Predicting the presence of the mountain monkeyflower, *Mimulus tilingii*

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Background and objectives

Mimulus tilingii, the mountain monkeyflower, is confined to subalpine and alpine habitats throughout western North America. Populations are found in high altitude "habitat islands," which inherently provide replicate experiments in trait divergence to common ecological influences. Although populations share similar montane habitats, phenotypic data suggest a complex of closely related species in multiple stages of adaptation to similar montane environments. These have been described as *M. tilingii* var. *caespitosus* in the Cascade mountains of Washington and southern British Columbia (hereafter, "northern populations") from *M. tilingii* var. *tilingii* in the Sierra Nevada of California ("southern populations") (Pennell 1951). The taxonomic delineation of these two species has been supported by quantitative genetic evidence (Wu CA unpublished data).

Figure 1. *M. tilingii* var. *caespitosus* (back) and *M. t.* var *tilingii* (foreground).

An important part of understanding species adaptation is to examine the environmental variables predicting the distribution of the species. Recently, predictive habitat models have been developed to identify these key abiotic factors that define a species' range. Maximum entropy (MaxEnt) models combine a set of layers or environmental variables with georeferenced occurrence locations, to produce a model of the range of the species of interest (Baldwin 2009). Here this model is used to create a predictive habitat model of *Mimulus tilingii* populations as well as for the north and south populations separately. It is expected that elevation, and therefore temperature, provides the highest percent contribution as a predictor variable of *M. tilingii* presence. If the north and south populations show predictor variables of different importance, this will provide support for the adaptation of two different species.

Input data for the MaxEnt model

Point data for known presence of *M. tilingii* populations (Figure 2a) and environmental variables in raster format (Figure 2b-h) in the region surrounding presence locations. Together these two data types are used to model the suitable habitat for the species.

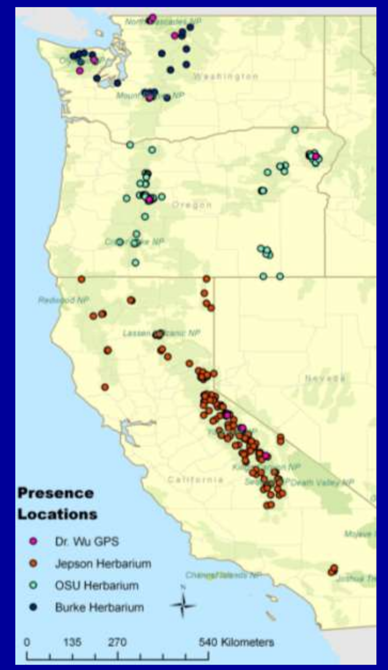

Figure 2a. **Point data** of known population presence.

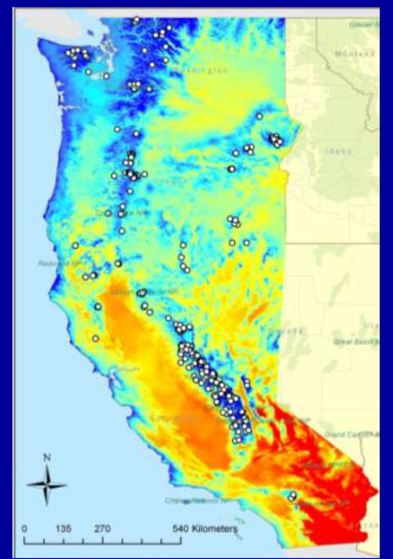

Figure 2b. **Average Maximum Temperatures** for August from 1971-2000. Input data included average max and min temperatures for June, July, and August. Courtesy of PRISM Climate Group.

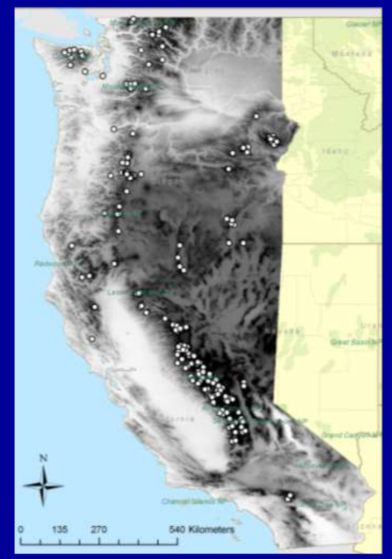

Figure 2c. **Elevation**, with higher values corresponding to darker areas. Courtesy of USGS.

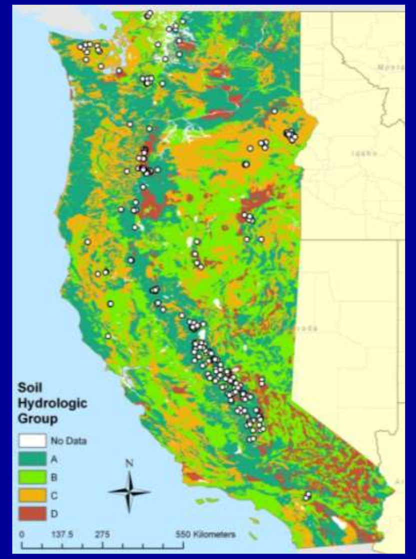

Figure 2d. **Soil hydrological group** from STATSGO2 US General Soil Map.

Figure 2e. **Solar Radiation** calculated from USGS Digital Elevation Model. Higher values are in red and lower values in blue.

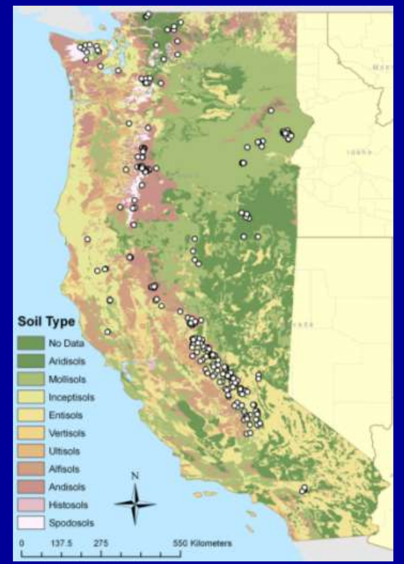

Figure 2f. **Soil type**. Dominant soil orders courtesy of STATSGO2 General Soil Map.

Figure 2g. **Wetness Index** calculated from USGS Digital Elevation Model. Darker areas correspond to higher wetness

Figure 2h. **Distance from water bodies**, calculated from USGS Water Bodies Layer. Distance from glaciers was also calculated.

Data analysis/applying the models

We used the maximum entropy program (MaxEnt, Baldwin 2009) to model the geographic distribution of habitat suitability based on continuous and discrete environmental variables. Model was run four times: (1) Full model using all populations and all environmental variables, (2) Parsimonious model using variables that were not correlated, (3) Northern population point data with parsimonious variables, (4) Southern population point data with parsimonious variables.

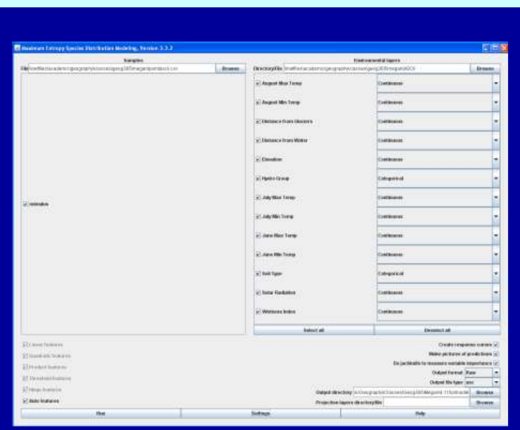

Figure 3. MaxEnt Interface

Full MaxEnt model results

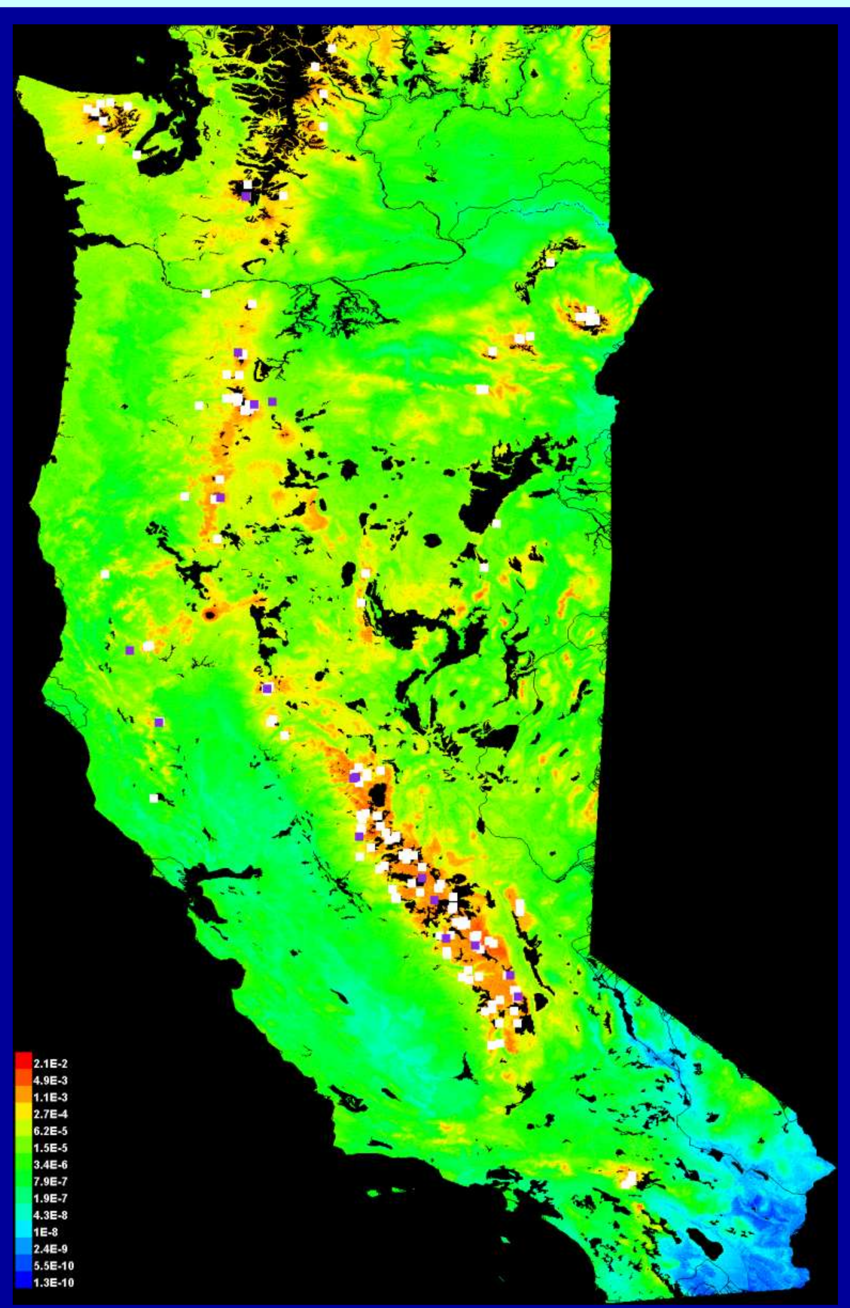

Figure 4. Map showing MaxEnt raw output; colors correspond to lthe probability of *M. tilingii* occurrence, with warmer colors corresponding to higher likelihood. White points were used as training data for the model; purple for test data (10% of input points).

Table 1. MaxEnt output of percent contribution of each environmental variable in determining the presence of *M. tilingii*

Variable	Percent contribution
Elevation	39.1
August Max Temp	22.1
June Max Temp	10.4
July Max Temp	10.3
Distance from Glaciers	4.4
Soil Type	3.3
Distance from Water	2.7
Wetness Index	2.6
Hydro Group	1.8
Solar Radiation	1.4
June Min Temp	1.1
August Min Temp	0.7
July Min Temp	0

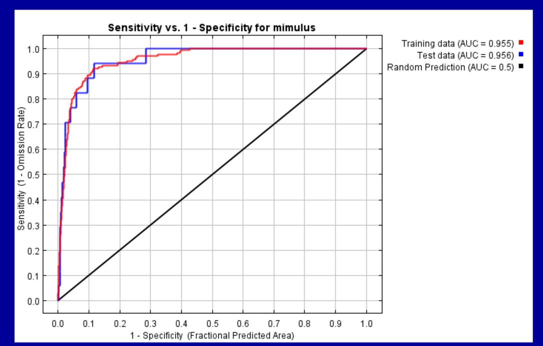

Figure 5. Area under the curve (AUC) showing goodness of fit of the model, which is ~9.14 times better than random (unregularized test gain=2.213).

Stronger models are based on weakly correlated variables. To identify the most informative variables in our initial dataset for a refined model, we ran a jackknife procedure in MaxEnt (Figure 6) and Band Collection Statistics for a correlation matrix in ArcGIS (Table 2).

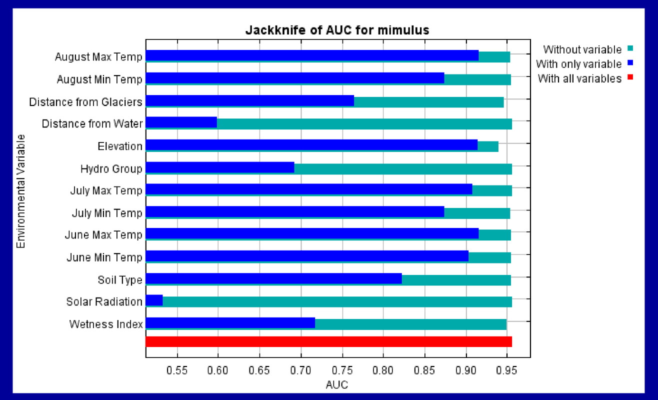

Figure 6. Jackknife results from full model showing which variables contribute the most to predicting locations of *M. tilingii*.

Table 2. Correlation Matrix of environmental variable layers.

Layer	Temp*	Glaciers	Water	Elevation	Hydrgrp	SoilType	Radiation	Wetness
Temp*	1	-0.64	-0.7	0.99	0.97	0.91	0.9	0.7
Glaciers	-0.64	1	0.68	-0.66	-0.63	-0.58	-0.6	-0.54
Water	-0.7	0.68	1	-0.7	-0.68	-0.63	-0.63	-0.51
Elevation	0.99	-0.66	-0.7	1	0.97	0.9	0.89	0.73
HydrGrp	0.97	-0.63	-0.68	0.97	1	0.93	0.87	0.69
SoilType	0.91	-0.58	-0.63	0.9	0.93	1	0.8	0.62
Radiation	0.9	-0.6	-0.63	0.89	0.87	0.8	1	0.59
Wetness	0.7	-0.54	-0.51	0.73	0.69	0.62	0.59	1

*Temp is August Max data; all temperature layers showed same correlation trends.

Parsimonious MaxEnt model with all populations

All temperature data and elevation data were highly correlated (R=.999), so only August Max Temp was used in the next run to provide a parsimonious model.

Unregularized test gain was 1.581. (=4.86 times better than random)

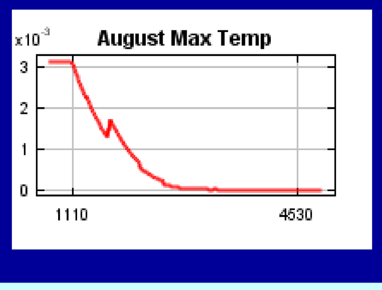

Figure 7. Response curve for August Maximum Temperatures. Cooler temperatures are more predictive of population occurrence.

Table 3. Percent contribution of predictor variabes on the presence of *M. tilingii*. Population occurrence is most strongly predicted by August maximum temperature.

Variable	Percent contribution
August Max Temp	80.5
Distance from Glaciers	7
Hydro Group	3.8
Distance from Water	3.6
Solar Radiation	2.1
Soil Type	1.8
Wetness Index	1.3

Predictor variables for northern and southern populations

Southern Populations

Table 4. Percent contribution of predictor variables on the presence of southern *M. tilingii* populations. Occurrence is most strongly predicted by August maximum temperatures.

Variable	Percent contribution
August Max Temp	60.7
Soil Type	17.5
Hydro Group	9.4
Distance from Water	4.8
Distance from Glaciers	3.5
Solar Radiation	3.3
Wetness Index	0.8

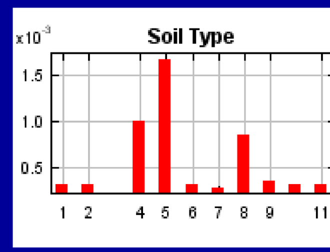

Figure 8. Response curve for soil type. Inceptisols, Entisols, and Alfisols (types 4,5,9) are most predictive of *M. tilingii* presence.

This model was ~7.23 times better than random (unregularized test gain= 1.982).

Northern Populations

Table 5. Percent contribution of predictor variables on the presence of northern *M. tilingii* populations. Occurrence is most strongly predicted by distance from glaciers.

Variable	Percent contribution
Distance from Glaciers	49.2
August Max Temp	24
Soil Type	14.9
Hydro Group	7.5
Wetness Index	2.1
Distance from Water	1.6
Solar Radiation	0.7

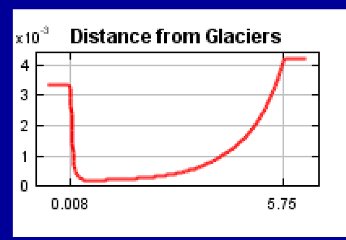

Figure 9. Response curve for distance from glaciers. Very small distances from glaciers as well as larger distances are more predictive of population occurrence.

This model was ~4.86 times better than random (unregularized test gain= 1.582).

Conclusions

- Based on the results of the full MaxEnt model and further supported by the parsimonious model, temperature is the greatest predictor variable for *M. tilingii* presence.
- Although the fit of the model decreased when correlated environmental variables were removed, the parsimonious model is a better model as it is more general.
- While August maximum temperature was important for predicted presence of all populations, distance from glaciers was even more influential for northern populations (Table 5).
- These results support the idea of multiple evolutionary transitions to montane environments in the species complex.

Acknowledgements:

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References:

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