies along elevation gradient

Overall, we found a decrease in the abundance of non-natives species (sum of non-native species frequencies) with increasing elevation at RMNP sites and across all sites combined (Figure 6). Only at plots above 3500m in elevation did we find a significant correlation between plot distance from road and species frequency (frequency decreased with distance from road) (Figure 7). Lack

of a significant decrease overall may have been due to large variation between sites or between transects, however a Bayesian regression analysis of site effects determined that differences in sites did not explain much of the variation in species richness among sites (Figure 8).

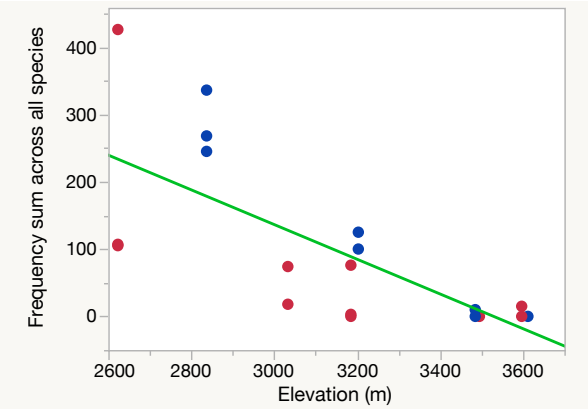

Figure 6. Frequency sum across all species for each plot within ROMO along elevation gradient. Red plots represent Old Fall River Rd. and blue plots represent Trail Ridge Rd. Linear fit: $p < 0.0001$*, $R^2 = 0.5725$

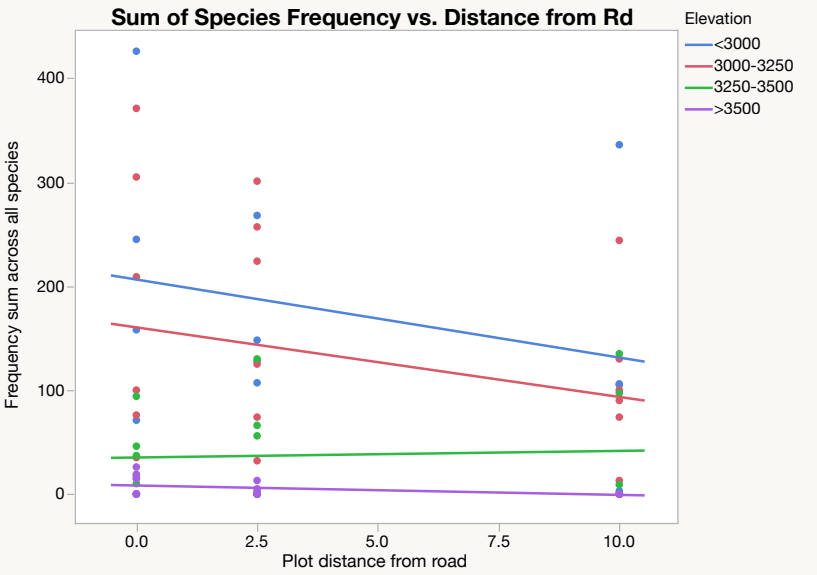

Figure 7. Frequency sum across all species at all sites vs. distance from road, binned by elevation ranges. <3000m range: $p = 0.3853$ (N.S.), $R^2 = 0.0761$. 3000-3250m range: $p = 0.2563$ (N.S.), $R^2 = 0.0672$. 3250-3500m range: $p = 0.8187$ (N.S.), $R^2 = 0.0034$. >3500m range: $p = 0.0229$*, $R^2 = 0.2438$.

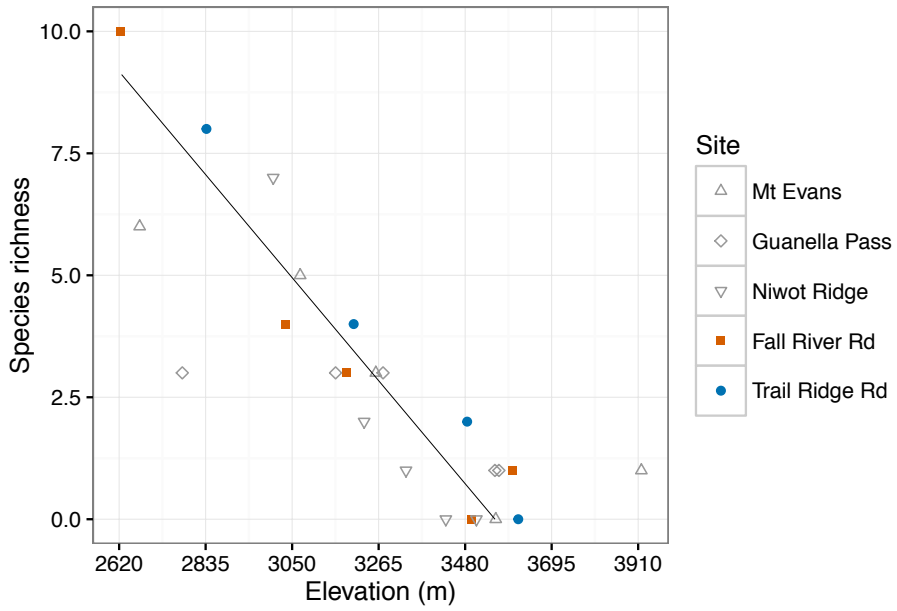

Figure 8. shows the relationship between the number of invasive species and elevation ($p < 0.001$, $R^2 = 0.704$). Each point represents the total number of species within each transect, regardless of distance from road. Species occurrences at Rocky Mountain National Park sites are highlighted in color.

Site	Transect	Elevation (m)	Location	Zone	Position	Coordinates	Distance from Road (m)	SPECIES RELATIVE FREQUENCY (within each plot)											
								Bromus inermis	*Bromus tectorum*	*Phleum pratense*	*Poa pratensis*	*Tragopogon dubius*	*Taraxacum officinale*	*Trifolium hybridum*	*Trifolium repens*	*Melilotus officinalis*	*Verbascum thapsus*	*Rumex acetosella*	*Carduus nutans*
Fall River	1	2623	Fork in road where road transitions from paved to gravel.	Montane	Upslope	40°24'51.0"N 105°39'17.7"W	0.0	0	0.768	0.784	0.752	0.096	0.552	0	0.232	0.16	0.032	0	0.032
							2.5	0	0.592	0.008	0	0.032	0.04	0	0	0	0.16	0	0.024
							10.0	0.104	0.632	0.008	0.024	0	0	0	0	0	0.072	0	0
	2	3033	Clearing before large rock cage supports.	Subalpine	Upslope	40°25'30.4"N 105°42'19.7"W	0.0	0.008	0	0	0.008	0	0.088	0.04	0	0	0	0	0
							2.5	0.12	0	0	0.424	0	0.048	0	0	0	0	0	0
							10.0	0	0	0	0.592	0	0	0	0	0	0	0	0
	3	3185	Meadow with willows, spruce.	Subalpine	Downslope	40°25'54.9"N 105°43'59.4"W	0.0	0	0	0	0.2	0.056	0.352	0	0	0	0	0	0
							2.5	0	0	0	0.024	0	0	0	0	0	0	0	0
							10.0	0	0	0	0	0	0	0	0	0	0	0	0
	4	3495		Alpine	Downslope	40°26'24.3"N 105°44'48.7"W	0.0	0	0	0	0	0	0	0	0	0	0	0	0
							2.5	0	0	0	0	0	0	0	0	0	0	0	0
							10.0	0	0	0	0	0	0	0	0	0	0	0	0
	5	3597	Near Alpine Visitor Center.	Alpine	Upslope	40°26'30.2"N 105°45'10.0"W	0.0	0	0	0	0	0	0.12	0	0	0	0	0	0
							2.5	0	0	0	0	0	0	0	0	0	0	0	0
							10.0	0	0	0	0	0	0	0	0	0	0	0	0
Trail Ridge	1	2837	Off of side road near Hidden Valley parking lot.	Subalpine	Downslope	40°23'45.9"N 105°39'3.3"W	0.0	0.88	0	0.072	0.12	0	0.288	0	0	å	0	0	0
							2.5	1	0	0	0.168	0	0.36	0	0	0.008	0	0.608	0
							10.0	0.72	0	0.8	0.504	0	0.248	0.408	0.008	0	0	0	0
	2	3203	Old ski area.	Subalpine	Downslope	40°23'22.2"N 105°40'30.7"W	0.0	0.568	0	0	0.216	0	0.016	0	0	0	0	0	0
							2.5	0.168	0	0	0.744	0.024	0.064	0	0	0	0	0	0
							10.0	0	0	0	0.16	0	0.64	0	0	0	0	0	0
	3	3485	Near Ute Trailhead.	Alpine	Upslope/ Flat	40°23'36.1"N 105°41'41.0"W	0.0	0	0	0	0.064	0	0.016	0	0	0	0	0	0
							2.5	0	0	0	0	0	0	0	0	0	0	0	0
							10.0	0	0	0	0	0	0	0	0	0	0	0	0
	4	3612	Across road from pullout.	Alpine	Downslope/ Flat	40°25'5.9"N 105°44'51.5"W	0.0	0	0	0	0	0	0	0	0	0	0	0	0
							2.5	0	0	0	0	0	0	0	0	0	0	0	0
							10.0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Results for all plots at all transects in RMNP. Values associated with species are recorded here as decimals (or x 100 for percentage) of each 1m x 5m plot containing individuals (ramets) of each species.

Maximum elevations at Trail Ridge Rd

Species	Common Name	Trail Ridge Rd Max Elevation (m)
Poa pratensis	Kentucky Bluegrass	3485
Taraxacum officinale	Common Dandelion	3485
Rumex acetosella	Sheep Sorrel	3450
Bromus inermis	Smooth Brome	3316
Tragopogon dubius	Salsify	3203
Melilotus officianalis	Yellow Sweet Clover	3203
Carduus nutans	Musk Thistle	3203
Cirsium arvense	Canada Thistle	3203
Bromus tectorum	Cheatgrass	2930
Trifolium hybridum	Alsike Clover	2837
Trifolium pratense	Red Clover	2837
Trifolium repens	White Clover	2837
Plantago major	Common Plantain	2837

Maximum elevations at Old Fall River Rd

Species	Common Name	Old Fall River Rd Max Elevation (m)
Rumex crispus	Curly Dock	3599
Taraxacum officinale	Common Dandelion	3597
Plantago major	Common Plantain	3597
Bromus inermis	Smooth Brome	3459
Rumex acetosella	Sheep Sorrel	3441
Poa pratensis	Kentucky Bluegrass	3185
Tragopogon dubius	Salsify	3185
Phleum pratense	Timothy Grass	3110
Trifolium hybridum	Alsike Clover	3033
Trifolium repens	White Clover	2623
Melilotus officianalis	Yellow Sweet Clover	2623
Verbascum thapsus	Common Mullein	2623
Carduus nutans	Musk Thistle	2623
Dactylis glomerata	Orchard Grass	2623

Table 2. reports the highest elevation that each species was found at RMNP sites.

CONCLUSION

In summary, our data support our hypotheses that the frequency and abundance of invasive species decreases with increasing elevation along road sides. In general, common dandelion is the only species that is commonly found above tree-line, but several species have established near tree-line, which may indicate a need for future monitoring and management to prevent expansion of populations.

For an additional analysis we addressed whether certain non-native plant species traits are associated with invasions at high elevations (see Appendix B). Our predictions were supported that short plant species average height, vegetative reproduction, long lifespan, and wind disperal are significantly more common traits among non-native species that have established at high elevations. These traits may help predict whether species can colonize at high elevations. There were no traits that were signficantly correlated with species' ability to spread from roadside edges. The survey data will be used with the trait data for a publication in a peer-reviewed ecology journal article.

Additional information is provided below which describes non-native species populations on each transect (Appendix A), as well as graphics associated with Ben's trait analysis (Appendix B).

APPENDIX A: Non-native species population descriptions on transects:

Old Fall River Rd.

Transect 1 (subalpine) was placed upslope from the road, immediately before the fork in the road where Old Fall River Rd. transitions from paved to gravel, at 2,623 m (8,606 ft) in elevation. We found fairly dense (>50% cover) *Bromus tectorum* (cheatgrass) in all three plots. We found dense *Taraxacum officinale*, *Phleum pratense*, and *Poa pratensis* in the 0.0 m plot, with significantly less of these species in the farther plots. *Trifolium repens* and *Melilotus officinale* were present only in the 0.0 m plot, and *Verbascum thapsus* and *Tragapogon dubius* were present sparsely throughout the plots. *Bromus inermis* was only present in the 10.0 m plot, with only ~10% cover.

Species that extended beyond the edge of our plots were *Bromus tectorum* (up to 19 m from road), *Phleum pretense* (19 m), *Poa pratensis* (25 m), *Bromus inermis* (30 m), *Verbascum thapsus* (30 m), and an unknown thistle (18 m – likely *Carduus nutans*). Across the road from this transect was a large amount of *Bromus inermis* and *Poa pratensis*. At the picnic area nearby to this transect, we found *Rumex acetosella*, *Dactylis glomerata,* and *Plantago major.*

Transect 2 was placed upslope from the road, at the clearing before the large rock cage supports, at 3,033 m (9,951 ft) in elevation. We found sparse *Bromus inermis*, *Taraxacum officinale,* and *Trifolium hybrdidum* in our 0.0 m and 2.5 m plots. *Poa pratensis* was sparse in the 0.0 m plots, but fairly dense (~50% cover) in the 2.5 m and 10.0 m plots. Beyond our plots, *Bromus inermis*, *Poa pratensis,* and *Taraxacum officinale* all extended beyond 35 m from the road. Other species found near the transect included *Rumex acetosella* (plentiful) *Tragapogon dubius* (1 individual), and *Rumex crispus* (ID not certain – may have been a different *Rumex* species).

Transect 3 was place downslope from the road, into a meadow containing willows and spruce, at 3,185 m (10,449 ft) in elevation (subalpine meadow). In our 0.0 m plots, we found *Poa pratensis* and *Taraxacum officinale* with ~25% cover, and *Tragapogon dubius* in very small amounts. In our 2.5 m plot, we found only *Poa prantensis* in small numbers. Beyond our plots, *Taraxacum officinale* was present sparsely but consistently greater than 35 m from the road, and *Poa prantensis* was present up to 11 m. The only other non-native species near the transect was *Rumex crispus* (ID uncertain).

Transect 4 was placed downslope of the road in the alpine area at 3,495 m (11,467 ft) in elevation. We found no non-native species in this transect, nor anywhere close nearby. We began this transect in the road cut (gravel), because of the presence of plants there.

Transect 5 was placed upslope of the road near the Alpine Visitor Center, where Old Fall River Rd. dead ends into the parking lot; the transect was in between Old Fall River Rd. and the Alpine Ridge Trail. Pocket gopher disturbance was present 6+ m from the road. We found ~10% cover of *Taraxacum officinale* in our 0.0 m plot only, and no other non-native species in any of the plots. Near the visitor center, we found 1 *Rumex crispus* individual (ID uncertain), and possibly 1 *Bromus inermis* individual (ID uncertain since plant was young). Note that we began this transect in the road cut (gravel), because of the presence of plants there.

Trail Ridge Rd.

Transect 1 was placed downslope off of the side road that leads to the Hidden Valley parking lot, at 2837 m (9308 ft) in elevation. In all three plots, we found very dense *Bromus inermis*, fairly dense *Poa pratensis*, and ~30% cover of *Taraxacum officinale*. *Phleum pratense* and *Trifolium hybridum* were sparse near the road but fairly dense at the 10.0 m plot. *Melilotus officinale* was dense near the road but sparse farther from the road, and *Rumex acetosella* was dense in the 2.5 m plot.

We found *Bromus inermis, Phleum pratense*, *Poa pratensis, Taraxacum officinale, Trifolium hybridum, Trifolium repens*, and *Rumex acetosella* all beyond 35 m from the road. Other species present in small numbers included *Rumex crispus* (ID uncertain), *Trifolium pratense*, *Plantago major,* and an unknown thistle species.

Transect 2 was placed downslope near the old ski area at 3,203 m (10,509 ft). Close to the road we found somewhat dense *Bromus inermis* and moderate *Poa pratensis*, and at 2.5m we found moderate *Bromus inermis* and somewhat dense *Poa pratensis*. In the 10m plot we found dense *Taraxacum officinale*. The only other non-native species found in plots was sparse amounts of *Tragapogon dubius*. *Bromus inermis* was present up to 34 m from the road, and *Tragopogon dubius* and *Taraxacum officinale* were present more than 35 m from the road. Other species nearby included *Cirsium arvense* (patch in gravel near downslope pull-out), *Rumex acetosella* (small patch), *Rumex crispus* (ID uncertain), *Carduus nutans* (1 individual), and *Melilotus officinalis* (1 individual).

Transect 3 was placed upslope of the road near the Ute Trailhead at 3,485 m (11,434 ft) in elevation. In our plots, we only found non-native plants in our 0 m plots, a few individuals of *Poa pratensis* and *Taraxacum officinale*.

Directly next to the trailhead, we found more *Taraxacum officinale* individuals. Up the road we found a few individuals of *Rumex acetosella*.

Transect 4 was placed in the alpine tundra across the road from a pullout at 3,612m (11,850 ft). We found no non-native species here or anywhere nearby.

APPENDIX B: Non-native species trait analyses

In order to assess our predictions regarding species traits, we assigned trait scores to each plot by weighting the trait of a species by the frequency of that species within a plot, and summing all scores together across the species present in a plot. Trait data from the TRY database was requested and used for these analyses (https://www.try-db.org). These analyses include all plots from all sites (including non-RMNP sites). For nearly all of our comparisons of trait scores with plot elevation, we found a 'wedge-shaped' fit with the trait score as the dependent variable and elevation as our independent variable, meaning that at lower elevations we found a wide range of trait scores, but at higher elevations we found a very narrow range of trait scores confined to one extreme (Figures 7, 8, 9, 10, 11, 12). At elevations greater than 3400m we rarely found more than two non-native species. Thus trait scores at these elevations may not have contained a large enough sample size to be informative.

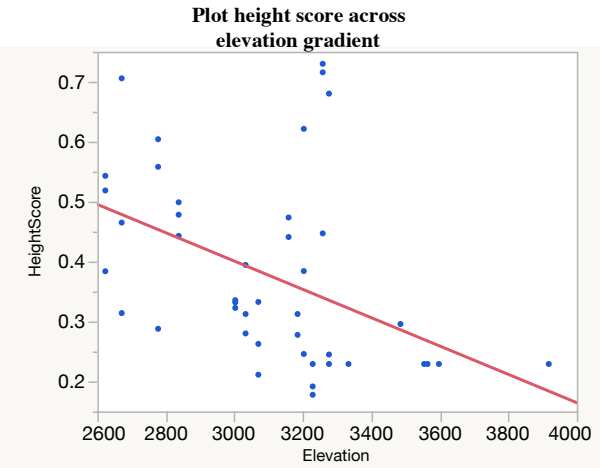

Figure A1. Non-native plant height scores showed a decrease with increasing elevation. Linear fit: $p = 0.0014$*; $R^2 = 0.2015$. Each point represents a non-native species at high elevations in Colorado.

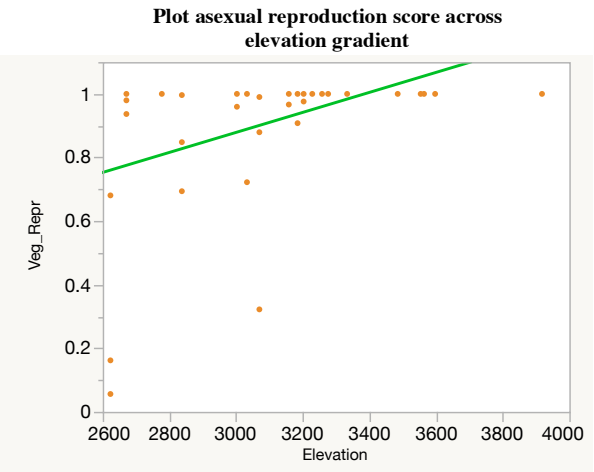

Figure A2. Non-native plant vegetative (asexual) reproduction showed and increase with increasing elevation. Linear fit: $p = 0.0015$*; $R^2 = 0.1976$. Each point represents a non-native species at high elevations in Colorado.

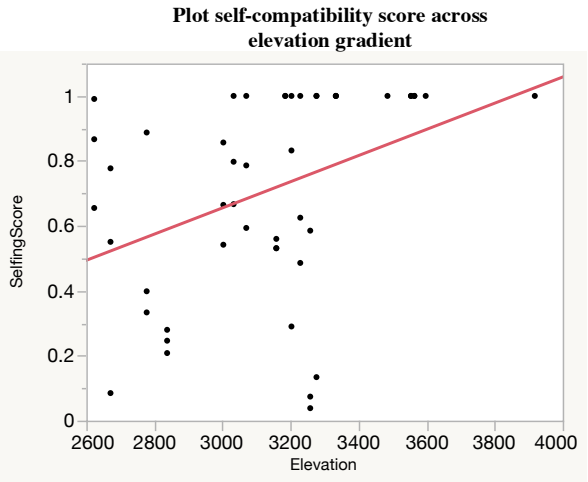

Figure A3. Non-native plant self-compatibility showed an increase with increasing elevation. Linear fit: $p = 0.0074$*; $R^2 = 0.1459$

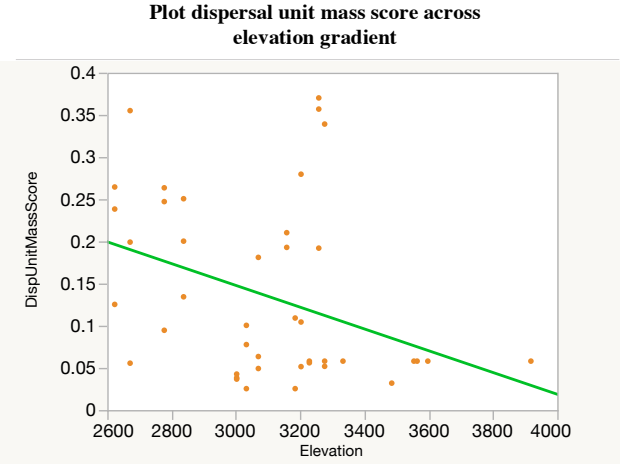

Figure A4. Non-native plant species dispersal unit mass showed a decrease with decreasing elevation. Linear fit: $p = 0.0091$*; $R^2 = 0.1388$.

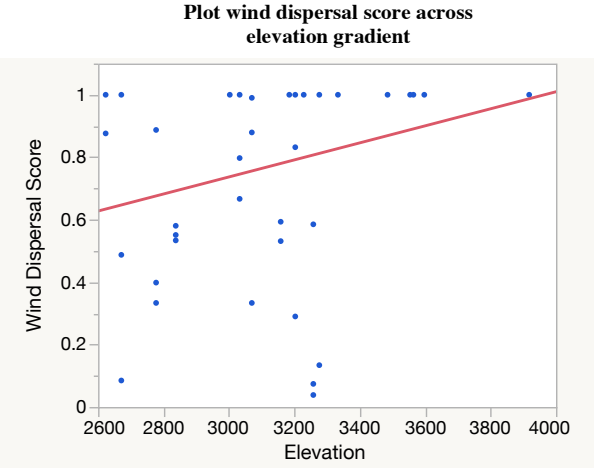

Figure A5. Non-native plant wind dispersal showed a positive correlation with increasing elevation, with a moderately significant linear fit. Linear fit: $p = 0.0722$; $R^2 = 0.0686$.

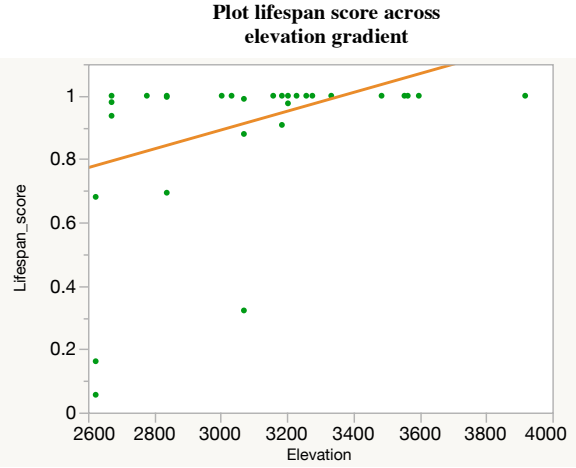

Figure A6. Non-native plant lifespan scores showed an increase with increasing elevation. Linear fit: $p = 0.0028$; $R^2 = 0.1781$.

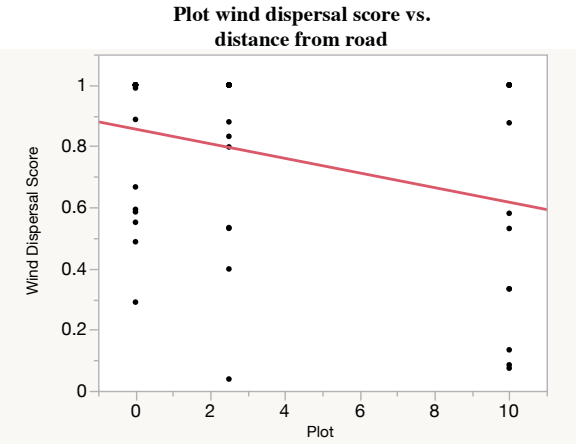

Figure A7. Wind dispersal score showed a decrease with increasing distance from road. $p = 0.0268$, $R^2 = 0.1021$.

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