

Ecography

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**Supplementary material**

## **Appendix 1. Model methods**

### **Habitat Suitability Model**

To evaluate the change in predicted suitable habitat for *Carlina vulgaris* under climate change, current habitat suitability was modeled using Maxent Version 3.3.3f (Phillips *et al.* 2006; Phillips & Dudik, 2008) in the Dismo package for R (Hijmans *et al.* 2011). Maxent has been shown to perform better than most other species distribution modeling methods for predicting suitable habitat with presence only data (Elith *et al.* 2006). Occurrence only data for *Carlina vulgaris* at 24,417 locations were obtained on 7/15/2011 from Global Biodiversity Information Facility (GBIF 2011). Data were cleaned to remove erroneous entries. To reduce geographic bias and match the scale of the climate data, occurrence locations were reduced to one record per 10 arc-minute grid cell, leaving 3,907 occurrences. Pseudo-absences of 1000 random points were drawn from the climate area bounded by land masses within -10 to 38° longitude and 39 to 66° latitude. Nineteen bioclimatic (bioclim) factors were evaluated for their correlation at presence locations. These factors were evaluated for their suitability to predict the occurrence of *C. vulgaris*. Non-influential factors (those with less than 1% contribution to modeled predictions) and strongly correlated factors were removed from the predictive models, leaving six influential climate factors (Table 1) with an AUC of 0.822. The maximum correlation between remaining climate factors was 0.643. In particular, sufficient soil moisture (explained by climate factor precipitation seasonality) is considered to be important for seed germination and thus for the distribution of *C. vulgaris* (Klinkhamer *et al.* 1996; Löfgren *et al.* 2000), and dry summers (Max temperature warmest month) should benefit the species (H.H. Bruun, pers. obs).

### **Survival rates**

A stochastic matrix model with dormant seeds, juveniles, and rosettes was developed for *Carlina vulgaris*. Probability of flowering is generally a function of the size of the individual rosette in the previous year (Klinkhamer *et al.* 1991, 1996; de Jong *et al.* 2000; Rose *et al.* 2002). Within one year, seeds produced by rosettes (represented as fecundity) are integrated into the seedbank or emerge as seedlings and become juveniles, which do not produce seeds (Klinkhamer *et al.* 1996; de Jong *et al.* 2000). Survival of juveniles (first-year, non-flowering plants) was

calculated by averaging the survival probabilities reported in Klinkhamer *et al.* (1996), who provided data for seedling survival over a number of years for Dutch populations. At the onset of the second year, juveniles become adult rosettes, hereafter termed “rosettes”. In subsequent years, rosettes may flower and die or stay as rosettes. Rosette survival and transition values were based on data from Becker *et al.* (2006) and additional unpublished data from Becker (pers. comm.). Standard deviations were calculated from the variation in these data across years.

Disturbance, typically in the form of grazing, is associated with increased growth of *Carlina vulgaris* populations (Löfgren *et al.* 2000); without disturbance, population growth rates tend to be less than one. Several studies found declining populations of *C. vulgaris* in the landscape (Klinkhamer *et al.* 1991, 1996; Löfgren *et al.* 2000; Rose *et al.* 2002). However, they also found persisting or increasing populations, and the formation of new populations. Since disturbance is required to achieve positive population growth, it is thought that *C. vulgaris* is characterized by short term dispersal and frequent new establishment of populations rather than stable population dynamics (Klinkhamer *et al.* 1996). For our model, patches (clusters of adjacent cells of suitable habitat, described above) are at least one kilometer square; thus, local extinction, short-distance dispersal and local recolonization events all take place within the patch. However, using a metapopulation model with multiple patches allows us to evaluate how changing habitat suitability due to climate change impacts the species at the landscape scale.

Juvenile survival differed among studies. In Sweden, juveniles were found to have >95% survival during their first season (Löfgren *et al.* 2000). However, Klinkhamer *et al.* (1996) found that in the Netherlands 30-80% of juveniles survived to June of the year after germination. Since survival rate seems to depend on characteristics within microsites and the cell size for the matrix model will encompass a variety of microsites, we averaged these values to determine a transition rate of  $(0.63 \pm 0.11)$ , Table 3) for juveniles to rosettes, which encompasses survival of juveniles. A survival rate for rosettes  $(0.61 \pm 0.14)$ , Table 3) was determined using data on individuals from 5 locations across Europe (unpublished data, Becker, pers. comm).

### **Seed Production and Emergence**

*Carlina vulgaris* generally does not flower or produce seeds in the first year after germination, and many plants will delay flowering to a third or later year (Klinkhamer *et al.* 1991, 1996; Rose *et al.* 2002). Mean age at flowering in a British study was 3.04 years with a maximum of 8 years (Rees *et al.* 2006). Optimal size for flowering is a tradeoff between increase

in seed production and mortality risk (de Jong *et al.* 2000). Probability of flowering increases with rosette diameter and weight, and seed production is proportional to plant biomass (Klinkhamer *et al.* 1991, 1996; de Jong *et al.* 2000; Rees *et al.* 2006). Individuals generally die after producing seed. Thus, the effect of age is indirect: older plants are larger and, thus, more likely to flower. Since the matrix model uses stages rather than ages, this results in a high annual mortality rate for the rosette stage with fecundity averaged between non-reproducing and reproducing individuals on a yearly basis.

In the matrix model, fecundity was represented using unpublished data from Becker. Rather than have a separate stage for flowering plants, this model averaged seed production across all living individuals. The average number of seeds produced by a flowering individual was multiplied by the proportion of reproductive rosettes, and divided by the total number of rosettes. This resulted in average fecundity per individual per year of 33.13. Seeds of *C. vulgaris* are produced in September to December, and seedlings emerge from April to June (Klinkhamer *et al.* 1996; de Jong 2000; Rose *et al.* 2002). *Carlina vulgaris* tends to accrue only small and transient seedbanks (van Tooren and Pons 1988; Eriksson and Eriksson 1997; Thompson *et al.* 1997; de Jong *et al.* 2000; Rees *et al.* 2006), with disappearance of seeds from the seedbank mainly due to germination (Pons 1991). De Jong *et al.* (2000) retrieved 15% of seeds sown as juveniles the first year after sowing, and 2% the second and third year after sowing. Therefore, within a year some seeds will enter the seedbank while others will emerge as juveniles.

Establishment of seedlings can be limited by available microsites (Klinkhamer *et al.* 1996; Löfgren *et al.* 2000; Rose *et al.* 2002), or by seed availability (Greig-Smith and Sagar 1981; Löfgren *et al.* 2000). The percentage of seeds that germinate varied among studies. In lab trials, 60-100% of *Carlina vulgaris* seeds germinated (van Tooren and Pons 1988). Greig-Smith and Sagar (1981) found 10-17% emergence in open plots, and 63-65% in plots protected from predators (survival March-June). Few seedlings survive to the end of the first year. Klinkhamer *et al.* (1996) found that  $9.4 \pm 1.9\%$  of seeds survived to seedling establishment one year later in a stable population in good habitat, while a declining population had  $0.5 \pm 0.3\%$  survival. De Jong *et al.* (2000) found 15% of seeds survived as seedlings the following year. Becker (2005) found that 2.5% of sown seeds produced seedlings which survived until summer. Since the model incorporated both declining and growing areas within each patch and included survival through

the first year, we used an average of the four values which included seed and seedling mortality over a year ( $6.85\% \pm 0.57485$ , Table 3), and multiplied this by the number of seeds produced to estimate the transition rate between rosettes and juveniles ( $2.269 \pm 1.937$ , Table 3).

Transition from rosettes to seeds in the seedbank included 30% of the fecundity ( $9.941 \pm 8.483$  seeds per individual per year, Table 3). In subsequent years, seeds in the seed bank had a  $0.3 \pm 0.03$  annual survival rate. Seedbank survival combined with a 6.85% germination rate results in 2% emergence of the original seedbank in the second year and less than 1% of the seed cohort remaining by the 5<sup>th</sup> year. This aligns with results from de Jong *et al.* (2000).

### **Initial abundance**

Initial abundance was estimated using information from Jakobsson & Eriksson (2005), who found the number of flowering individuals in a  $3.14 \text{ km}^2$  circle to average 1029.28 (or  $327.8 \text{ per km}^2$ ) over two different Swedish counties. The percentage of individuals flowering per year averaged 20% (Klinkhamer *et al.* 1996), so after including non-flowering individuals the density per  $1 \text{ km}^2$  would be 1639 individuals. Since the cell size used for the models was  $0.0625 \text{ km}^2$ , the actual density per cell was set at 102. The number of flowering individuals varied greatly between  $2 \text{ km}^2$  circles (Jakobsson & Eriksson 2005), so for comparison we ran simulations with a range of initial abundances: 10%, 50%, 150%, and 170% of the above density (spanning the minimum and maximum densities found by Jakobsson & Eriksson 2005). In some places abundances may be much higher than this (Matthies personal observation), so these numbers are likely not an accurate estimation of total population size. However, since the numbers are kept the same between simulations, comparing results from different scenarios reflects relative performance of the scenarios. The total initial population was distributed across stages in the model according to the stable stage distribution.

### **Carrying capacity and density dependence**

Limitation by carrying capacity,  $K$ , means that all suitable habitats in the landscape are occupied (Münzbergová & Herben 2005). At a local scale (e.g. within each patch), the population is limited by microsite availability (Münzbergová & Herben 2005). Thus, while each patch in the model is climatically suitable for *Carlina vulgaris*, in reality within each patch the distribution would be limited to recently disturbed grasslands. To provide a plausible estimate for

carrying capacity the maximum observed density (1710 flowering individuals per 3.14 km<sup>2</sup> circle) was scaled to account for the availability of suitable microsites;  $K$  was set at 2723 rosettes per km<sup>2</sup>, or 170 individuals per cell. Total  $K$  for each patch is the sum of  $K$  across all cells within the patch.

The carrying capacity (defined here as the maximum number of individuals that can be accommodated per habitat patch) was based on available space and thus depends on the size of plants. Carrying capacity could potentially be greater for smaller plants than for larger plants. Since juveniles take up proportionally less space per plant than rosettes, the carrying capacity for juveniles could reasonably be expected to be larger than the carrying capacity for rosettes; thus we set the carrying capacity for rosettes to be 9.5% the carrying capacity for juveniles. In this way the plants in each stage are weighted, relative to the largest-sized rosette stage, to calculate a “stage equivalent” total abundance for comparison to the rosette-specific carrying capacity. These calculations were based upon the difference between the maximum observed seedling abundance per 1 m<sup>2</sup>, (400, Rees *et al.* 2006) and the maximum observed for rosettes (34, Klinkhamer *et al.* 1996). Density dependence is primarily exhibited during recruitment (Rees *et al.* 2000; Rose *et al.* 2002); however, adult density can impact plant growth (Rose *et al.* 2002). When populations exceed carrying capacity, it is likely that mortality would be increased as well. Within the model, a ceiling density dependence function reduced the population to  $K$  by the following time step whenever the population exceeded  $K$ .

## **Vital rates and climate**

The demographic data collected from a translocation experiment was performed to investigate regional adaptation in *Carlina vulgaris* (Becker 2005; Becker *et al.* 2006) was analyzed for correlation between vital rates and climate. We compared vital rates with climate at the location grown in multiple ways: we regressed (a) average fecundity per translocation scenario with bioclim factors (Supporting Figure 1) (b) average population growth rate (finite rate of increase, or lambda) per translocation scenario versus habitat suitability value (Supporting Figure 2) (c) seed production per reproducing individual versus bioclim factor at the growing site (Supporting Figure 3) and (d) seed production per reproducing individual, separated by origin versus bioclim factor at the growing site (Supporting Figure 4).

## Additional References

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Table A1. Sensitivity analysis for life history parameters. Each matrix parameter was perturbed by + or – 10%. The resulting expected minimum abundance (EMA) was compared with the ‘baseline’ EMA (home matrix with no changes in parameters). A positive change in transition values between stages is indicated by “Stage1+Stage2”, with three possible stages: seeds, juveniles, and rosettes. When the change in the resulting EMA is more than 10%, the model is considered to be sensitive to that parameter. The model is somewhat sensitive to those parameters highlighted in light orange, and more sensitive to those highlighted in darker orange.

Scenario	Percent change from Baseline
Duration 50	0.249
Duration 250	0.228
Juvenile+Rosettes	0.131
Duration 150	0.125
Rosette+Juvenile	0.115
Rosette-Juvenile	0.108
Juvenile-Rosette	0.104
Rosette-	0.074
Rosette+	0.060
Seeds+Juveniles	0.039
Seeds-Juveniles	0.034
Rosette+Seeds	0.031
IA -70%	0.017
IA -10%	0.014
Juvenile-	0.010
IA -90%	0.010
IA +90%	0.008
IA -50%	0.008
Rosette-Seeds	0.005
Initial abundance +10	0.004
Juvenile+	0.003
IA +70%	0.002
IA +50%	0.001

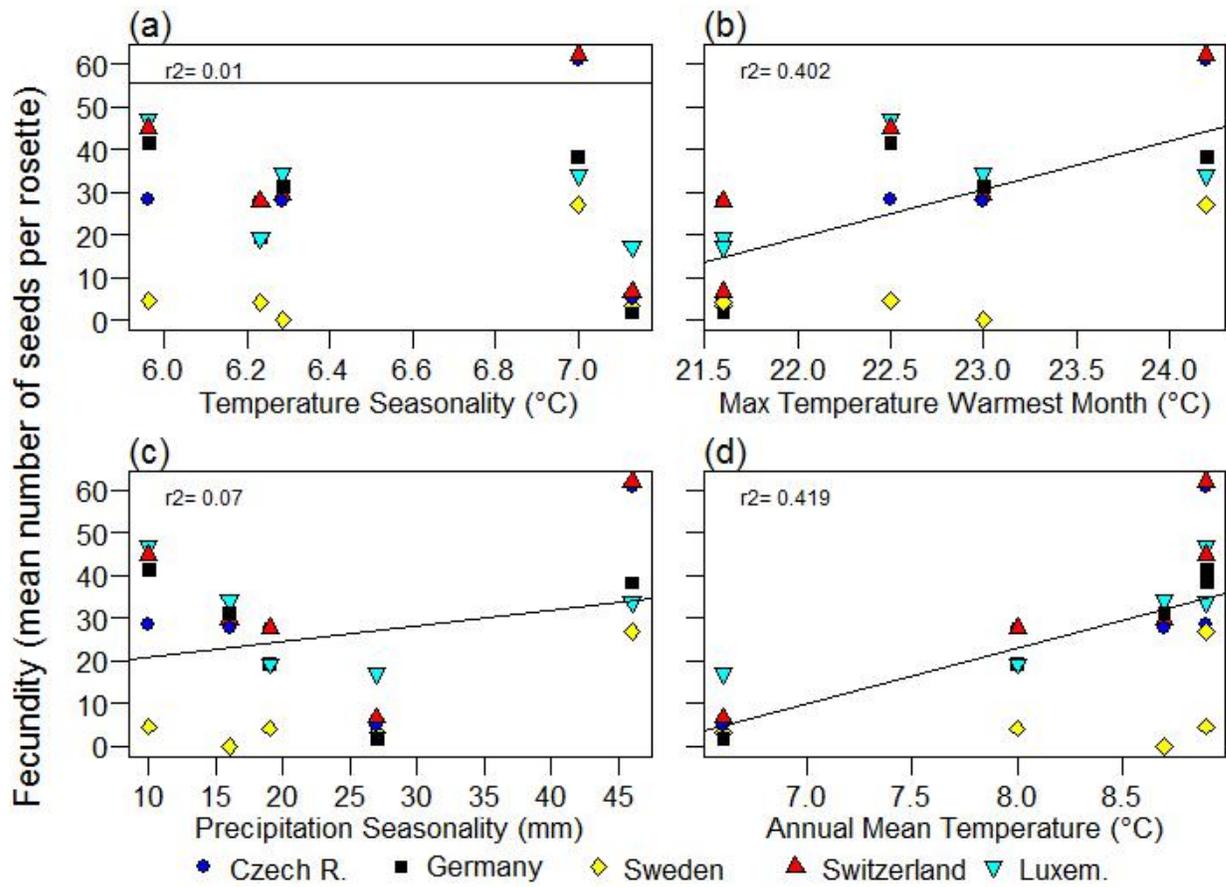


Figure A1. Predicted fecundity, *i.e.* mean number of seeds per rosette (average seed production per reproducing individual multiplied by proportion of rosettes flowering annually) per translocation scenario versus bioclim factors at the location grown. Colors and shapes indicate location of origin. Cell size for climate factors for this comparison was 30 seconds.

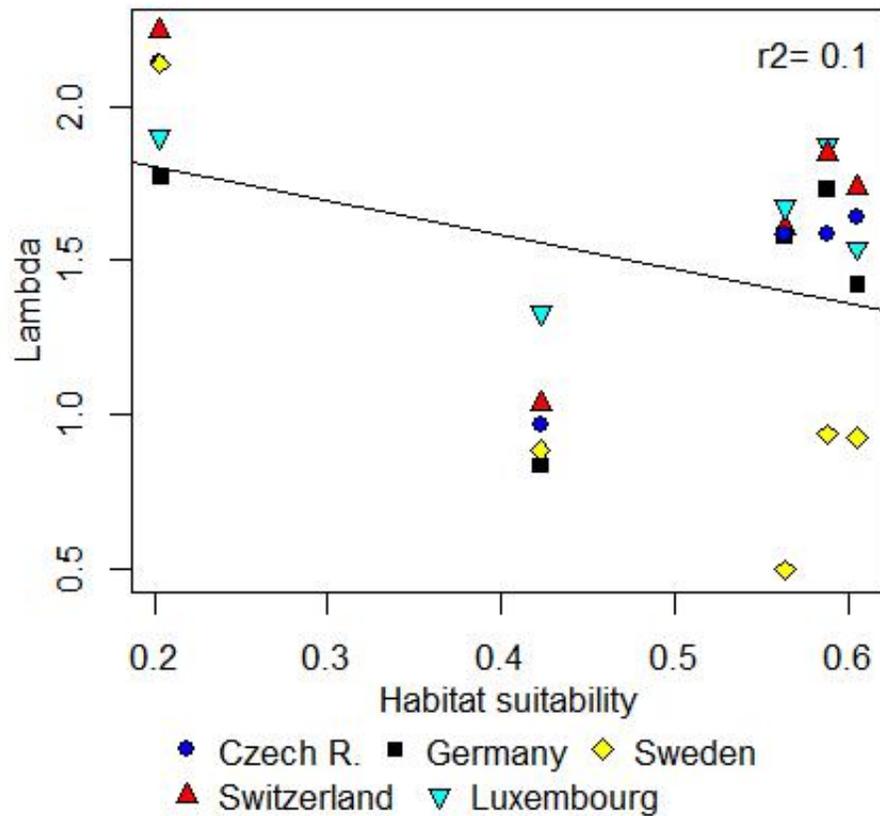


Figure A2. Habitat suitability factor versus lambda (average population growth rate) for the 25 various translocations performed on *Carlina vulgaris* individuals. Colors and shapes indicate origin of the individuals. Lambda values are the dominant eigenvalues of matrices developed for each translocation scenario with survival rates, fecundity, and transition values calculated using data from the translocation experiment.

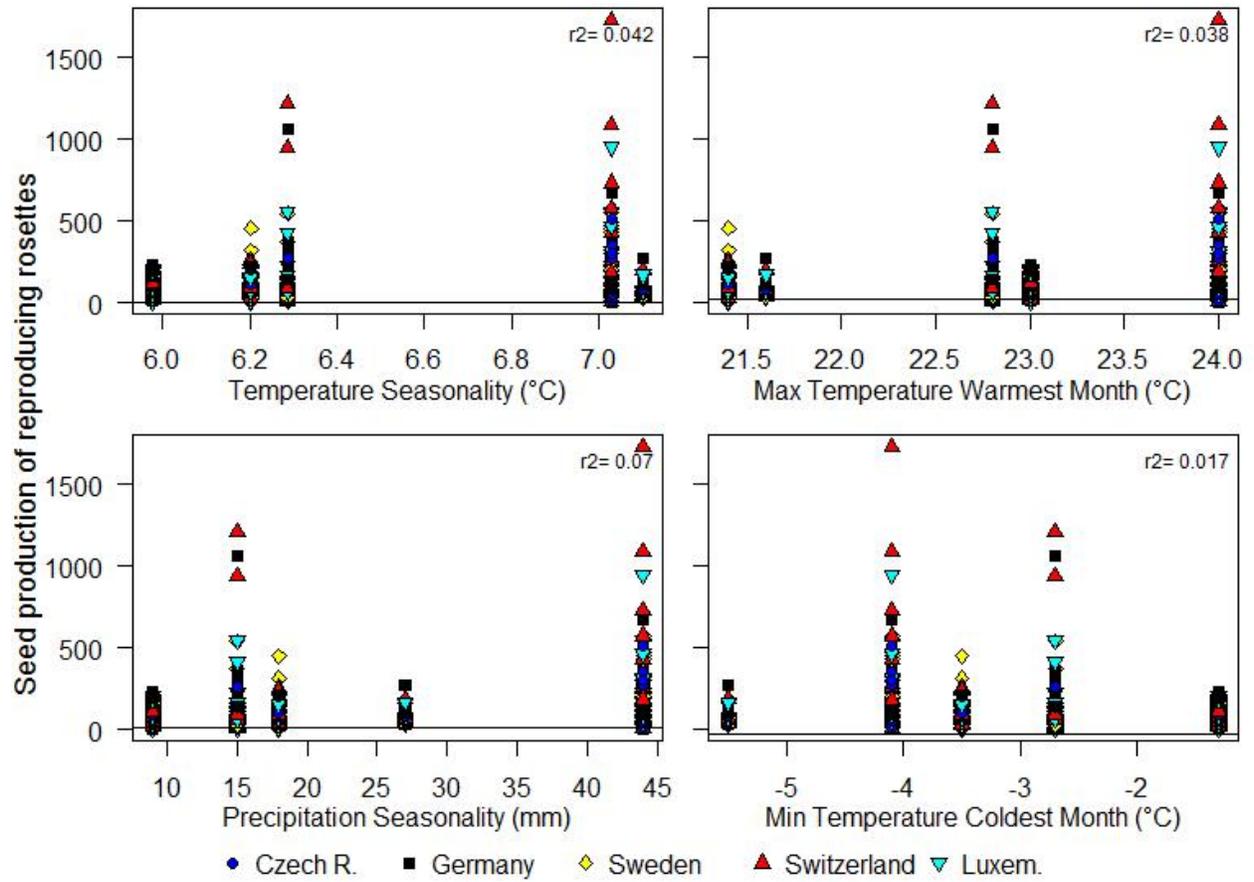


Figure A3. Seed production of reproducing individuals (based on rosette size) versus bioclim factors at the location grown (colors and shapes indicate location of origin).

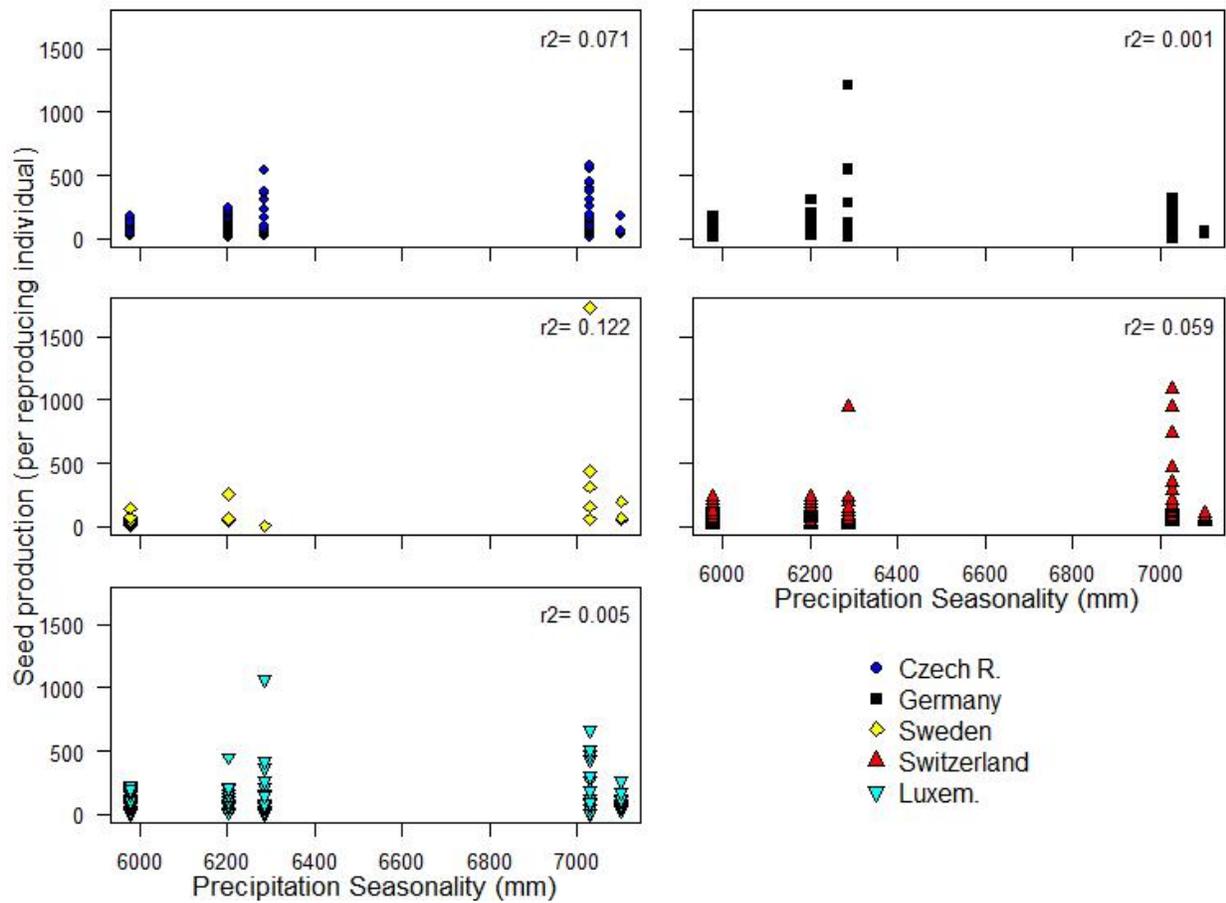


Figure A4. Climate factor Bio 4, precipitation seasonality versus predicted seed production (based on rosette size) for reproducing *Carlina vulgaris* individuals. Each figure shows individuals originating at each of the five different translocation sources.

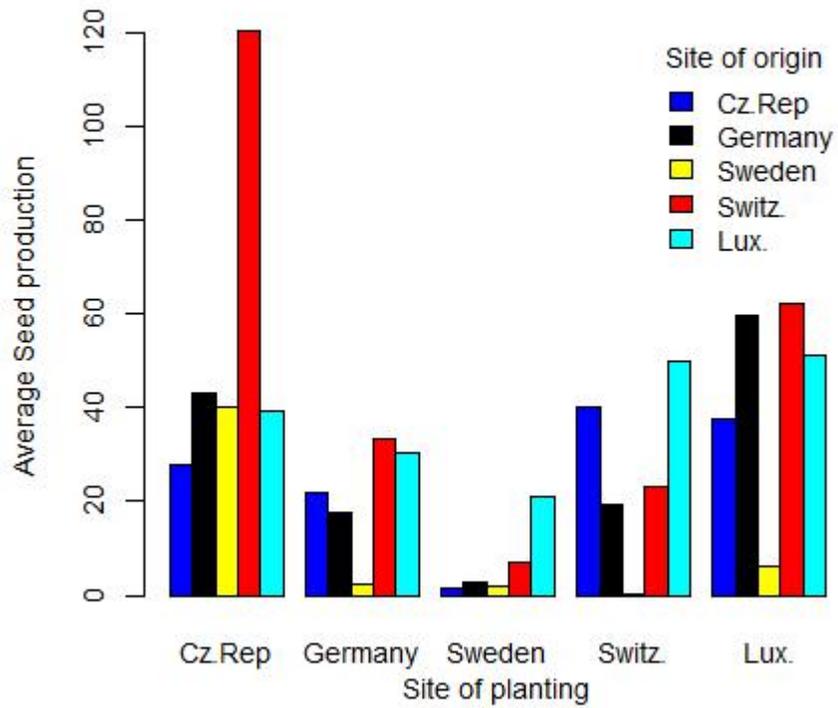


Figure A5. Expected average seed production per reproducing individual of *Carlina vulgaris* (grouped by site of planting), when planted at home and translocated to other sites.

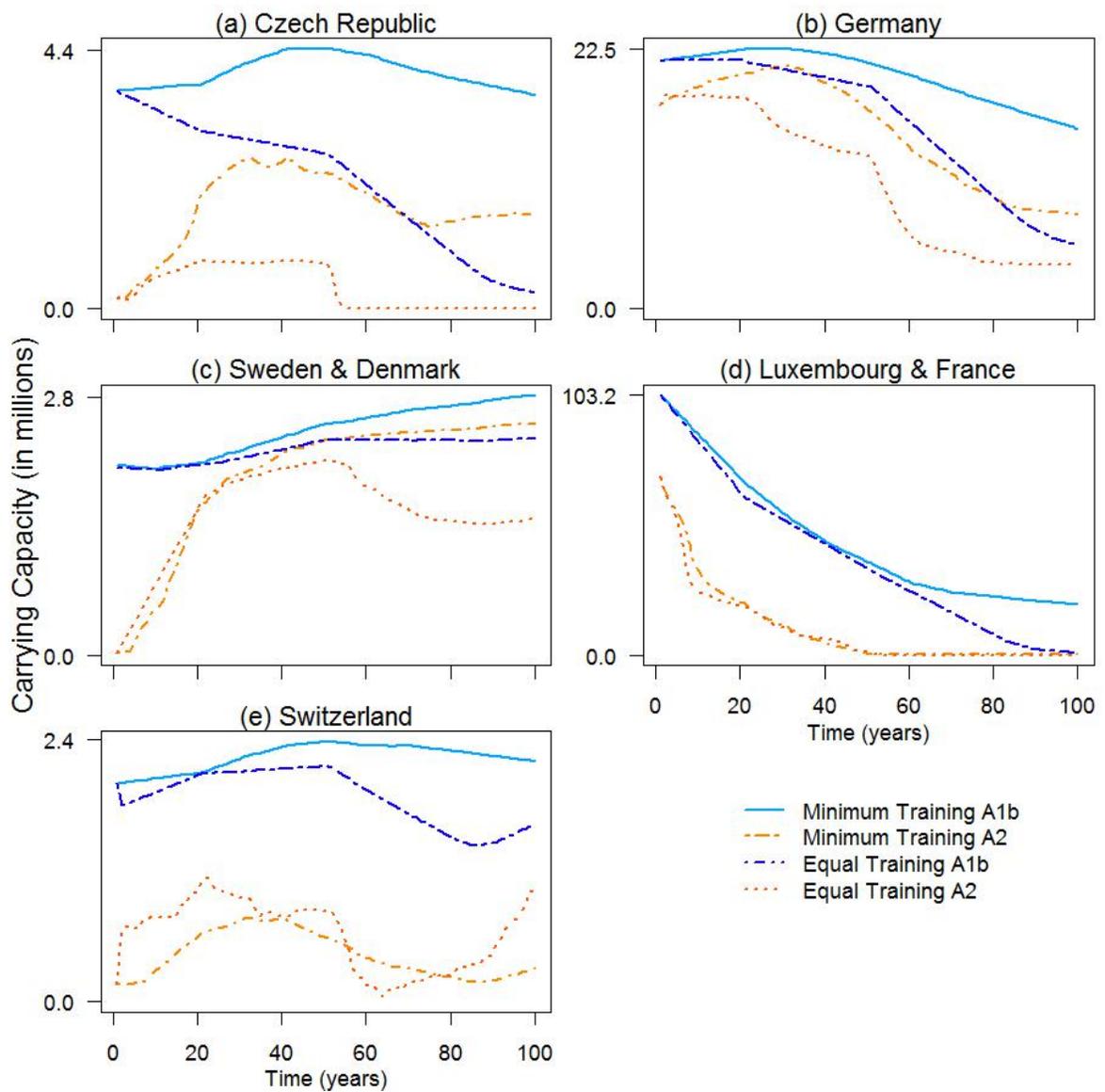


Figure A6. Carrying capacity through time for *Carlina vulgaris* metapopulations based on habitat suitability in (a) the Czech Republic, (b) Germany, (c) Sweden & Denmark, (d) Luxembourg & France, and (e) Switzerland

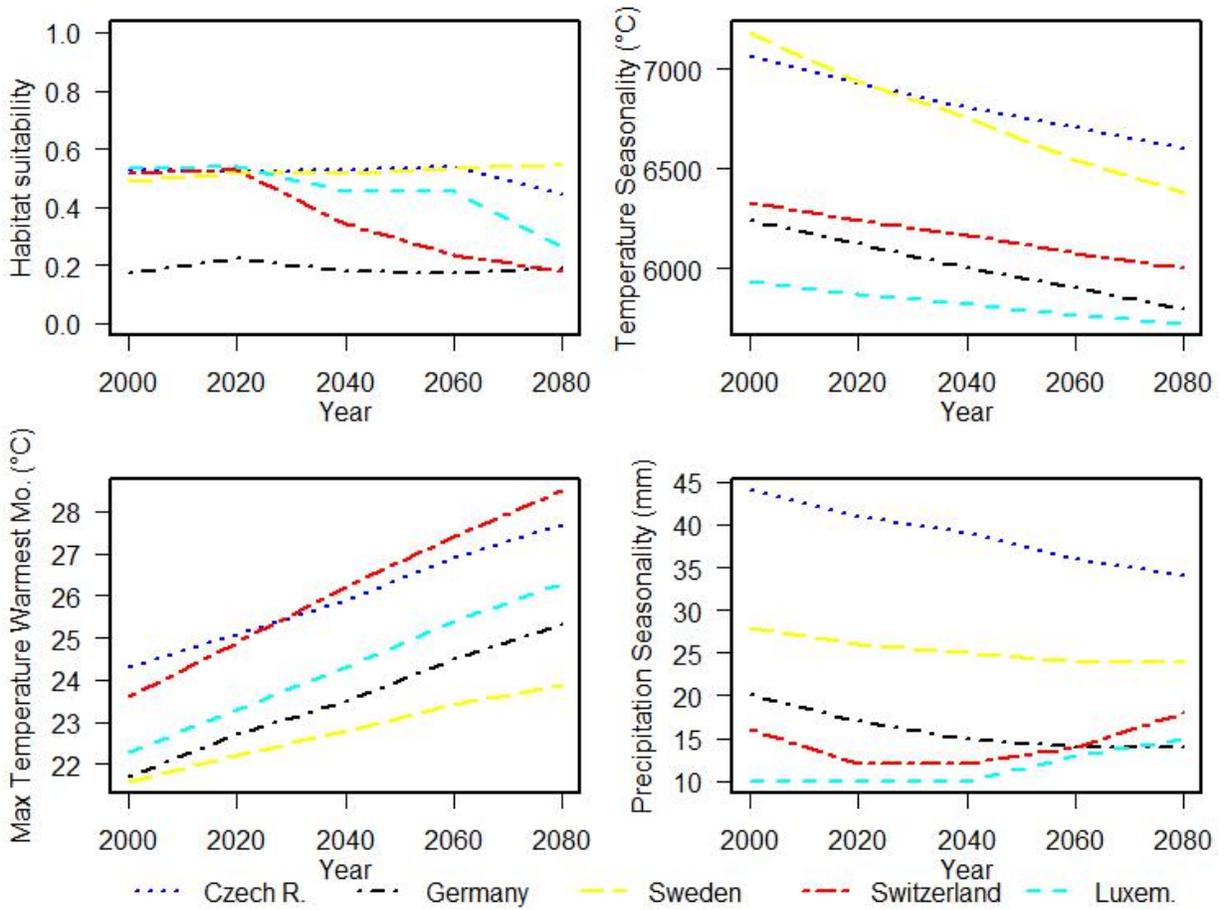


Figure A7. Predictions of a) Habitat suitability for *Carlina vulgaris* through time b) Temperature Seasonality c) Max Temperature of the Warmest month and d) Precipitation Seasonality. Values are taken from the grid cell containing the translocation site within each country.

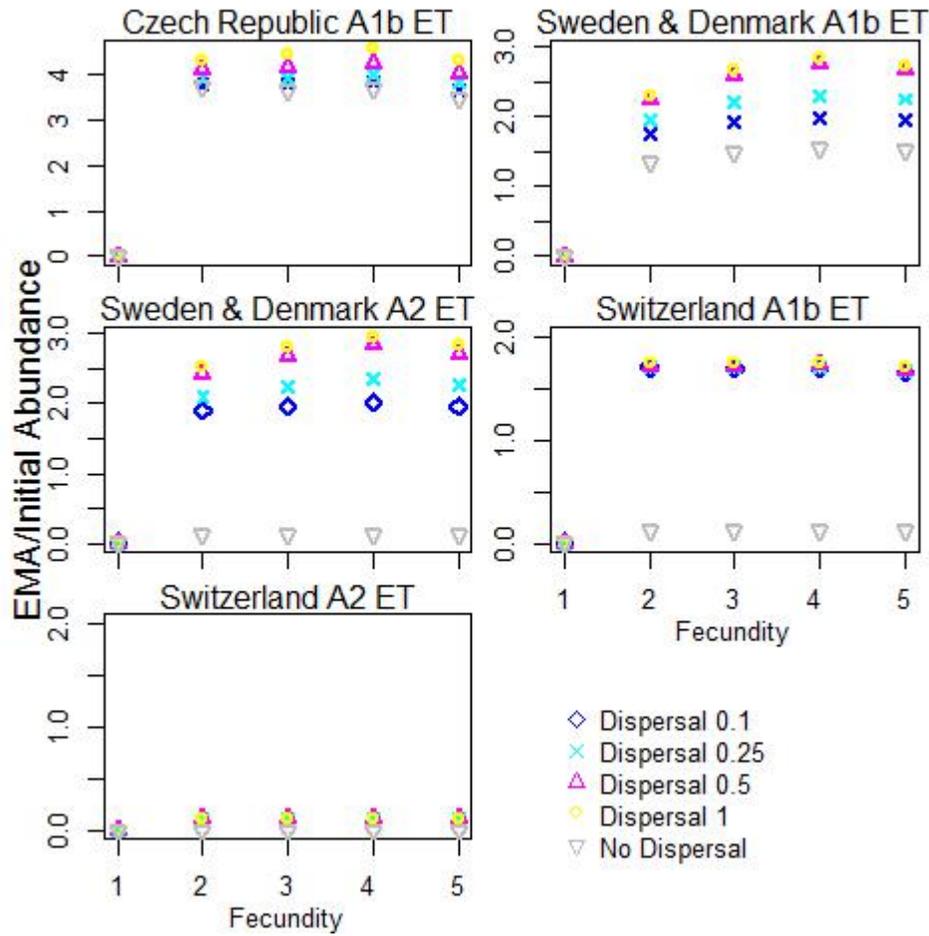


Figure A8. EMA/IA and fecundity category for scenarios with increasing proportions of seed dispersal. Only scenarios in which dispersal affected EMAs are shown.