***Appendix S3. Sensitivity analyses***

*Results partitioned by different fitness proxy*

To explore the effects of combining different “best fitness” estimates in our analysis, we reran the analyses separately for each type of fitness proxy, using all species for which that proxy had been reported. Similar declines in fitness across range limits were observed for these different subsets of species (Table S1).

*ENM sensitivity analyses*

We examined the effects of many of the decisions made during ENM calibration on our conclusions by conducting several additional rounds of model calibration followed by re-analysis of results across species. The first of these ENM sensitivity tests replaced the more complex hinge features (where used) with linear, product and quadratic features. A second set of sensitivity tests explored two alternatives to the minimum convex polygon around points for background sampling for each species: a background area defined by the rectangular extent encompassing all of the species’ localities plus an additional 200 km in each cardinal direction (equivalent to defining an arbitrary study region) and a background area defined by buffering the localities by ~300 km (which avoids some problems inherent to MCP for species who ranges are not well described by a simple convex shape; Fig. S3-1). Finally, we generated a relatively unrestricted set of models based on all 19 bioclim variables and all feature types (i.e. allowing Maxent to do its own variable selection: Elith et al., 2011) while allowing background sampling to come from a 200 km2 rectangular area around each species’ range (this latter configuration most closely represents a decision-free approach to using Maxent and is consistent with the setup of many of the earliest studies using the software). Most analyses were robust to the different calibration strategies (Tables S2-S3). However, the statistical significance of the tests of concordance when vertical limits were treated separately varied across runs (Table S3).

Table S3-1. Differences in the fitness of transplanted individuals across range limits when different fitness components are analyzed separately. Comparisons between the full and reduced model (i.e. without site type) were based on likelihood ratio tests (LRT). Significant values (p<0.05) are in bold.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Analysis | Fitness estimate (number of species) | Mean coefficient (SE) | LRT | P value |
| Combined | Survival (n=37) | -0.32 (0.054) | LRT5,4=32.25 | **<0.0001** |
| Growth (n=16) | -0.26(0.061) | LRT5,4=16.17 | **<0.0001** |
| Reproduction (n=8) | -0.31 (0.14) | LRT5,4=4.57 | **0.033** |
| Fitness (n=21)\* | -0.50 (0.10) | LRT6,5=22.47 | **<0.0001** |
| Best estimate (n=40)† | -0.25 (0.049) | LRT7,6=21.03 | **<0.0001** |
| Horizontal | Survival (n=23) | -0.17 (0.051) | LRT5,4=10.62 | **0.0011** |
| Growth (n=14) | -0.19 (0.064) | LRT5,4=8.74 | **0.0031** |
| Fitness (n=11) | -0.27 (0.10) | LRT5,4=6.90 | **0.0086** |
| Best estimate *(*n=25)† | -0.16 (0.055) | LRT6,5=8.38 | **0.0038** |
| Vertical | Survival *(*n=18)\* | -0.48 (0.098) | LRT6,5=19.91 | **<0.0001** |
| Growth (n=6) | -0.37 (0.15) | LRT5,4=5.80 | **0.016** |
| Fitness (n=10)\* | -0.88 (0.18) | LRT6,5=15.98 | **<0.0001** |
| Best estimate (n=19)† | -0.35 (0.077) | LRT7,6=13.58 | **<0.0001** |

\* To improve homoscedasticity, variances were allowed to vary by site type.

†To improve homoscedasticity, variances were allowed to vary by the type of fitness estimate.

Table S3-2. Differences in the suitability of transplant sites across range limits when niche models are calibrated in different ways. Comparisons between the full and reduced model (i.e. without site type) were based on likelihood ratio tests (LRT). Significant values (p<0.05) are in bold.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Analysis | ENM methodology | Mean coefficient (SE) | LRT | p value |
| Combined(N = 40) | Hinge features, PCA predictors, MCP background extent (V1) | -0.29 (0.056) | LRT4,3=25.50 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, MCP background extent (V2) | -0.31 (0.059) | LRT4,3=25.01 | **<0.0001** |
| Hinge features, PCA predictors, 200 km rectangular background extent\* (V3) | -0.38 (0.065) | LRT6,5=31.91 | **<0.0001** |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | -0.41 (0.081) | LRT4,3=25.01 | **<0.0001** |
| Hinge features, PCA predictors, buffered points background extent\* (V5) | -0.38 (0.060) | LRT6,5=36.73 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | -0.34 (0.061) | LRT4,3=28.94 | **<0.0001** |
| Horizontal(N = 25) | Hinge features, PCA predictors, MCP background extent (V1)  | -0.35 (0.063) | LRT4,3=27.24 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, MCP background extent (V2) | -0.44 (0.078) | LRT4,3=27.83 | **<0.0001** |
| Hinge features, PCA predictors, 200 km rectangular background extent (V3)  | -0.46 (0.086) | LRT4,3=25.40 | **<0.0001** |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | -0.48 (0.11) | LRT4,3=16.89 | **<0.0001** |
| Hinge features, PCA predictors, buffered points background extent\* (V5)  | -0.48 (0.078) | LRT5,4=32.14 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | -0.50 (0.087) | LRT4,3=29.00 | **<0.0001** |
| Vertical(N = 19) | Hinge features, PCA predictors, MCP background extent (V1) | -0.22 (0.053) | LRT4,3=16.70 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, MCP background extent (V2) | -0.14 (0.046) | LRT4,3=9.57 | **0.002** |
| Hinge features, PCA predictors, 200 km rectangular background extent (V3) | -0.27 (0.057) | LRT4,3=20.82 | **<0.0001** |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | -0.32 (0.058) | LRT4,3=26.27 | **<0.0001** |
| Hinge features, PCA predictors, buffered points background extent (V5) | -0.26 (0.055) | LRT4,3=19.90 | **<0.0001** |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | -0.14 (0.051) | LRT4,3=7.11 | **0.0077** |

\* To improve homoscedasticity, variances were allowed to vary by site type.

Table S3-3. Concordance between the direction of the change in the performance of individuals (best fitness proxy) and the suitability of sites across range limits when niche models are calibrated in different ways. The results are based on binomial tests with probability of success = 0.5. Significant values (p<0.05) are in bold.

|  |  |  |  |
| --- | --- | --- | --- |
| Analysis | ENM methodology | Number of species with fitness and suitability changing in the same direction | p value |
| Combined(N = 40) | Hinge features, PCA predictors, MCP background extent (V1) | 31 | **0.00068** |
| Linear-product-quadratic features, PCA predictors, MCP background extent(V2) | 30 | **0.0022** |
| Hinge features, PCA predictors, 200 km rectangular background extent (V3) | 30 | **0.0022** |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | 27 | **0.038** |
| Hinge features, PCA predictors, buffered points background extent (V5) | 29 | **0.0064** |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | 27 | **0.038** |
| Horizontal(N = 25) | Hinge features, PCA predictors, MCP background extent (V1) | 17 | 0.11 |
| Linear-product-quadratic features, PCA predictors, MCP background extent (V2) | 17 | 0.11 |
| Hinge features, PCA predictors, 200 km rectangular background extent (V3) | 16 | 0.23 |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | 15 | 0.42 |
| Hinge features, PCA predictors, buffered points background extent (V5) | 15 | 0.42 |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | 15 | 0.42 |
| Vertical(N = 19) | Hinge features, PCA predictors, MCP background extent (V1) | 15 | **0.019** |
| Linear-product-quadratic features, PCA predictors, MCP background extent (V2) | 13 | 0.17 |
| Hinge features, PCA predictors, 200 km rectangular background extent (V3) | 15 | **0.019** |
| All features, all bioclim predictors, 200 km rectangular background extent (V4) | 12 | 0.36 |
| Hinge features, PCA predictors, buffered points background extent (V5) | 15 | **0.019** |
| Linear-product-quadratic features, PCA predictors, buffered points background extent (V6) | 13 | 0.17 |

Table S3-4. Fitness and suitability patterns across range limits (- indicates fitness or suitability declined across range limits; + indicates a lack of decline) when sites were categorized as in-range or over-the-edge without consideration of the type of range limit (horizontal versus vertical). See Table S3-2 for key to the parameter settings for the different analyses (V1-V6).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Source of TE Data** | **Type of Range Limit\*** | **Fitness Pattern** | **Suitability Pattern V1** | **Suitability Pattern V2** | **Suitability Pattern V3** | **Suitability Pattern V4** | **Suitability Pattern V5** | **Suitability Pattern V6** |
| *Abutilon theophrasti* | Andersen et al. 1985 | H | -  | - | - | - | + | - | - |
| *Acer* *saccharum* | Kellman 2004 | H | -  | - | - | - | - | - | - |
| *Anelosimus baeza* | Purcell & Aviles 2008 | V | -  | - | - | - | - | - | - |
| *Aphragmus oxycarpus* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | + |
| *Arnica* *montana* | Bruelheide & Scheidel 1999 | V | -  | - | - | - | + | - | - |
| *Atalopedes campestris* | Crozier 2004 | H | -  | - | + | - | - | - | - |
| *Betula**papyrifera* | Hobbie & Chapin 1998 | H | -  | - | - | - | - | - | - |
| *Camissoniopsis cheiranthifolia*\*\* | Samis & Eckert 2009 | H | -  | + | - | - | - | - | - |
| *Chamaecrista fasciculata*†† | Stanton-Geddes et al. 2012 | H | -  | - | - | - | - | - | - |
| *Clarkia xantiana ssp. parviflora*‡‡ | Geber & Eckhart 2005 | H | -  | - | - | - | - | + | + |
| *Clarkia xantiana ssp. xantiana*‡‡ | Geber & Eckhart 2005 | H | -  | - | - | + | + | + | + |
| *Digitalis purpurea* | Bruelheide & Heinemeyer 2002 | Both | -  | - | - | - | - | - | - |
| *Draba* *altaica* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | - |
| *Draba* *oreades* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | - |
| *Euphorbia amygdaloides* | Schulz & Bruelheide 1999 | H | +  | - | - | - | - | - | - |
| *Gilia capitata ssp. capitata* | Nagy & Rice 1997 | H | -  | - | - | - | - | - | - |
| *Hordeum murinum* | Davison 1977 | V | -  | - | - | - | - | - | - |
| *Lactuca* *serriola* | Prince & Carter 1985 | H | +  | - | - | - | - | - | - |
| *Lipoptena**cervi* | Härkönen et al. 2010 | H | -  | - | - | - | - | - | - |
| *Lomatium dissectum var. dissectum* | Marsico & Hellmann 2009 | H | -  | - | - | + | - | + | + |
| *Lomatium nudicaule* | Marsico & Hellmann 2009 | H | +  | - | - | - | - | - | - |
| *Lomatium utricularium* | Marsico & Hellmann 2009 | H | -  | - | - | - | - | - | - |
| *Mimulus cardinalis* | Angert & Schemske 2005 | V | -  | - | - | - | - | - | - |
| *Mimulus**lewisii* | Angert & Schemske 2005 | V | -  | - | - | - | - | - | - |
| *Mnium arizonicum* | Cleavitt 2004 | V | +  | - | - | - | - | - | - |
| *Mnium spinulosum* | Cleavitt 2004 | V | +  | - | - | - | - | - | + |
| *Pegaeophyton scapiflorum* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | + |
| *Phlox drummondii*‡‡ | Levin & Clay 1984 | H | -  | - | - | - | - | - | - |
| *Picea* *glauca* | Hobbie & Chapin 1998 | H | -  | - | - | - | - | - | - |
| *Pinus* *albicaulis* | McLane & Aitken 2012 | H | +  | - | - | - | - | - | - |
| *Poa* *attenuata* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | - |
| *Populus tremuloides* | Hobbie & Chapin 1998 | H | -  | - | - | - | - | - | - |
| *Protea* *aurea* | Latimer et al. 2009 | Both | -  | - | - | - | + | - | - |
| *Protea* *mundii* | Latimer et al. 2009 | H | -  | - | - | - | - | - | - |
| *Protea* *punctata* | Latimer et al. 2009 | Both | -  | - | - | - | - | - | - |
| *Saxifraga* *nanella* | Klimeš & Dolezal 2010 | V | -  | - | - | - | - | - | - |
| *Stellaria depressa* | Klimeš & Dolezal 2010 | V | -  | - | + | - | + | - | - |
| *Thaumetopoea pityocampa* | Battisti et al. 2005 | Both | -  | - | - | - | - | - | + |
| *Vulpia fasciculata*§§ | Norton et al. 2005 | H | +  | - | - | - | - | - | - |
| *Waldheimia tridactylites* | Klimeš & Dolezal 2010 | V | +  | - | - | - | - | - | - |

\* “Both” indicates that the authors of the transplant experiments tested both horizontal and vertical range limits. In-range and over-the-edge sites from both types of range limits were analyzed together in the “combined” version of our analysis and separately in our analyses of horizontal and vertical range limits.

Table S3-5. Fitness and suitability patterns across horizontal range limits (- indicates fitness or suitability declined across range limits; + indicates a lack of decline). See Table S3-2 for key to the parameter settings for the different analyses (V1-V6).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Source of TE Data** | **Fitness Pattern** | **Suitability Pattern V1** | **Suitability Pattern V2** | **Suitability Pattern V3** | **Suitability Pattern V4** | **Suitability Pattern V5** | **Suitability Pattern V6** |
| *Abutilon theophrasti* | Andersen et al. 1985 | -  | - | - | - | + | - | - |
| *Acer* *saccharum* | Kellman 2004 | -  | - | - | - | - | - | - |
| *Atalopedes campestris* | Crozier 2004 | -  | - | + | - | - | - | - |
| *Betula**papyrifera* | Hobbie & Chapin 1998 | -  | - | - | - | - | - | - |
| *Camissoniopsis cheiranthifolia*\*\* | Samis & Eckert 2009 | -  | + | - | - | - | - | - |
| *Chamaecrista fasciculata*†† | Stanton-Geddes et al. 2012 | -  | - | - | - | - | - | - |
| *Clarkia xantiana ssp. parviflora*‡‡ | Geber & Eckhart 2005 | -  | - | - | - | - | + | + |
| *Clarkia xantiana ssp. xantiana*‡‡ | Geber & Eckhart 2005 | -  | - | - | + | + | + | + |
| *Digitalis purpurea* | Bruelheide & Heinemeyer 2002 | + | - | - | - | - | - | - |
| *Euphorbia amygdaloides* | Schulz & Bruelheide 1999 | +  | - | - | - | - | - | - |
| *Gilia capitata ssp. capitata* | Nagy & Rice 1997 | -  | - | - | - | - | - | - |
| *Lactuca* *serriola* | Prince & Carter 1985 | + | - | - | - | - | - | - |
| *Lipoptena**cervi* | Härkönen et al. 2010 | -  | - | - | - | - | - | - |
| *Lomatium dissectum var. dissectum* | Marsico & Hellmann 2009 | - | - | - | + | - | + | + |
| *Lomatium nudicaule* | Marsico & Hellmann 2009 | + | - | - | - | - | - | - |
| *Lomatium utricularium* | Marsico & Hellmann 2009 | -  | - | - | - | - | - | - |
| *Phlox drummondii*‡‡ | Levin & Clay 1984 | -  | - | - | - | - | - | - |
| *Picea* *glauca* | Hobbie & Chapin 1998 | -  | - | - | - | - | - | - |
| *Pinus* *albicaulis* | McLane & Aitken 2012 | + | - | - | - | - | - | - |
| *Populus tremuloides* | Hobbie & Chapin 1998 | -  | - | - | - | - | - | - |
| *Protea* *aurea* | Latimer et al. 2009 | - | - | - | - | + | - | - |
| *Protea* *mundii* | Latimer et al. 2009 | -  | - | - | - | - | - | - |
| *Protea* *punctata* | Latimer et al. 2009 | - | - | - | - | - | - | - |
| *Thaumetopoea pityocampa* | Battisti et al. 2005 |  - | + | + | + | + | + | + |
| *Vulpia fasciculata*§§ | Norton et al. 2005 | +  | - | - | - | - | - | - |

Table S3-6. Fitness and suitability patterns across vertical range limits (- indicates fitness or suitability declined across range limits; + indicates a lack of decline). See Table S3-2 for key to the parameter settings for the different analyses (V1-V6).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Species** | **Source of TE Data** | **Fitness Pattern** | **Suitability Pattern V1** | **Suitability Pattern V2** | **Suitability Pattern V3** | **Suitability Pattern V4** | **Suitability Pattern V5** | **Suitability Pattern V6** |
| *Anelosimus baeza* | Purcell & Aviles 2008 | -  | - | - | - | - | - | - |
| *Aphragmus oxycarpus* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | + |
| *Arnica* *montana* | Bruelheide & Scheidel 1999 | -  | - | - | - | + | - | - |
| *Digitalis purpurea* | Bruelheide & Heinemeyer 2002 |  - | - | - | - | - | - | - |
| *Draba* *altaica* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | - |
| *Draba* *oreades* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | - |
| *Hordeum murinum* | Davison 1977 | -  | - | - | - | - | - | - |
| *Mimulus cardinalis* | Angert & Schemske 2005 | -  | - | - | - | - | - | - |
| *Mimulus**lewisii* | Angert & Schemske 2005 | -  | - | - | - | - | - | - |
| *Mnium arizonicum* | Cleavitt 2004 | +  | - | - | - | - | - | - |
| *Mnium spinulosum* | Cleavitt 2004 | +  | - | - | - | - | - | + |
| *Pegaeophyton scapiflorum* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | + |
| *Poa* *attenuata* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | - |
| *Protea* *aurea* | Latimer et al. 2009 | - | - | - | - | + | - | - |
| *Protea* *punctata* | Latimer et al. 2009 | + | - | - | - | - | - | - |
| *Saxifraga* *nanella* | Klimeš & Dolezal 2010 | -  | - | - | - | - | - | - |
| *Stellaria depressa* | Klimeš & Dolezal 2010 | -  | - | + | - | + | - | - |
| *Thaumetopoea pityocampa* | Battisti et al. 2005 | - | - | + | - | - | - | + |
| *Waldheimia tridactylites* | Klimeš & Dolezal 2010 | +  | - | - | - | - | - | - |



Figure S3-1. Example of the different types of background extents examined in the ENM sensitivity analyses. Blue, green and red lines represent the MCP, buffered-points and 200 km rectangular backgrounds (respectively) for *Aphragmus oxycarpus* and were generated based on the locality data for this species (black circles). The grey shading depicts part of Central Asia, the continent on which the species is found. The axes give latitude and longitude (albers equal area projection).