Appendix C: Ecological and economic parameter estimates for the bioeconomic model and sensitivity analysis.

Ecological Components

For the native, we used values from four native genera (*Geum*, *Lathyrus*, *Ipomopsis*, and *Potentilla*) that commonly occur in areas where *Linaria vulgaris* grows (Wilke and Irwin 2010) and for which parameter estimates were available. In cases where we had parameter values from multiple natives, we used average values. For *L. vulgaris*, we used values from the field or greenhouse specific to Colorado, or when parameter estimates were not available, we used average values from the literature for other regions or for invaders with similar life history characteristics. Parameter estimates for the case study of *L. vulgaris* and for the sensitivity analysis are listed in Table 2 of the main text.

Intrinsic growth rate. Native intrinsic growth rate was calculated as 0.06, based on an average from three native genera (*Geum*, *Ipomopsis*, and *Lathyrus*) in the published literature (Ehlrén 1995, Kiviniemi 2002, Weppler et al. 2006, Price et al. 2008). Minimum and maximum values for the intrinsic growth rate for the sensitivity analysis came from the same published data. Although all three genera can grow in Colorado and in some of the same sites as *L. vulgaris*, it is important to note that some of the data are not specific to Colorado. The intrinsic growth rate for *L. vulgaris* was calculated from field data in southwest Montana as 0.622 (Lehnhoff 2008). The range of values used in the sensitivity analysis came from Lehnhoff (2008) and included 0.09 as the minimum and 0.77 as maximum *L. vulgaris* intrinsic growth rate.

Carrying capacity. Values of K_{x_i} for the native were estimated from field observations in the Elk Mountains of Colorado at the Rocky Mountain Biological Laboratory during the years

2006-2008 (R. E. Irwin, unpublished data). We evaluated six relatively undisturbed sites that were 4 m^2 each and contained approximately 22 common native species (Wilke and Irwin 2010). The six sites were in close proximity to areas with *L. vulgaris* but did not have *L. vulgaris* present. We estimated K_{x_i} as the mean maximum number of plants per m^2 for the most common native, *Potentilla pulcherrima* (Rosaceae). Like *L. vulgaris*, the growth form of *P. pulcherrima* makes it difficult to definitely identify genets in the field without digging plants up. Thus, we counted stalks in a similar manner as for *L. vulgaris*. We estimated the density as 90 *P. pulcherrima* per m^2. Values of K_{y_i} for *L. vulgaris* were estimated from field observations during the years 2000-2010 in 6 sites that were each 4 m^2. The sites had *L. vulgaris* present for over 20 years, and we estimated the carrying capacity as the highest stable maximum density observed over time (120 *L. vulgaris* per m^2). Values for the sensitivity analysis for the native and invader came from these same data and were simply the minimum and maximum recorded densities in any one site-year combination.

Competition coefficients. For the case study, we calculated competition coefficients using data from a greenhouse experiment in which we grew a representative native, *I. aggregata*, and *L. vulgaris* alone and together using a partially additive design (R. E. Irwin, unpublished data). We measured leaf length and number of leaves of *I. aggregata* and leaf length, number of leaves, and plant height of *L. vulgaris*. Our experimental design allowed us to measure the effects of *I. aggregata* on *L. vulgaris* and vise versa. We calculated a competition coefficient for the effect of *L. vulgaris* on the native, α_{xy}^{i}, as 2.5 and a competition coefficient for the effect of the native on *L. vulgaris*, α_{yx}^{i}, as 0.001, or effectively 0. For the sensitivity analysis, we used values for α_{xy}^{i} between 0 and 3.6 and values for α_{yx}^{i} between 0 and 2.5. We used 3.6 as the maximum competition coefficient for the effect of the invader on natives based on estimates of invisibility from Lehnhoff (2008). We used 2.5 as the maximum competition coefficient for the effect of natives on the invader to simulate the scenario where the native and invader would have similar competitive ability.

Movement between properties. Values were calculated for natives and *L. vulgaris* based on seed production per plant, seed movement, and seed germination. For both the native and *L. vulgaris* we assumed that only 8% of seeds move beyond 1 m^2 from the parent plant (F. and Roché 1991, Nadeau and King 1991, Lehnhoff 2008). Seed production for common natives average 95 seeds per plant (Ehlrén 1995, Kiviniemi 2002, Weppler et al. 2006, Price et al. 2008) with an average germination rate of 7% (Price et al. 2008). We multiplied dispersal probability by mean seed production per plant by the probability of seed germination to calculate $m_{x_{ji}}$ equal to 0.54 plants per plant per m^2. For the sensitivity analysis, the range of values for $m_{x_{ji}}$ was calculated using minimum and maximum parameters from Price et al. (2008), which resulted in the minimum $m_{x_{ji}}$ equaling 0.012 plants per plant per m^2 and maximum $m_{x_{ji}}$ equaling 1.52 plants per plant per m^2. For the invader, *L. vulgaris* produces an average of 272 seeds per ramet (Saner et al. 1995, Lehnhoff 2008) with a probability of seed germination of 0.18% (Nadeau and King 1991). We calculated $m_{y_{ji}}$ equal to 0.05 *L. vulgaris* per *L. vulgaris* per m^2. For the sensitivity analysis, minimum and maximum values of $m_{x_{ji}}$ were calculated using published parameters from Saner et al. (1995) and Lehnhoff (2008), which resulted in the minimum $m_{y_{ji}}$ equaling 0.0077 *L. vulgaris* per *L. vulgaris* per m^2 and maximum $m_{y_{ji}}$ equaling 0.151 *L. vulgaris* per *L. vulgaris* per m^2.

Economic Components

Benefits. Benefits were calculated from the aesthetic value of native plants and an increase in property value associated with natives. Because little data exist on the aesthetic value of natives, especially native wildflowers, we assumed that the economic value of natives approximated their benefits, similar to a replacement-cost approach (Garrod and Willis 1999). In Colorado, native plants can be purchased for $0.40 per stalk on average (or $10 per plant and plants have approximately 23 stalks) (Tagawa Gardens, Centennial, CO, *personal communication*, April 2011). Stigarll and Elam (2009) estimated vegetation in a yard can increase property value by 3%. Using an average property value of $20 per m^2 (Kaan, 2011) leads to a maximum benefit of $0.60 per native. The total benefit is the sum of aesthetic value and increased property value, which totals $1. For the sensitivity analysis, the range of values was calculated by using aesthetic value only ($0.40) to represent the minimum benefit value, and the maximum property size and property value per m^2 of $3.4 as the maximum benefit value (data retrieved October 2011 from www.census.gov/const/C25Ann/medavgsoldlotsize_cust.xls and http://www.zillow.com/local-info/CO-home-value/r_10/). One caveat is that *L. vulgaris* was introduced as an ornamental and may have folk medicinal properties (reviewed in Mitich 1993, Saner et al. 1995, Sing and Peterson 2011); we did not include these potential benefits of *L. vulgaris* in our calculation given that *L. vulgaris* is listed as a species to control in many US states in western North America, including Colorado.

Damages. For the case study, we calculated damages from *L. vulgaris* based on increased soil erosion, $0.001-$0.0198 (Palmquist and Danielson 1989), and reduced caloric intake for cattle and subsequent reduced cattle production on private property with small subsistence farms (Finnoff et al. 2008 and http://www.ers.usda.gov/statefacts/co.htm retrieved March 2011) as a function of *L. vulgaris* density ($0.0013). Together, damages from increased soil erosion and reduced cattle production total \$0.00472 per *L. vulgaris*. For the sensitivity analysis, damages ranged in value using the minimum and maximum damages from soil erosion plus damage to cattle (\$0.0023 to \$0.0218).

Cost of planting natives. The average cost of a native plant is \$0.40 (Tagawa Gardens Centennial, CO, *personal communication*, April 15, 2011), and we assumed that other costs of planting, such as labor or materials, were minimal and thus not included in the estimate. Because planting natives was never cost effective for management (see *Case study: Results and Discussion)*, we did not vary this parameter in the sensitivity analysis.

Cost of removing invaders. Mechanical and chemical control are the two most successful removal strategies for *L. vulgaris* (Lajeunesse 1999). Landscaping companies estimate that they can manually pull 137 *L. vulgaris* per hour (during dry and wet conditions) at a cost of \$45 per hour (Rocky Mountain Trees & Landscaping, Crested Butte, CO, *personal communication*, April 2011), producing an average mechanical removal cost of \$0.33 per *L. vulgaris*. The cost of chemical control is based on chemicals (approx. \$0.0069 per m^2) and labor (approx. \$0.03 per m^2). Averaging mechanical and chemical control provides a maximum removal cost of \$0.185 per *L. vulgaris*. For the sensitivity analysis, assuming an herbicide only treatment provided the minimum removal cost of \$0.037 per *L. vulgaris*, whereas a hand-pulling only treatment provided the maximum removal cost of \$0.33 per *L. vulgaris*.

Discount rate. The discount rate was obtained from Executive Order 12866 and was calculated using both low-yield and high-yield interest rates.

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