Distribution Modeling for
Colorado SWAP Plants of Greatest Conservation Need

COLORADO NATURAL HERITAGE PROGRAM

WARNER COLLEGE OF NATURAL RESOURCES
COLORADO STATE UNIVERSITY

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Recommended Citation:

Decker, K., J.P. Smith, M. Fink, J. Handwerk, G. Doyle, and S.S. Panjabi. 2023. Distribution Modeling for Colorado SWAP Plants of Greatest Conservation Need. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado.

Cover photo: *Penstemon acaulis* var. *yampaensis* in Moffat County, Colorado. © 2020, Jessica Smith.

Abstract

Species distribution models for 81 of the 117 plant species listed in the Rare Plant Addendum of the Colorado State Wildlife Action Plan (CPW 2015) were created using information on known locations and species habitat requirements. These distribution models have been included in the conservation data sharing platform, the Colorado Conservation Data Explorer (CODEX), to help conserve and protect these Plants of Greatest Conservation Need (PGCN) through environmental review and conservation planning. Expert review of species distribution models was solicited from regional botanists; Forty-six individual botanists reviewed a total of 75 species distribution models, with a total of 113 reviews. Over 80% of reviews concluded that the model in question was in the “Reasonable” or higher level of overall correctness. Also included in this report are results of a pilot project to predict changes in suitable habitat under two potential future climate scenarios for *Astragalus microcymbus, Astragalus osterhoutii, Draba smithii, Eutrema penlandii, Frasera coloradensis* and *Ipomopsis polyantha*. The modeling work of this project amplifies our knowledge, building upon decades of field work preserved in CNHP’s database, and advances our understanding of species habitat.

Acknowledgement

The authors would like to thank the Colorado Natural Areas Program (CNAP)/Colorado Parks & Wildlife (CPW) for financial support of this project. Special thanks to CNAP Program Coordinator, Raquel Wertsbaugh, for her support of the project and CNHP staff, Amy Greenwell, for her GIS expertise and coordination with CODEX.

Contents

Introduction

Background

The revised 2015 Colorado State Wildlife Action Plan (SWAP) includes 117 Plant Species of Greatest Conservation Need (PGCN) in the Rare Plant Addendum (Colorado Parks and Wildlife 2015). These species are ranked globally critically imperiled (G1) or imperiled (G2), at risk throughout their range and under threat of extinction. Known locations of these species are recorded in a statewide geospatial database maintained by the Colorado Natural Heritage Program (CNHP). However, surveys for these species have not been comprehensive, and therefore information on their distribution is incomplete. For this project, species distribution models were created using information on known locations and species habitat requirements. These distribution models are now included in the conservation data sharing platform, the Colorado Conservation Data Explorer (CODEX), in order to help conserve and protect these PGCN through environmental review and conservation planning. The following objectives were met in this project:

Objectives

1) Create distribution models for 80 of the 117 plant species listed in the Rare Plant Addendum of the SWAP which did not previously have a model (Table 1) to complete the goal of providing a distribution model for all PGCN. Species included in this project were prioritized by species conservation need and development threats. Whenever possible, distribution models were produced as probability surfaces. These raster digital datasets can be converted to other formats as needed, albeit with some loss of information.

2) Produce binary versions of the distribution models for inclusion in the Colorado Conservation Data Explorer (CODEX), released in 2021 and hosted by CNHP, in order for PGCN to be considered in statewide conservation planning and environmental review.

Table 1. PGCN species modeled. Common names are those used in Colorado. “Priority” indicates Tier 1 or Tier 2 Status in the SWAP. “G” and “S” refer to Global and State Rank (see https://cnhp.colostate.edu/ourdata/help/heritage/ for more information on heritage ranking). “Fed. status” denotes the Federal Agency Listing status; “% CO Range” denotes the percent of the species range in Colorado as reported in the SWAP (CPW 2015).

Scientific Name	Common Name	Priority	G/S Status Ranks	Fed. Status	% CO Range	Project Priority
Aliciella sedifolia	Stonecrop gilia	Tier 1	G1 / S1	USFS	Endemic	Highest - Tier 1
Ipomopsis ramosa	Coral ipomopsis	Tier 1	G1 / S1		Endemic	Highest - Tier 1
Lepidium huberi	Huber's pepperwort	Tier 1	G1G2 / S1S2		High	Highest - Tier 1
Lygodesmia doloresensis	Dolores River skeletonplant	Tier 1	G1G2 / S1S2	BLM	High	Highest - Tier 1
Mimulus gemmiparus	Budding monkey flower	Tier 1	G1 / S1	USFS	Endemic	Highest - Tier 1
Oenothera coloradensis ssp. *coloradensis*	Colorado butterfly plant	Tier 1	G3T2 / S1		Medium	Highest - Tier 1
Packera mancosana	Mancos shale packera	Tier 1	G1 / S1		Endemic	Highest - Tier 1
Pediocactus knowltonii	Knowlton cactus	Tier 1	G1 / SNA	LE	Historical	Highest - Tier 1
Penstemon gibbensii	Gibben’s beardtongue	Tier 1	G1G2 / S1	BLM	High	Highest - Tier 1
Penstemon scariosus var. *albifluvis*	White River penstemon	Tier 1	G4T1 / S1	BLM	Low	Highest - Tier 1
Phacelia gina-glenneae	Troublesome phacelia	Tier 1	G1/S1		Endemic	Highest - Tier 1
Physaria rollinsii	Rollins twinpod	Tier 1	G1 / S1		Endemic	Highest - Tier 1
Physaria scrotiformis	West Silver bladderpod	Tier 1	G1 / S1		Endemic	Highest - Tier 1
Asclepias uncialis ssp. uncialis	Dwarf milkweed	Tier 2	G3G4T2T3 / S2	BLM/USFS	Very High	High
Astragalus sparsiflorus	Front Range milkvetch	Tier 2	G2 / S2		Endemic	High
Mentzelia rhizomata	Roan Cliffs blazing star	Tier 2	G2 / S2	BLM	Endemic	High
Nuttallia chrysantha	Golden blazing star	Tier 2	G2 / S2	BLM	Endemic	High
Oonopsis puebloensis	Pueblo goldenweed	Tier 2	G2 / S2		Endemic	High
Oxybaphus rotundifolius	Round-leaf four o’clock	Tier 2	G2 / S2		Endemic	High
Thalictrum heliophilum	Sun-loving meadow rue	Tier 2	G2 / S2	BLM/USFS	Endemic	High
Aletes humilis	Larimer aletes	Tier 2	G2G3 / S2S3		Endemic	Medium
Astragalus rafaelensis	San Rafael milkvetch	Tier 2	G2G3 / S1	BLM	High	Medium
Camissonia eastwoodiae	Eastwood evening primrose	Tier 2	G2 / S1	BLM	Medium	Medium
Castilleja puberula	Downy Indian-paintbrush	Tier 2	G2G3 / S2S3		Endemic	Medium
Cleome multicaulis	Slender spiderflower	Tier 2	G2G3 / S2S3	BLM	High	Medium

Scientific Name	Common Name	Priority	G/S Status Ranks	Fed. Status	% CO Range	Project Priority
Draba smithii	Smith whitlow-grass	Tier 2	G2 / S2	USFS	Endemic	Medium
Frasera coloradensis	Colorado green gentian	Tier 2	G2G3 / S2S3		Endemic	Medium
Herrickia horrida	Canadian River spiny aster	Tier 2	G2? / S1		Medium	Medium
Ipomopsis globularis	Globe gilia	Tier 2	G2 / S2	USFS	Endemic	Medium
Lupinus crassus	Payson lupine	Tier 2	G2 / S2	BLM	Endemic	Medium
Nuttallia densa	Arkansas Canyon stickleaf	Tier 2	G2 / S2	BLM	Endemic	Medium
Oenothera acutissima	Narrow-leaf evening primrose	Tier 2	G2 / S2	BLM	Medium	Medium
Oonopsis foliosa var. *monocephala*	Rayless goldenweed	Tier 2	G3G4T2 / S2		Endemic	Medium
Oreocarya revealii	Gypsum Valley cat's- eye	Tier 2	G2 / S2	BLM	Endemic	Medium
Oxytropis besseyi var. *obnapiformis*	Bessey locoweed	Tier 2	G5T2 / S2		Very High	Medium
Penstemon acaulis var. *yampaensis*	Yampa beardtongue	Tier 2	G3T2 / S2		High	Medium
Penstemon degeneri	Degener beardtongue	Tier 2	G2 / S2	BLM/USFS	Endemic	Medium
Penstemon fremontii var. *glabrescens*	Fremont's beardtongue	Tier 2	G3G4T2 / S2		Endemic	Medium
Penstemon scariosus var. *cyanomontanus*	Plateau penstemon	Tier 2	G4T2 / S2		High	Medium
Physaria bellii	Bell's twinpod	Tier 2	G2G3 / S2S3		Endemic	Medium
Physaria parviflora	Piceance bladderpod	Tier 2	G2 / S2	BLM	Endemic	Medium
Physaria vicina	Good-neighbor bladderpod	Tier 2	G2 / S2	BLM	Endemic	Medium
Ptilagrostis porteri	Porter feathergrass	Tier 2	G2 / S2	USFS	Endemic	Medium
Puccinellia parishii	Parish's alkali grass	Tier 2	G2G3 / S1		Low	Medium
Townsendia glabella	Gray's Townsend-daisy	Tier 2	G2 / S2		Endemic	Medium
Eriogonum coloradense	Colorado wild buckwheat	Tier 2	G2 / S2	BLM	Endemic	Low
Lepidium crenatum	Alkaline pepperwort	Tier 2	G2 / S2		Medium	Low
Lomatium concinnum	Colorado desert-parsley	Tier 2	G2G3 / S2S3	BLM	Endemic	Low
Penstemon mensarum	Grand Mesa penstemon	Tier 2	G2 / S2		Endemic	Low
Physaria alpina	Avery Peak twinpod	Tier 2	G2 / S2		Endemic	Low
Physaria pruinosa	Pagosa bladderpod	Tier 2	G2 / S2	BLM/USFS	Endemic	Low
Thelypodiopsis juniperorum	Juniper tumble mustard	Tier 2	G2 / S2		Endemic	Low
Aletes macdougalii ssp. *breviradiatus*	Mesa Verde aletes	Tier 2	G3T2T3 / S1		Medium	Lowest

Scientific Name	Common Name	Priority	G/S Status Ranks	Fed. Status	% CO Range	Project Priority
Anticlea vaginatus	Alcove death camas	Tier 2	G2 / S2		Low	Lowest
Astragalus cronquistii	Cronquist milkvetch	Tier 2	G2 / S2		High	Lowest
Astragalus equisolensis	Horseshoe milkvetch	Tier 2	G5T1 / S1	BLM	Low	Lowest
Astragalus iodopetalus	Violet milkvetch	Tier 2	G2 / S1	USFS	Medium	Lowest
Astragalus missouriensis var. *humistratus*	Missouri milkvetch	Tier 2	G5T1 / S1	USFS	Endemic	Lowest
Astragalus naturitensis	Naturita milkvetch	Tier 2	G2G3 / S2S3	BLM	High	Lowest
Astragalus piscator	Fisher Towers milkvetch	Tier 2	G2G3 / S1	BLM	Low	Lowest
Boechera crandallii	Crandall's rock-cress	Tier 2	G2 / S2	BLM	High	Lowest
Calochortus ciscoensis	Cisco sego lily	Tier 2	G2 / S1		Low	Lowest
Cirsium perplexans	Adobe thistle	Tier 2	G2G3 / S2S3		Endemic	Lowest
Delphinium ramosum var. *alpestre*	Colorado larkspur	Tier 2	G4T2 / S2		High	Lowest
Delphinium robustum	Wahatoya Creek larkspur	Tier 2	G2? / S2?		Medium	Lowest
Draba graminea	San Juan whitlow-grass	Tier 2	G2 / S2		Endemic	Lowest
Erigeron kachinensis	Kachina daisy	Tier 2	G2 / S1	BLM	Low	Lowest
Eriogonum clavellatum	Comb Wash buckwheat	Tier 2	G2 / S1	BLM	Medium	Lowest
Limnorchis zothecina	Alcove bog orchid	Tier 2	G2 / S1		Low	Lowest
Mentzelia paradoxensis	Paradox stickleaf	Tier 2	G2? / S2?		Endemic	Lowest
Mertensia humilis	Rocky Mountain bluebells	Tier 2	G2 / S1		Medium	Lowest
Oreocarya osterhoutii	Osterhout cat's-eye	Tier 2	G2G3 / S2	BLM	Low	Lowest
Salix arizonica	Arizona willow	Tier 2	G2G3 / S1	USFS	Low	Lowest
Thelypodium paniculatum	Northwestern thelypody	Tier 2	G2 / SH		Low	Lowest
Townsendia fendleri	Fendler's Townsend-daisy	Tier 2	G2 / S2		High	Lowest
Trifolium dasyphyllum ssp. *anemophilum*	Whip-root clover	Tier 2	G5T2? / S1		Low	Lowest
Descurainia kenheilii	Heil's tansy mustard	Tier 1	G1G2/S2		Endemic	New model
Eriogonum brandegeei	Brandegee wild buckwheat	Tier 1	G1G2 / S1S2	BLM/USFS	Endemic	New model
Eriogonum pelinophilum	Clay-loving wild buckwheat	Tier 1	G2 / S2	LE	Endemic	New model
Potentilla rupincola	Rocky Mountain cinquefoil	Tier 2	G2 / S2	USFS	Endemic	New model
Telesonix jamesii	James telesonix	Tier 2	G2 / S2		Very High	New model

Methods

Occurrence update and review

Element occurrences for the 81 species were updated prior to the modeling effort. The primary data source searched for new information was SEINet, the online herbarium database (SEINet 2021). SEINet records were compared to existing CNHP BIOTICS database records (CNHP 2021-2022) and SEINet specimens representing new locations were mapped as new or updated element occurrences in the CNHP database. All SEINet records dated 2000 and newer were mapped as well as selected older SEINet records that represented range extensions. In addition, all backlog data from CNHP files for the species of interest were incorporated into the CNHP database. A total of 307 new or updated Element Occurrence (EO) records were produced during the project.

A shapefile of occurrence polygons for each species was exported from BIOTICS. Using ArcGIS 10.4 (ESRI 1999-2015), this multipart shapefile was converted to a single-part shapefile, separating polygons belonging to the same EO into individual features. These polygon features were converted to centroid points, with the constraint that the point fall within the polygon. Coordinates (XY in UTM NAD83 zone 13) were added to the points and used to produce the location input .csv file for each species. Older historic records with poor location precision were sometimes omitted from the modeling dataset but retained for model review. In a few cases, additional points were added to very large polygons, using a 500m square net to ensure that added points were not exactly duplicating environmental locations. In contrast, for a few species that had many mapped polygons within a smaller well-surveyed area, a randomly selected subset of points in these areas was used in the model to decrease the influence of one smaller area on the predicted range as a whole.

Modeling process

Species distribution models (also called environmental/ecological niche models, or predictive habitat models), are based on the premise of finding places on the landscape where environmental conditions (climate, soils, exposure, etc.) are similar to conditions at documented locations of the species of interest. This can be as simple as extracting environmental covariate values for known points and using them to select portions of spatial datasets that match those values or value ranges (deductive modeling) or can involve using complex algorithms that compute an approximate probability that a species could occur at a particular point (inductive modeling). Distribution models can, but do not typically, consider the biogeographic history of a species, or its ability to disperse to new areas or tolerate novel conditions.

For this project at least one inductive model using the maximum entropy (Maxent) modeling procedure (Phillips et al. 2004, 2006) was produced for each species with more than two occurrence records. This procedure is particularly useful for modeling species where absence data is lacking. We used the Maxent version 3.4.3 java-based software (Phillips et al. 2020). Maxent has been widely used in species distribution modeling and performs well in comparison with other methods (Elith et al. 2011). This procedure uses the environmental covariate values from occurrence points plus 10,000 randomly selected background points to estimate a probability distribution that is consistent with data from known locations. This estimate is as close as possible (has maximum entropy) to the estimate from the background data (the null model), since, without any data, we would have no reason to think that the species would be more likely to be in one location than any other. Species distribution is estimated by minimizing the distance between the occupied and background, subject to constraining the means of estimated occupied factors to be close to observed means. Constraints ensure that the mean for a variable in the estimated distribution is close to the mean across the locations with occurrences. The raw solution is transformed to complementary log-log (cloglog) output with a potential range of 0 to 1, becoming more-or-less a probability estimate of occurrence.

In addition to the spatial location of known occurrences, inputs for the model are generally data matrices as raster digital data representing the value of an environmental factor for every cell across the entire study area. The Maxent software requires that environmental factors be in ASCII grid format, and all grids must share a common spatial reference, extent, cell size, and alignment, and be in the same folder. Environmental inputs were produced in ArcGIS using a 30m resolution digital elevation model (DEM) raster with a rectangular extent covering the state of Colorado plus a buffer of approximately 8km on each edge of the boundary as the reference extent to which all other rasters were aligned. All data used the NAD 1983 UTM Zone 13N spatial projection. Input rasters were produced as GeoTIFFs, then converted to ASCII and stored together. In a few instances values for a particular environmental factor were not available across the entire study area. If these areas of "no data" fell outside the reasonable expected range of a species, the raster was used anyway. The resulting slight reduction in background point data available for that factor was a reasonable tradeoff for the potential contribution of additional environmental information.

For each species, habitat description information was extracted from individual element occurrence records in BIOTICS (typically in the General Description field, but sometimes useful information was in additional fields) and compiled in a spreadsheet. This information was used to identify important environmental factors such as characteristic geologic substrate, vegetation type, landform, aspect, slope, elevation and others, if known. Some environmental inputs were chosen to reflect particular documented habitat details for a species (e.g., a single geologic formation or a habitat type), but general climatic (temperature and precipitation), soil, and topographic inputs were also used for all species (Appendix A).

Climate data for precipitation were grouped seasonally. Winter includes the months December, January, and February; spring includes March, April, and May; summer includes June, July, and August and fall includes September, October, and November. Temperature-related climate data were either based on monthly averages (monthly minimum temperatures), seasonal extremes (winter minimum or summer maximum), or growing season boundaries (first and last frost dates, or total number of frost-days). Seasonal extreme temperatures indicate the lowest winter or highest summer temperature for a location over a 30-year normal period, not an annual average low or high.

If a species was reliably reported as being associated with a particular geologic substrate or substrates, a Euclidian distance to mapped geologic unit areas input layer was generally preferred over a categorical geology input layer. This technique compensates for the fact that geology mapping is highly inexact at the scale which matters to individual plants. Local erosive processes may also spread the appropriate substrate beyond its formation of origin. Finally, identification of geologic substrates by field botanists can be incorrect. Moreover, the continuous surface of the distance layer produces model surfaces characterized by gradual suitability changes that are more likely to reflect ecological conditions on the ground. If substrate appeared to be important but not described in detail, a categorical geology layer was used. Likewise, soil characteristics represented as continuous values (e.g., percent silt, clay, or sand), were used preferentially rather than individual soils units. In some instances, distance to a particular type of vegetation, or a categorical vegetation layer was used. A brief summary of the modeling process is found in Appendix B.

The use of statewide input layers facilitated an economy of scale because layers did not have to be adjusted to the range of each species (a potentially time-consuming process). However, one potential consequence of this practice is to introduce areas of predicted suitable habitat that are simply too far from the known distribution into the final model. The use of numerous "distance to factor" layers mitigated against this issue to some extent. Ideally, future modeling efforts will be able to develop a cost-effective method of either selecting small portions of statewide environmental datasets, or else constraining background samples to be closer to known occurrences.

Model review and threshold setting

Maximum entropy model results, in the form of the model raster image and a layer file classified into three tiers of probability, were reviewed in ArcMap for acceptable geographic extent, inclusion of element occurrence records, and overall correctness. The analysis provided in the Maxent results was also reviewed, with special attention paid to which environmental factors were the most important in creating the model.

Maxent returns a continuous probability surface of approximately 0-100% (0 to 1) likelihood that a species would be present at a location (assuming the model adequately represents required environmental conditions). Models were primarily intended to suggest a need for field survey in the sense of indicating if an area of interest to a CODEX user was likely to contain suitable habitat for a particular PGCN species. Our threshold standard is based on this use; other potential model uses (e.g., identifying critical habitat, targeted inventory, etc.) might require a different threshold standard. Our threshold decision tree is based on commonly used thresholding methods reported in Pearson (2010, Table 4).

Modeled area to be included in CODEX was determined by setting a cut-off value for the probability of species presence to return a yes or no (binary) value for potential species presence in the environmental review. The typical probability used to classify the CODEX models was 0.50, i.e., at least a 50% chance that the species would be present at the location according to the model. Thus, the top threshold level was the fixed value of probability = 0.50. If this threshold was not useful, the second threshold level considered was the value of equal training sensitivity and specificity. If neither of these thresholds was satisfactory, a method of looking for the lowest predicted value corresponding to documented occurrences was used. This last threshold was applied using a flexible "best professional judgement" method that reflected the variable quality of occurrence record mapping and the limitations of the modeling process. In general, we sought to identify a nuanced threshold that would cover portions of all high-quality occurrences while not simultaneously greatly increasing the area suggested for survey. Reasons for threshold adjustment included:

- Including all occurrences or occurrence polygons for Tier 1 species, or all high-quality occurrences for Tier 2 species, in the binary model
- Generally increasing the number and/or area of occurrences included in the binary model

- Widening the predicted area to avoid too close a fit to known occurrences, or to include at least a portion of historic or low confidence occurrences.
- Expanding the binary model to increase area represented in key habitats or edge of range, or in general for poorly known species with few occurrences

Expert review of species distribution models was solicited from regional botanists, and comments and notes on revisions are included below in the "Individual species results" section below. Details and results of the review process are found in Appendix C.

All models were produced with a statewide extent; if the modeled range extended far outside the known species range, a decision was made on where to clip the model. Typically, models were clipped to exclude areas further than one county away from the known range or further than 30-40 miles from an occurrence record. This wide buffer accounted for uncertainties in cases where a species had few element occurrence records, limited survey attention, or a wide range of ecological conditions.

Post-review processing

Reviewed and approved models were converted to binary rasters using the Reclassify tool in ArcGIS. Cells below the cutoff value were reclassified as NoData; cells >=threshold value were classified with a value of 1. The binary raster was then clipped as needed, as specified by the reviewer. Clipping was done using an appropriate polygon shape as the clipping geometry. The final binary models with metadata were converted to vector format for use in CODEX. Binary and full raster models and classified vector (shapefile) model versions will be retained in CNHP botany files for use in future survey work.

Metadata was created and included with the models in GIS. Metadata includes the list of input environmental factors, and indicates which factors made a non-zero contribution to the result. Use constraints and caveats are also included.

Results

Altogether, about 200 Maxent model runs were made in order to produce the final 81 CODEX models. Twenty-six species required only a single run to produce a satisfactory model, 25 needed a second run to incorporate corrected or additional factors, and 26 species required additional runs. Three species could not be modeled using maximum entropy methods (too few documented locations) and a deductive model was constructed instead, using substrate, vegetation types, elevations, and/or climate factors matching conditions at the documented locations.

Ninety-three separate environmental input layers were produced for use in this modeling effort (Appendix A, Table 1), although not all of these proved useful in final model results. The full list of important environmental variables and their relative percentage of contribution is included in the metadata for each species model.

Individual species results

Model input details and key results, including important environmental variables are summarized by species below. Common names are Colorado state common names. For more detail on model inputs and results, see the metadata for the GIS model.

Aletes humilis (Larimer aletes), Tier 2

This Colorado endemic is known from 27 locations in Larimer and Boulder counties in the northern Front Range. Habitat is primarily tied to outcrops of granitic rock in the 1400-MY age group. Spring warm-up timing, slope, and seasonal temperature extremes are also contributing factors. The modeled range generally extends west from the mountain front in Larimer County north of the Poudre River up to elevations between 7500 and 8500 feet (2290-2590 m), and from the vicinity of Glen Haven near the Big Thompson Canyon in southern Larimer County down to Left Hand Creek in central Boulder County. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who ranked it as reasonable. This reviewer noted that the model included areas where they had observed the species in the field, but it was on the coarse side and should exclude Lake Estes and Halligan Reservoir. The model was revised to exclude the reservoirs.

Aletes macdougalii ssp. *breviradiatus* (Mesa Verde aletes), Tier 2

In southwestern Colorado this species is documented from five locations in Mesa Verde National Park, where it grows in crevices of the sandstone canyon walls. Habitat was limited to areas where extreme low winter temperatures do not fall below -16.6°F (-27°C). Steep slopes were an important factor. Substrates east of the Navajo Wash valley are primarily Cretaceous sandstones characteristic of the area, including Cliff House and Point Lookout sandstones, while habitat on the Sleeping Ute Mountain laccolith is on younger Laramide intrusives. Modeled habitat is largely west-facing canyon walls and similar slopes from School Section Canyon to the west rim of the larger Mesa Verde area, with additional areas of potential habitat to the south of the mesa in canyons tributary to the Mancos or San Juan rivers, and in scattered mid-elevation areas of Sleeping Ute Mountain on Ute Mountain Ute tribal lands. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two reviewers, who believed the model was either good or reasonable. One reviewer noted that portions of the model to the northeast, southeast and west should be checked for species presence. This review also noted that the model appeared underfit and geology, aspect and soil moisture may be the best predictor of species presence; of these factors, geology did play an important role in constraining the CODEX model and aspect was picked up in the result. The second reviewer believed the fit was suitable.

Aliciella sedifolia (Stonecrop gilia), Tier 1

A Colorado endemic, this species is known from four locations in San Juan and Hinsdale counties in the San Juan Mountains. Habitats are barren alpine gravelly soils below ridgelines. Elevation (generally above 12000 ft; 3660 m) was the primary factor contributing to the model. Distance to surface geology of Tertiary volcanic tuff was also important and could explain nearly 85% of the distribution in a single factor model. Extreme maximum summer temperatures are generally not above 77°F (25°C). A threshold value of 0.5 was used for the probability in the CODEX version of the model. The modeled range extended 75 km (47 miles) east from nearest EO record, which seemed a reasonable extent for this under-surveyed species; therefore, the full extent of the model was retained.

This model was reviewed by one expert reviewer, who ranked it as poor. Field observations by this reviewer point to the species being restricted to areas of fine-grained texture of more widespread volcanic soils above 13,000' feet.

Anticlea vaginatus (Alcove death camas), Tier 2

This is a species of canyon wall alcove habitats, found where perennial seeps supply pocket wetland habitats in otherwise dry sandstone dominated cliffs. Seven Colorado occurrences have been documented from the Yampa River canyon in Dinosaur National Monument in western Moffat County. Modeled habitat was constrained to canyon wall areas by using distance to steep slopes (>=30 degrees) factor. This habitat is among the driest in Colorado, with annual precipitation less than 12 inches (30 cm), which was an important contributing factor in the model, along with the greater frost-free period characteristic of lower elevations. A threshold value of 0.5 was used for the probability in the CODEX version of the model. Modeled habitat was clipped to constrain predicted suitable areas to the Yampa River canyon from the vicinity of Schoonover Buttes west to the Utah border, and the Green River south of the Gates of Lodore.

This model was reviewed by one reviewer, who believed the model was reasonable, but was underfit. The reviewer disagreed with modeled suitable habitat along the Green River through the Canyon of Lodore, along the Yampa River near the Utah border and to the west, and on lower elevations of benches south of the Yampa River. The reviewer believed the model missed potentially suitable areas north of the Yampa River in Dinosaur National Monument and an area in Utah. A shapefile of these areas was provided.

Asclepias uncialis ssp. *uncialis* (Dwarf milkweed), Tier 2

In Colorado, this species is found on a variety of soil types and microsites, generally associated with grasslands. The large but sparsely populated range and lack of obvious narrow environmental influence on this diminutive, early flowering species make it extremely challenging to model. Furthermore, much of the original species' habitat has probably been converted to agricultural use, causing occurrences in the northern portion of the Colorado range to appear as outliers in the species' environmental niche. Numerous Maxent model runs with different inputs were made, but as they appeared to converge on a common solution, the version that included more of the northern habitat was selected for comparison with a deductive model. Ultimately, the Maxent model was chosen, as it captured a greater number of highly ranked EOs. Important environmental factors included distance to shortgrass prairie and soil depth. A lower probability cut-off of 0.107 was used to include modeled habitat in the northeast corner of the state, and the full extent of the model was retained.

This model was reviewed by two expert reviewers. Two reviewers responded with comments but did not return a survey form. They agreed the model looked reasonable. One reviewer believed the distribution of the model corresponded well with their field observations. The other thought the distribution may extend too far to the west and wondered if a different environmental factor might show a different projection.

Astragalus cronquistii (Cronquist milkvetch), Tier 2

In Colorado this species is primarily known from Ute Mountain Ute tribal lands in southwestern Montezuma County; it also occurs in Utah. Nearly all the 11 Colorado occurrences are ranked as historical, with no updated observations contributed to the database for a couple of decades or more.

Predicted suitable habitat was limited to areas where extreme low winter temperatures do not fall below -15°F (-26°C). Distance to substrates derived from Mancos Shale was an important factor. Seasonal precipitation patterns also constrained predicted suitable habitat to arid areas; plants are apparently able to tolerate spring or summer precipitation amounts less than 2 inches (5 cm). A threshold value of 0.5 was used for the probability in the CODEX version of the model, and modeled habitat was clipped to the southwestern corner of Montezuma County. Modeled habitat included primarily alluvial fans below Sleeping Ute Mountain or the western edge of Mesa Verde where saltbush shrublands intermix with more barren areas.

An expert reviewer could not be identified for this model.

Astragalus equisolensis (Horseshoe milkvetch), Tier 2

This narrow Utah-Colorado endemic is known from nine occurrences in the Dolores River drainage in western Mesa County, which are disjunct from the Utah population. Geology was the primary factor determining potential suitable habitat; occurrences are mapped on the Moenkopi and Cutler formations as a combined unit in that area. Early spring (March average) low temperatures that are just below freezing were also a notable contributing factor, along with extreme low winter temperatures that remain above -15°F C (-26°). The suitable habitat predicted by the model aligns fairly well with the canyon slopes near the inner Dolores River canyon from Roc Creek confluence in northwestern Montrose County northwest to the Utah state line. A few scattered bands of habitat further east in Mesa County are also present. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers who believed the model was either good or reasonable and the fit was suitable, with the broad overall elevation range correct. The second reviewer agreed with the inclusion of model habitat between the Colorado and Gunnison Rivers, noting surveys in this area were warranted.

Astragalus iodopetalus (Violet milkvetch), Tier 2

This species has a large range in southwestern Colorado, from southern Gunnison County to the New Mexico border. A total of 17 occurrences are documented; nearly all are considered historical as they have not been observed for more than 20 years. Vegetation type was the most important contributing factor, although variable from sagebrush shrublands in the north to a selection of dry woodland types such as ponderosa pine or Gambel oak in the south. Soils are characterized by higher clay and lower sand percentage. Climatic environmental factors contributing to the model are characteristic of drier valleys and foothills on north and south flanks of the San Juan Mountains. Seasonal patterns indicate a somewhat drier spring, but otherwise precipitation is more-or-less equally distributed across the seasons. Extreme winter low temperatures are -31°F (-35°C) at the highest elevations, while extreme maximum summer temperatures can reach near 100°F (37.5°C) in the warmer locations. A threshold value of 0.5 was used for the probability in the CODEX version of the model. Modeled suitable habitat was clipped to include all sides of the San Juan Mountains and includes areas of interest in eastern San Miguel County as well as the western San Luis Valley north of the Rio Grande River.

This model was reviewed by one expert reviewer who believed the model was good but should exclude black sagebrush communities and areas south of Highway 149 and Sapinero Mesa, as this species is more typically found with Wyoming sagebrush at lower elevations in the Gunnison area.

Astragalus missouriensis var. *humistratus* (Missouri milkvetch), Tier 2

A narrow endemic known from 13 occurrences in Colorado and several in New Mexico, the species is restricted to the upper basin of the San Juan River in southwestern Colorado and northwestern New Mexico. Distance to Mancos Shale substrates was the most important contributing factor in the model. Soils have a fairly high clay content. The overall climate envelope of the distribution reflects moderately arid and warm conditions with average seasonal precipitation of around 5-6 in (12-15 cm), together with an average of 220 frost days per year. The model threshold was adjusted to 0.36 to better capture documented locations, and the model extent was clipped to exclude habitat outside of Archuleta, La Plata and small amounts of southern Hinsdale and Mineral counties.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good, including known occurrences and surrounding areas that likely contain suitable habitat with a suitable fit. The botanist believed more information is needed about the habitat parameters which support this subspecies.

Astragalus naturitensis (Naturita milkvetch), Tier 2

This species has been documented from 63 occurrences in Colorado and is also found in Utah and New Mexico. Locations stretch from southern Garfield County to the Four-Corners area. Recorded habitat characteristics for the species are fairly broad, but it tends to occur on substrates primarily derived from sandstone, which was an important contributing factor in the model. May minimum temperatures comfortably above freezing were also important. A subset of occurrences in the De Beque Canyon area were used for modeling to decrease the influence of this densely populated region in model results. The model threshold was adjusted to 0.25 to better capture documented locations, and the model extent was clipped to exclude habitat patches on the eastern slope.

This model was reviewed by two expert botanists. One, who had not seen the species in the field but was familiar with its distribution and habitat, believed the model was excellent with a suitable fit. The second reviewer did not fill out the model review form but provided a shapefile to indicate areas which they did not believe were suitable habitat. This included areas around Rangely, which they considered to be marginal, areas south of Park Canyon in Rio Blanco County, which they believed not to be habitat, a large swath of area north of De Beque in Garfield County, which was believed to be marginal, an area east of Dela believed to be marginal, and an area in La Plata County believed to no longer be habitat. The reviewer also believed the model missed an areas of potential habitat south of the Colorado River near Loma.

Astragalus piscator (Fisher Towers milkvetch), Tier 2

This species is documented from four occurrences in western Mesa County, none further than 5 miles from the Utah border. Distance to substrates derived from the Permian sandstone dominated Cutler Formation was the most important contributing factor. April minimum temperatures generally not below freezing were also important, as were extreme minimum winter temperatures not below about -15°F. The model threshold was adjusted to the equal training sensitivity and specificity (0.242) to include all documented locations. Modeled suitable habitat is restricted to the Dolores River drainage in the vicinity of Gateway.

This model was reviewed by two expert reviewers who believed the model was either good or reasonable and the fit was suitable. The first reviewer liked the broad elevational range of the model, and noted the species likely requires scarification, so gritty soil and moisture may be required. This reviewer agreed the species is only found on the Cutler Formation. The second reviewer desired additional refinement in the model, excluding riparian and developed areas, and questioned the inclusion of upper drainages of the Dolores River. Areas in the upper drainages were retained in the final model as reasonable suitable habitat close to known locations.

Astragalus rafaelensis (San Rafael milkvetch), Tier 2

This species is known from eastern Utah and western Colorado, where it is documented from 28 occurrences in Mesa, Delta, Montrose, and northern San Miguel counties. Habitats are generally on soils derived from Morrison Formation units; distance to this type of surface geology was the major contributing factor in the model. Precipitation in the dry season of summer was important, with a minimum requirement of generally in the range of 6-8 cm; southern occurrences receive more precipitation in comparison with northern stands. Extreme winter minimum temperatures are generally not below -22°F (-30°C). The model predicted suitable habitat in Montezuma County, but this was excluded from the final version, as the predicted habitat was over 50 miles and 2 counties away from known EOs. A probability cut-off of 0.35 was used to include additional habitat matching highly ranked EOs which were excluded at the 0.5 threshold. Predicted habitat follows the known distribution fairly closely, with the addition of habitat just downstream from the Black Canyon of the Gunnison River, where Morrison Formation units are common. The model extent was clipped to exclude areas in Montezuma County.

This model was reviewed by two expert reviewers. Two reviewers agreed the model was reasonable. One reviewer stated that the model correctly matched potential habitat but also included areas in Mesa County not currently considered potential habitat. The second reviewer also believed the model overstated potential a bit, but it did pick up all areas where surveys for the species would be recommended in their management area.

Astragalus sparsiflorus (Front Range milkvetch), Tier 2

This Colorado endemic is documented from 21 occurrences at mid-montane elevations ranging in a north-south distribution from Boulder to Custer County. Granitic substrates are common in this region. Distance to surface geology of Precambrian age metamorphic and igneous rock was the most important environmental factor in the model. These rocky soils are typically shallow. Summer precipitation generally greater than 20 cm and May minimum temperatures averaging just above freezing were also contributing factors. A threshold value of 0.5 was used for the probability in the CODEX version of the model. The modeled area was clipped to include only areas of the Front Range and southern mountain front, from northern Larimer County to northern Huerfano County. Predicted habitat is especially prevalent at elevations of 7000-9500 feet (2130-2895 m) in the vicinity of the Platte Canyon, Rampart Range, Pikes Peak, and the eastern flank of the Wet Mountains.

This model was reviewed by one expert reviewer, who ranked it as good. The reviewer noted that the model appeared to capture the range of the species and identified habitat in the expected topographic position. The reviewer chose "Suitable" for fit, but noted the model was a bit underfit due to presumed coarseness of data.

Boechera crandallii (Crandall's rock-cress), Tier 2

The Colorado distribution of this species is centered in the Gunnison Basin, but occurrences are known from Grand County to northern Hinsdale County, as well as from southern Wyoming. A total of 55 Colorado occurrences were used in modeling. Habitats are generally open, rocky slopes within montane shrubland or forest types, which was reflected in the importance of both geology and biophysical type as model inputs. The species is found in areas where there are an average of 250 frost days per year and seasonal precipitation is generally on the low end, especially in winter. The model threshold was adjusted to the equal training sensitivity and specificity (0.213) to include most documented locations. Modeled suitable habitat was clipped to exclude areas along the southern mountain front, or west of Delta County.

This model was reviewed by one expert reviewer, who ranked it as good. The reviewer noted the model appeared to capture known occurrences but was a bit underfit, including quite a few aspen stands where the species would be unlikely to occur in areas of Saguache County.

Calochortus ciscoensis (Cisco sego lily), Tier 2

A regional endemic from western Colorado / eastern Utah, this species is documented in Colorado from only three occurrences in the Grand Valley west of Fruita where Mesa and Garfield counties about the Utah state line. Habitats are in saltbush shrublands on substrates derived from Mancos Shale; distance to these two features were primary contributing factors in the model. The area is dry, averaging less than 3 inches (75 cm) in both spring and summer seasons. March minimum temperatures warm to just under freezing, while extreme summer high temperatures are generally over 105°F (41°C). A handful of extra points were added to the model set to better represent some of the larger polygon occurrence features. A threshold value of 0.5 was used for the probability in the CODEX version of the model. Modeled suitable habitat is constrained to the western end of the Grand Valley.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good but a bit overfit. The reviewer would have liked to see the model extend up to the Book Cliffs in the Grand Valley and further east and north of Grand Junction.

Camissonia eastwoodiae (Eastwood evening primrose), Tier 2

This Colorado Plateau endemic has been documented from 11 Colorado locations in Mesa and Delta counties. Occurrences are concentrated on nearly barren Mancos shale salt-shrub habitats in the Grand Valley north and west of Grand Junction, and on lower mesa slopes north of the Gunnison River valley near Hotchkiss. The most important environmental factor contributing to the model was distance to Mancos shale. An average day of last frost in early May and summer precipitation of at least 7 cm in what is regionally a dry season were also important. Extreme minimum winter temperatures are also fairly warm, generally not reaching below -20°F (-29°C). Predicted habitat follows the known distribution around the two separated population centers. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who ranked it as reasonable with a suitable fit. The reviewer noted the model covers a broader area than known occurrence records, but soils, elevations and overall setting seems correct.

Castilleja puberula (Downy Indian-paintbrush), Tier 2

This Colorado endemic is found in rocky alpine habitats on high peaks of the Continental Divide, with 22 documented occurrences ranging from Larimer to Park County. As could be expected for a species of high elevation cool habitat, extreme maximum summer temperatures were an important factor, rarely exceeding 82°F (28°C). Precipitation amounts in all seasons were also contributing factors, especially for winter and spring; totals across all seasons average nearly 35 inches (90 cm) per year. Aspects tend towards east-facing, and elevations were generally above 10,000 ft (3000 m). Modeled habitat ranges from the vicinity of Hague's Peak (highest point of the Mummy Range) in Rocky Mountain National Park south to around Weston Peak in the Mosquito Range, with smaller areas to the west in the Sawatch Range and is generally concentrated within 25 km of the Continental Divide. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, who believed the model was either reasonable or excellent. One believed the model was underfit, the other suitable. One reviewer questioned the southern extent of the model but the second agreed with this. The second reviewer believed this species is likely more widespread than is currently documented and thought the model showed potentially suitable places which would be good candidates for finding the species.

Cirsium perplexans (Adobe thistle), Tier 2

A Colorado endemic of barren clay "adobe" soils derived from shales of the Mancos or Wasatch formations, this species is documented from 45 locations in the Gunnison and Colorado river drainages of Colorado's western slope. Distances to the two key surface geology types were the primary contributing factors in the model. Days without frost were also a contributing factor; the species appears to tolerate the cooler conditions found in drainages above the Grand Valley, but rarely occurs in more exposed areas of higher elevations to the east. The model threshold was adjusted to 0.25 to better capture documented locations. Predicted suitable habitat extends from western Rio Blanco County southeast to the lower Gunnison Basin and northeastern edge of the Uncompahgre Plateau north of Ridgeway. The full extent of the model was retained.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good with a suitable fit. However, they believed a bit of the model in western Montrose and San Miguel Counties was too far outside the known range to be included. This model was revised to clip out this area in the fall of 2022.

Cleome multicaulis (Slender spiderflower), Tier 2

In Colorado, this species is limited to the high intermountain San Luis Valley in Saguache, Rio Grande, Alamosa, Conejos, and Costilla counties, where it occurs in saline or alkaline wetland soils. Fifty-two documented occurrences range from Russell Lakes in the northern valley south to the Rio Grande River valley near the San Luis Hills but are especially frequent in the *sabkha* wetlands south and west of the Great Sand Dunes. The most important environmental factors included roughly equal contributions of soil pH (basic soils preferred) and spring precipitation of at least 5 cm, and, to a lesser extent, distance to palustrine emergent wetland types. Maximum temperatures in summer are slightly higher on the eastern side of the valley where occurrences are most frequent. Modeled predicted habitat follows the known distribution fairly closely but includes quite a bit of additional area in the closed basin wetlands and greasewood flats west of Saguache Creek. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, who both believed the model was good. One reviewer believed the model was suitable and agreed pH should be an important factor in habitat prediction. A second reviewer the scale was too coarse and should exclude irrigated farmland and urban areas around Alamosa.

Delphinium ramosum var. *alpestre* (Colorado larkspur), Tier 2

In Colorado this species of high elevation habitats is documented from 20 occurrences ranging from near the Continental Divide in northwestern Park County south to the Sangre de Cristo Range near the New Mexico border, with a single disjunct historical occurrence from the northern edge of Hinsdale County. Habitats are upper sub-alpine forested types such as spruce-fir and aspen or adjacent alpine rocky areas. At these elevations, average spring minimum temperatures even in May are below freezing, and there can be more than 300 days with frost per year; both factors contributed to the model. Also contributing were surface geology types characteristic of Colorado's central mountain mass, primarily substrates derived from metamorphic, granitic, or tertiary volcanic formations. The model threshold was adjusted to 0.21 to better capture documented locations and clipped to exclude disjunct patches of predicted habitat away from the main range.

This model was reviewed by one expert botanist, who both believed the model was reasonable, but underfit and should exclude certain areas. In a provided shapefile, this reviewer identified eleven polygons which were forested and therefore provided unsuitable habitat and another 10 polygons where habitat was marked as unsuitable. Polygons were marked primarily to the north and west of South Park. The reviewer also noted three areas in the Sawatch Range which they believed could be potential habitat.

Delphinium robustum (Wahatoya Creek larkspur), Tier 2

This enigmatic species (Sivinski in NMRPTC 1999) is the subject of some taxonomic disagreement, in that some specimens have been annotated to *D. ramosum* while others from the same collection, but at different herbaria, have not. The species is found in north-central New Mexico and south-central Colorado, where it is currently documented from 10 occurrences. Eleven different model runs failed to identify a good habitat-narrowing factor present in available data, indicating that additional research on this species is needed. The selected model primarily used temperature envelope, vegetation type, and aspect to identify a fairly broad extent of likely habitat. Extreme maximum summer temperatures for this prediction are on average are below 90°F (32°C), while extreme minimum winter temperatures average -25°F (-32°C) but may be as low as -33°F (-36°C) following the temperature envelope of Colorado's mid- to upper-elevation regions. Aspects tended to be somewhat west-facing. Vegetation type represented many of the common forest and shrubland types of southern Colorado, including aspen, mixed conifer, spruce-fir, oak-mountain shrub, and sagebrush. A threshold value of 0.5 was used for the probability in the CODEX version of the model, and the model extent was clipped to restrict habitat to central and southwestern Colorado.

This model was reviewed by one expert botanist, who did not complete the review form but provided a shapefile of areas believed to range from unsuitable, with too great of an elevational range and habitat types, to minimum potential. These marked areas ranged from north of and covering South Park, east of the northern Sangre de Cristo Range, directly east of the San Luis Valley along a 100 km stretch centered around Alamosa, northeast of the San Luis Valley, west of Saguache, and a large swatch of the San Juan Mountains centering around Silverton.

Descurainia kenheilii (Heil's Tansy Mustard), Tier 1

This species was not included originally in this project, as an acceptable model had already been created in an earlier 2010 project. However, in 2022, new data was published on this species updating the description of the species and greatly increasing the known locations, resulting in both updated state and global ranks (O'Kane and Heil 2022, CNHP 2021). Therefore, the model was updated during the fall of 2022. Only newly recognized locations listed in O'Kane and Heil (2022) were included in model training, resulting in a total of 15 presence points. Unverified points, included in the BIOTICS database but marked as identification in question pending herbarium specimen verification, were used to test the model (8 presence points). Fall precipitation was the most important factor in the new model, with volcanic geology (Tuff, Breccias and Conglomerates from associated lava and ash flows) following. A threshold value of 0.238 was used for the CODEX version of the model to include more of the known locations; despite this and five attempts at modeling with different inputs, the final model still missed one EO from the training set and 5 of the 8 testing locations. More input locations based on verified specimens are needed to produce a better model.

Draba graminea (San Juan whitlow-grass), Tier 2

A Colorado endemic of the San Juan Mountains in southwestern Colorado, this species is documented from 40 occurrences in alpine or upper sub-alpine habitats. Climatic conditions at high elevations were the primary contributing factors to the model. In particular, extreme maximum summer temperatures are generally lower than 80°F (27°C) and most areas experience more than 300 days a year where temperatures dip below freezing, and snow can fall in any month. Due to the southern Colorado location, these locations also receive monsoon moisture in late summer and early fall that contributes to the model prediction. The model threshold was adjusted to 0.10 to better capture documented locations and clipped to exclude disjunct patches of predicted habitat away from the core range in the San Juans.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good and the fit was suitable.

Draba smithii (Smith whitlow-grass), Tier 2

This species is essentially a Colorado endemic, although it may also occur in adjacent New Mexico. The 31 documented Colorado occurrences are clustered in a few widely separated areas, including the San Juan Mountains near and south of Creede, the Sangre de Cristo Range north of Blanca Peak, and the vicinity of Fishers Peak south of Trinidad. Occurrences are generally on talus and scree slopes from upper foothills to lower alpine elevations. Important environmental factors for this species included distance to selected Tertiary volcanic formations in south-central Colorado, terrain roughness index (which, together with slope indicates rugged, steep terrain), and winter (driest season) and summer (wettest season) precipitation. Only modeled habitat in southern Colorado counties was included (areas of Teller and Montrose counties were omitted). Predicted suitable habitat is generally within the three regions described above, with the addition of substantial habitat in the southern Wet Mountains, around and north of Greenhorn Mountain. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model had three reviewers, one with limited experience, one with experience in the San Luis Valley and another with experience east of the Continental Divide. Comments centered around the distribution of the model. Two reviewers commented that the distribution was suitable, although one wondered why the Spanish Peaks were not included. The geology of the Spanish Peaks is similar to the Raton Mesa, and therefore another factor must have excluded this habitat. A third reviewer questioned the inclusion of the Wet Mountains. This reviewer had many negative survey results in that mountain range. The Wet Mountains did have patchy areas of similar geology to the Sangre de Cristo Range, but based on negative surveys of the expert reviewer, this model was revised to exclude the Wet Mountains.

Erigeron kachinensis (Kachina daisy), Tier 2

A species of canyon wall “alcove” wetlands that form where water seeps between less permeable geologic layers, this narrow endemic of southwestern Colorado and adjacent Utah is documented in Colorado from just three occurrences in western Montrose and Mesa counties. As might be expected, steep slopes were the most important contributing factor in the model, which was also limited by using distance to very steep slopes as a factor. Other contributing factors were the number of frost days per year and distance to springs. Although not in the warmest of west slope habitats, these locations generally experience fewer than 160 days with freezing temperatures in a year. A threshold value of 0.5 was used for the probability in the CODEX version of the model. Modeled suitable habitat extent was clipped to the Dolores and San Miguel River drainages.

This model was reviewed by two experts, one who was familiar with the species in Colorado and one who had observed the species in Colorado and two locations in Utah where the bulk of the species range is present. The reviewer familiar with the species in only Colorado believed the model was reasonable and agreed with the limitation of suitable habitat to steep slopes. The second reviewer believed the model was poor, and believed the species is more typically observed on lower slopes, benches and ledges in sandy soils associated with cliffs with seeps (e.g., in hanging gardens). Therefore, this model was revised.

The new model still found frost days per year as an important constraining factor along with increasing terrain roughness, very steep slopes, and proximity to riparian vegetation. Distance to springs was dropped in this round of modeling, as the data seemed incomplete for this area and therefore not providing good information. Whereas the original model was limited to a narrow band of high elevation canyon walls across the species range, the new model captures a much wider elevational band and covers the southern-most known EO in Colorado much more fully. A threshold value of 0.481 (the 10th percentile training presence) was used for the CODEX version of the model and the model was clipped to only include habitat associated with the Dolores River in Mesa County and habitat in Montrose and San Miguel Counties associated with canyons. Modeled habitat around the Gunnison River and Colorado River in Mesa and Delta County was clipped out of the final model, as these locations were over twenty miles from a known location.

Eriogonum brandegeei (Brandegee wild buckwheat), Tier 1

This species was not originally included in the project. However, recent communication with federal partners regarding important climate factors for this species made it expedient to produce a revised model to replace the original deductive version for CODEX.

The nine documented occurrences of this Colorado endemic are centered around the upper Arkansas River drainage in central Colorado. Occurrences are closely associated with bentonite clay soils derived from steep, eroding outcrops of the Tertiary Dry Union Formation (in Chaffee County) and lower Cretaceous/upper Jurassic sedimentary layers of Dakota, Purgatoire, Morrison, and Rolston Creek Formations in the vicinity of Cañon City (Fremont County). These are generally very sparsely vegetated light-colored soils with an overstory of open pinyon-juniper woodland. Distance to either of the two geologic groups was the highest contributor to the model. The most important climate factor was fall precipitation, which is generally quite low (5-6 cm or about 2 inches) within the range of the species. Areas in Colorado with comparable low fall precipitation include most of the upper Arkansas River drainage, the central San Luis Valley, central South Park in the vicinity of Antero Reservoir, and the Point of Rocks vicinity east of Greeley. The model only included the upper Arkansas River drainage and a small area around the vicinity of Antero Reservoir in South Park. Annual precipitation for the range of the species is not exceptionally low for Colorado, but late growing season climate water deficit appears to be limiting to most other understory species. Soils are somewhat alkaline. Occurrences also tend to be on eastern exposures, where extreme summer temperatures are well over 100°F. The moisture retention capacity of bentonite clay-bearing soils may support the persistence of *Eriogonum brandegeei* in an otherwise challenging habitat. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, both who ranked it as reasonable. The reviewers noted the model excluded a known, well-documented location around Cañon City and did a better job picking up habitat around Salida. Additionally, the reviewers believed the model included too many flat or grassland areas. The species can be found on in flat areas but is more likely on steep eroded habitat. To address the model review, the threshold level for the CODEX model was lowered to a probability of 0.25 to include the known location outside of Cañon City. This added more modeled habitat throughout the range, and the model appears underfit in the Chaffee County.

Eriogonum clavellatum (Comb Wash buckwheat), Tier 2

A regional endemic of the Four-Corners area, this species is documented from 13 occurrences in Montezuma County in Colorado, none of which have been observed more recently than 2003. The fine textured soils of its mat saltbush shrubland habitats are derived from Mancos Shale. Together with extreme minimum winter temperatures not below -15°F (-26°C), distance to substrates of Mancos Shale accounted for more than 85% of model contribution. Soils have high clay content. Spring is the driest season; occurrences are in an area where precipitation is this season is less than 2.7 inches (6.8 cm). The model threshold was adjusted to 0.48 to better capture documented locations and clipped to restrict predicted habitat to Montezuma County.

An expert reviewer could not be identified for this model.

Eriogonum coloradense (Colorado wild buckwheat), Tier 2

A central Colorado endemic or alpine or near-alpine elevations documented from 26 locations in Chaffee, Gunnison, Park, Pitkin, and Saguache counties, this species is closely tied to soil type in some, but apparently not all locations (although it is difficult to be sure since soil data is of variable quality across the species' range). Although not associated with a particular geologic substrate, geology did contribute to the model, picking out locally mapped areas of a comprehensive selection of formations from ancient to more recent. As expected for a species of high elevations, temperature was most important. Extreme winter low temperatures of -40°F (-40°C) or lower are characteristic of the habitat. Mean April minimum temperatures are below freezing, and snow cover persists longer than at lower elevations. The model threshold was adjusted to 0.20 to better capture documented locations and clipped to exclude predicted habitat too far outside the known range. The model did a poor job of picking up known locations in atypical habitat of Redcloud channery loam, 3 to 30% slopes.

This model was reviewed by one expert reviewer who believed the model was reasonable, covering areas near occurrences which they had observed; however, the model generally missed the habitat on a soil type where many observations had been made (Redcloud channery loam). The modeling process included inputs of known species locations on this soil type, but similar habitat was not included in the model despite several test runs. More surveys and data collection in this soil type could help provide species input data for future model revisions. Additionally, the reviewer noted the model includes unsuitable habitat of riparian areas and developed areas.

Eriogonum pelinophilum (Clay-loving wild buckwheat), Tier 1

This species was not originally included in the project. However, recent communication with federal partners made it expedient to produce a revised model to replace the original deductive version for CODEX.

This Colorado endemic is federally listed as Endangered, with a small range in Delta and Montrose counties. The species has been the object of extensive survey and monitoring efforts and is currently documented from 22 well mapped occurrences on adobe clay soils derived from Mancos Shale west of the Uncompahgre River. As expected, distance to this substrate was the primary contributing factor in the model. These areas are also closely associated with mat saltbush shrublands. Under the constraints of data used for this project, we were not able to further refine the habitat beyond what is already known. The model threshold was adjusted to 0.30 to pick up mapped features, with the eastern edge of the range only picked up at this lower threshold, and habitat outside the known range was excluded.

This model was reviewed informally by members of the *Eriogonum pelinophilum* SSA technical team and critiqued as being too coarse-scale. Using LiDAR and finer scale geology data was considered but rejected as unsuitable for our current methodology. Fine-scale geology was not available across the entire range of the species and relying on this would result in a gap in the model across the species range. To incorporate LiDAR data, all other data, including climate data, would need to be down sampled to match the fine grid of LiDAR data. Down sampling climate data to this degree over-exaggerates the accuracy of this data.

Frasera coloradensis (Colorado green gentian), Tier 2

A Colorado endemic of shale and sandstone breaks in grasslands in extreme southeastern Colorado, this species has been documented across less than 300 acres in 32 occurrences. Documented locations range from small outcrops on plains below the slopes of Black Mesa, along a northeast trending line of shallowly dissected hills following the general direction of Two Butte Creek. This stretch more-or-less outlines the southern limb of surface exposures of Cretaceous age Carlisle shale/Greenhorn Limestone and Graneros shale (Kcg). Proximity to this group of sedimentary, outcrop-forming formations was the most important environmental variable in the model. Most occurrences were at increasing distance from shale outcrops of the Niobrara Formation, which is commonly adjacent to the Kcg north of the canyon of the Purgatoire River, with occasional surface presence on the south side. Extreme maximum summer temperatures in this area are somewhat cooler than in the valley of the Arkansas River to the north. Modeled habitat follows the overall range of the species fairly closely. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who provided comments over email that it appeared to be spot-on.

Herrickia horrida (Canadian River spiny aster), Tier 2

This species is found in extreme south-central Colorado and northern New Mexico, with only 10 element occurrence records in the state. Two Maxent models were reviewed for this species: one with the Raton Formation included and one without. The model with the Raton Formation was chosen to include a larger high probability modeled area. The most important environmental variables for this model were distance to the Raton Formation (81.4% contribution) with northness values near -1 (i.e., south-facing slopes) and summer precipitation combined explaining another 10%. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model in Colorado was retained.

This model had two expert reviewers. One believed it was spot-on. The second commented that areas to the western edge were not likely suitable habitat, although there could be some potential microsites, based on their survey work in nearby areas in New Mexico. There is one known location, documented by an EO, in the area this reviewer suggested should be excluded; therefore, we retained all the modeled area.

Ipomopsis globularis (Globe gilia), Tier 2

This Colorado endemic is restricted to the Mosquito Range in central Colorado except for a disjunct population found on Mt. Elbert in the Sawatch Range in 2015. The species is found on alpine ridges with gravelly, calcareous soils. Two Maxent models were run for this species: one without and one including glacial drift in an attempt to pick-up high-quality occurrences on erosional substrates near high elevation limestone. The model with glacial drift was chosen, but areas around the Collegiate Peaks, which are primarily granite, were excluded. The most important environmental factors explaining the model were distance to units containing Leadville (and Manitou) Limestone, elevation and distance to glacial drift of the Pinedale and Bull Lake age. The probability for the cutoff of the binary model in CODEX was set to 0.177 to include medium tier values of the model, which picked up the Mt. Elbert area. The model was also clipped to exclude the Cottonwood Pass/Collegiate Peaks areas as the geology is significantly different with granite versus limestone.

This model was reviewed by two expert reviewers, both who ranked it as good. Both reviewers believed the model to be at least a bit broad but recognized the ability to create a finer scale model could be limited.

Ipomopsis ramosa (Coral ipomopsis), Tier 1

This is a narrow Colorado endemic, found in two side canyons of the Dolores River Canyon in Montezuma County. Three occurrences are documented on soils derived from the red sandstones, siltstones, and shales of the Permian age Cutler Formation. The important environmental variables defining this model are distance to the Cutler Formation, northness (prefers south facing slopes), and average minimum May temperature. A threshold value of 0.5 was used for the probability in the CODEX version of the model. The entire extent of the model, which extended approximately 45 miles from EO records, was included in the version for CODEX. We felt this represented an acceptable potential range for this under-surveyed species.

This model was reviewed by two expert reviewers, one who believed the model was unusable and the other reasonable. Both reviewers were experienced with this species and thought the model covered too broad of a habitat. One reviewer reported negative surveys within 8 miles of the type locale for this species. This reviewer believed a model of the Cutler formation, north facing aspect and elevation between 8,000-9,200 would be more accurate. The second reviewer believes the species may be of a young evolutionary age and has not expanded into all potential habitat, making modeling difficult. This reviewer has surveyed the Hermosa Creek drainage, particularly the large valley west of Purgatory Ski Resort, many times and does not believe the species is there. The reviewer was also skeptical of habitat to the west of the core known area, although they were less familiar with this area.

Lepidium crenatum (Alkaline pepperwort), Tier 2

In western Colorado this species is largely known from pinyon-juniper woodlands or adjacent vegetation types, and ranges from Moffat County in the north to Montezuma and La Plata counties in the south. It is documented from 27 occurrences in Colorado, many of which are historical and would benefit from better mapping. The top contributing factor in the model was surface geology, which picked up a variety of Jurassic- to Cretaceous-age sandstone and shale bearing formations that are characteristic of Colorado’s west slope. Biophysical types were also widespread varieties typical of western Colorado. Extreme winter minimum temperatures are typically not below -22°F (-30°C). The model threshold was adjusted to 0.47 to better capture documented locations and the full extent of the model was retained. This species could benefit from additional survey and study; the known habitat does not well explain its rarity. If additional factors can be identified, a new model should be produced.

This model was reviewed by one expert botanist who believed the model was reasonable with a suitable fit.

Lepidium huberi (Huber's pepperwort), Tier 1

Little is known about this Tier 1 SWAP PGCN. Its range extends from eastern Utah to western Colorado, and the species is documented from 19 widely scattered occurrences in sagebrush to pinyon-juniper in Rio Blanco, Garfield, and northern Mesa counties. All EO records for this species are historical or extant. The best model included both distance to Green River Formation (widespread in this region) and a categorical surface geology layer. Together these two factors accounted for 85% of the model prediction. The species also appears to prefer areas where extreme minimum winter temperatures do not generally fall below -31°F (-35°C). The classification cutoff used for CODEX was 0.45 to include more modeled habitat associated with known EO records and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. The reviewer had made one collection of this rare species. The collection fit well within modeled boundaries and the modeled area looked to be of similar habitat.

Limnorchis zothecina (Alcove bog orchid), Tier 2

This species is found in canyon seep habitats of the Colorado Plateau where it occurs in Utah, Arizona, and Colorado. The Colorado range of this canyon-wall alcove species coincides with that of *Anticlea vaginatus*, although the two species do not necessarily occur together. It is documented from five occurrences in the canyon and side drainages of the Yampa River in Dinosaur National Monument. Annual precipitation in this dry region is less than 12 in. (30 cm). This factor was important in constraining the modeled range but is clearly not a requirement for the species since it occupies small wetlands within the arid environment. Distance to springs was correspondingly important, as the proximity of places where groundwater emerges indicates the likely presence of seep habitat in the vicinity, even if not mapped. Finally, as could be expected, proximity to slopes steeper than 30 degrees was an important contributing factor. The model threshold was adjusted to the equal training sensitivity and specificity (0.362) to include documented locations, and habitat outside of Dinosaur NM was excluded.

This model was reviewed by one expert reviewer, who believed the model to be reasonable, although underfit, missing some areas of potential habitat and including others with low potential. The reviewer provided a shapefile which marked areas along the Green River in Canyon of the Lodore, low elevation benches south of the Yampa River in Dinosaur National Monument, and an area along the Yampa River in Utah as unsuitable habitat. An area on the eastern edge of the model was marked as marginal and two areas along the Yampa River in Dinosaur National Monument were marked as unmodeled potential habitat.

Lomatium concinnum (Colorado desert-parsley), Tier 2

This Colorado endemic species has a range that largely overlaps that of *Eriogonum pelinophilum* in the valley of the Uncompahgre River between Montrose and Delta, but extends further south towards Ridgeway, and reaches east up the Gunnison River drainage to the vicinity of Hotchkiss. It is documented from 38 occurrences, typically in mat saltbush shrubland on soils derived from Mancos Shale. As expected, distance to Mancos Shale was the primary contributing factor in the model. Terrain roughness index also picked up the gentle to moderately sloping habitats of this species. Winter precipitation of at least 2 in. (5 cm) was important as well. The model threshold was adjusted to 0.15 to pick up mapped features, and habitat outside the known range was excluded.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good and the fit was suitable.

Lupinus crassus (Payson lupine), Tier 2

This Colorado endemic is documented from 17 occurrences in western Montrose County, where it is associated with sparsely vegetated pinyon-juniper woodland understory. Substrates are alluvium derived from Mancos shale or Chinle formation (upper Triassic mud/silt/sandstone). Primary environmental factors in the model were distance to Quaternary alluvium and eolian deposits, and to a lesser extent, extreme maximum summer temperatures exceeding 102°F (39°C). Predicted habitat follows the known distribution in Paradox Valley and on mesa parklands northeast of the San Miguel River canyon. Additional potential habitat is predicted in the Sinbad Valley at the Mesa/Montrose County line. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model in Colorado was retained.

This model was reviewed by one expert reviewer, who believed the model to be poor. The reviewer believed the model greatly overstated habitat suitability where modeled, and understated extent. This reviewer believes the species is found in or very near ephemeral drainages where either coal bearing, or relatively high clay content soils are present. Fine-scale mapping of these factors (ephemeral drainages and specific geology) are not available over the extent of our modeling area. The reviewer also noted the model missed known locations to the northeast and east of Nucla and believed modeled habitat should have included an expanded range of precipitation and elevation. Unfortunately, data on locations around Nucla were not available at the time of modeling (Spring 2021). This model was revised in the fall of 2022, after updating records in the BIOTICS database. Important environmental factors in the new model included pinyon-juniper woodland, sagebrush, and salt desert scrub vegetation types, warmer minimum winter temperatures and hotter maximum summer temperatures to a lesser degree. The new model was more refined, covering less area within the species range, and extended further east of Nucla. A threshold value of 0.50 was used in the CODEX model to retain the refined habitat modeling, although one known occurrence near Nucla was only partially covered by the model. The model was clipped to only include areas in Montrose County and southern Mesa County within 10 miles of a known EO, east of the Uncompaghre Plateau.

Lygodesmia doloresensis (Dolores River skeletonplant), Tier 1

This species is known from extreme eastern Utah and western Mesa County, Colorado, where 13 occurrences are documented. Soils are reddish alluvium or colluvium derived from the Permian age Cutler Formation. Many of the occurrences are along roads, and there appear to be fewer plants with increasing distance from the roadside, which led us to include CNHP's Landscape Disturbance Index as an environmental input. Summer precipitation (at least 5 cm) was the most important contributing factor in the model, followed by distance to surface geology of the Cutler Formation, an average last frost date in late April, and April minimum temperatures generally not below freezing. The model was clipped to exclude a small area of modeled habitat in Montrose County and eastern Garfield County, retaining modeled habitat in Mesa and southwestern Garfield County. A probability of 0.34 was chosen for the cut-off value for the binary version of the model for CODEX to include more modeled habitat associated with known EO records.

This model was reviewed by one expert reviewer, who believed the model to be good. The reviewer noted that the model included known occupied habitat for the species but excluded areas of known habitat in the north desert, east of Highway 139. The model was not able to pick that area up well, despite having those locations included as an input.

Mentzelia paradoxensis (Paradox stickleaf), Tier 2

This is a Colorado endemic of the salt anticline valleys in western Montrose and San Miguel counties, where it is documented from nine occurrences. Substrates are gypsum clay-dominated soils derived from Triassic to Jurassic sedimentary formations of area. This is a warm and dry area. Important climate factors were extreme minimum winter temperatures generally not falling below -20°F (-28.5°C), and April minimum temperatures near freezing. Summer and fall, while dry, are the highest precipitation seasons, and occurrences are in areas receiving precipitation of at least 2.5 inches (6.5 cm) in summer and 4 inches (10 cm) in fall. A threshold value of 0.5 was used for the probability in the CODEX version of the model. Model extent was clipped to habitat within approximately 35 miles of known occurrences.

An expert reviewer could not be identified for this model.

Mentzelia rhizomata (Roan Cliffs blazing star), Tier 2

This Colorado endemic species is known from 33 occurrences on the Roan Plateau in Garfield County. Habitats are steep, shale slopes formed in the Parachute Creek member of the Green River Formation (common both in the Roan Plateau and at the rim edges of the Piceance Basin to the north). Along with distance to the Green River Formation in general, distance to the Parachute Creek member contributed nearly 85% of information in the model. Moderate soil depth and somewhat alkaline soils were apparently sufficient to confine the modeled habitat to the Roan Plateau and a small area of Battlement Mesa. A few pixels of higher probability modeled habitat in upper Rio Blanco County were omitted from the final model as this was well outside the known range. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. This reviewer felt they had little experience with this species due to the remoteness of the habitat, but believed the elevation, setting and soils covered by the model appear accurate.

Mertensia humilis (Rocky Mountain bluebells), Tier 2

Colorado occurrences of this species are at the southern end of the core range of the species which is primarily in Wyoming. Nine occurrences are documented in north-central Colorado from Jackson and Larimer counties. This species does not appear to be narrowly restricted to particular habitats; it is found in sagebrush shrublands and open areas in montane forests. Vegetation was not a primary contributing factor in the model, which was largely driven by climate factors. The species occurs in high inter-mountain valleys (North Park, Laramie River Valley), where climatic conditions are cold compared to lower elevations, but also drier than surrounding mountain terrain. Extreme winter minimum temperatures below -37°F (-38°C) can be expected, and spring minimum temperatures do not consistently warm above freezing until June. Occurrences are in areas receiving precipitation amounts of at least 3.5 inches (9 cm) in summer, and 3 inches (7.5 cm) in winter. The model threshold was adjusted to the equal training sensitivity and specificity (0.528) and clipped to exclude habitat outside Jackson or Larimer counties.

This model was reviewed by one expert botanist familiar with the species outside of the state of Colorado. This reviewer did not assign a value for overall correctness but noted that the model appears to overpredict species distribution (i.e., underfit). The reviewer believed information on habitat specificity for this species is lacking and a review of herbarium specimens to verify identification is warranted

Mimulus gemmiparus (Budding monkey flower), Tier 1

This Colorado endemic is found on sheltered granite rock outcrops associated with seeps from Larimer to Park counties. This species was difficult to model due to lack of detailed environmental layers representing rock outcrops and seeps. A new environmental input layer of rock outcrops was created specifically for this model, with the modeler marking outcrops based on aerial photos. Two models were produced and reviewed, with the second model using a layer of rock outcrops marked from aerial photos ultimately chosen. The overwhelmingly important environmental factor for this model was the presence of rock outcrops, with aspect and climatic variables contributing around 4% of importance. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, both who believed the model was reasonable, but too coarse to accurately capture the habitat of this species, which is restricted to microhabitats. One reviewer suggested including landscape position as an environmental factor (mid-lower slopes with a drainage above), but this environmental input layer was not readily available. The second reviewer noted that as well as being underfit in places due to microhabitat requirements, the model also appeared overfit in places, with Horseshoe Park in Rocky Mountain National Park excluded from modeled habitat. They noted this population is ephemeral, and likely dependent on flood events, suggesting a metapopulation structure for this species.

Nuttallia chrysantha (Golden blazing star), Tier 2

This Colorado endemic is known from 28 occurrences in Fremont and Pueblo Counties The range includes the vicinity of the Cañon City embayment at the junction of the southern Front Range and the Wet Mountains, and along the Arkansas River as far as Pueblo Reservoir. Habitats are typically moderately steep, barren slopes formed in calcareous substrates of the Smoky Hill member of the Niobrara Formation or other upper Cretaceous geology. Distance to shale barrens formed a substantial portion of the model. A minimum level of fall precipitation around 5 cm, and gentle to moderate slopes were characteristic. Predicted suitable habitat matched the known distribution fairly closely. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who believed the model to be good, given the known distribution and habitat affinities of the species.

Nuttallia densa (Arkansas Canyon stickleaf), Tier 2

As indicated by its state common name, this Colorado endemic is largely known from the canyon of the Arkansas River between Salida and Cañon City. Twenty-six occurrences are documented from Fremont and Chaffee counties. Habitats are dry open areas in washes, roadsides, and naturally disturbed sites. Important environmental drivers included fall precipitation, distance to water as a surrogate for proximity to steeper drainage areas (i.e., canyon slopes) and degree of slope. The cut-off probability for the CODEX model was set to the medium probability value of 0.112 to include habitat covering highly ranked, large EOs. Consequently, predicted habitat extended up the Arkansas River drainage as far as Buena Vista, and to side drainages near and below Cañon City. The full extent of the model was retained originally.

This model was reviewed by two expert reviewers, one who believed the model was reasonable and the other good. Both believed the model covered too great of a spatial extent, noting they had never seen the species north of Salida or east of Cañon City. The model was clipped in the fall of 2022 to exclude areas north of Salida and east of Cañon City. One reviewer also believed the model did not cover enough habitat in the tributaries on the south side of the Arkansas River Canyon. This reviewer also suggested including geology as an environmental factor, as they have only observed the species on Precambrian rocks. A review of known occurrences shows this species is on older rocks, up to the Paleozoic era, but geology was not included in the modeling process, as mapping was not good enough to pick out a pattern.

Oenothera acutissima (Narrow-leaf evening primrose), Tier 2

In Colorado, this species is restricted to higher elevations in western Moffat County where 15 occurrences are known in the vicinity of Cold Spring Mountain, Douglas Mountain, and Round Top Mountain (areas that essentially form the extreme eastern end of Utah's Uinta Mountains). The species is reported to be associated with seasonally wet areas in this typically dry landscape. These small habitat patches may be related to the presence of faults and rock joints where seeps and springs form – a poorly mapped environment. Distance to known springs formed an important part of the model, along with summer precipitation of 5-10 cm. Winter extreme minimum temperatures are generally not lower than -40°F (-40°C). Sparse winter (driest season) precipitation and more abundant fall (wettest season) precipitation were characteristic. Modeled habitat matches the known distribution fairly closely. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who believed the model to be excellent. The reviewer emphasized the importance of a perennial water source for this species, and distance to springs was an important environmental driver in this model.

Oenothera coloradensis ssp. *coloradensis (*Colorado butterfly plant), Tier 1

This formerly federally listed threatened species is limited in range to southeastern Wyoming, western Nebraska, and northeastern Colorado, where it is documented from 14 occurrences. Habitats are generally sub-irrigated alluvial soils. The range of modeled habitat was truncated to only include areas in Douglas County and north. The western boundary of the range was clipped to a contour at the 6560 ft (2000 m) elevation level, which excluded some higher elevation habitat in the vicinity of Estes Park. Important environmental variables included distance to combined REGAP Western Great Plains floodplain and Basin wide herbaceous riparian ecological systems, distance to wetland polygons attributed to Palustrine Emergent Saturated and Palustrine Scrub-Shrub, and extreme maximum summer temperatures. The medium probability value returned by Maxent was used as the classification cut-off for the CODEX binary model to include more EOs covered by modeled habitat.

This model was reviewed by one expert reviewer, who believed the model to be good, given the known distribution and habitat preferences.

Oonopsis foliosa var. *monocephala* (Rayless goldenweed), Tier 2

This Colorado endemic is found in a restricted range in Las Animas County on semi-arid shortgrass steppe on highly eroded soils. The most important environmental drivers of the model were distance to shale barrens, average percent silt in soil, Colorado National Vegetation Classification type (developed areas excluded) and distance to the Niobrara Formation. This model predicted high probability habitat as far north as Denver, and was truncated to Kiowa, Crowley, Pueblo, Huerfano Counties and areas further south. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by two expert reviewers. One reviewer believed the model was reasonable, capturing the habitat, but questioned the extent of this model. There are documented occurrences of this species in in northern and western Las Animas County and Otero and Huerfano Counties. The reviewer was un-aware of these documented occurrences. The second reviewer returned comments only over email and noted the modeled habitat overlaps with the range of *Oonopsis puebloensis*.

Oonopsis puebloensis (Pueblo goldenweed), Tier 2

Endemic to a small area north and west of Pueblo, this species is believed to be confined to substrates formed by the Smoky Hill member of the Niobrara Formation. This chalky Cretaceous layer forms rounded hilly outcrops supporting sparse but extensive stands of pinyon-juniper over nearly bare, light-colored soil (shale barrens). A number of calciphilic (chalk-loving) species both rare and more common are found on these substrates in south-eastern Colorado. The 28 documented occurrences range from the grounds of Fort Carson south of Colorado Springs down to the area around Pueblo Reservoir, and back up the Arkansas River drainage to the vicinity of Cañon City. Distance to shale barrens and distance to surface geology of the Niobrara Formation were the primary contributing factors in the model. Areas flooded by Pueblo Reservoir were removed from the modeled habitat. Using a cutoff of 0.42, the predicted habitat fits fairly closely with the known distribution, although the southernmost location is not covered.

This model was reviewed by one expert reviewer, who believed the model to be reasonable, showing known areas of suitable habitat, matching their observations.

Oreocarya osterhoutii (Osterhout cat’s-eye), Tier 2

This is a species of the iconic regional Colorado Plateau pinyon-juniper landscape, occurring in canyons and mesas of western Colorado, adjacent Utah, and northern Arizona. There are eight documented occurrences in Mesa County. Percent cover of Colorado Plateau Pinyon-Juniper vegetation type was the factor contributing most to the model; occurrences were generally in areas with moderate cover, indicating more open woodland areas. Distance to steep slopes was also important; mesa rims and steep canyon slopes are typical habitat. Areas with fewer than 170 days of frost per year were also an important factor. The model threshold was adjusted to the equal training sensitivity and specificity (0.11). Modeled suitable habitat was not clipped and shows potential habitat in adjacent counties as well as close to the documented locations.

This model was reviewed by one expert botanist who had not seen the species in the field but was familiar with its distribution and habitat; this reviewer believed the model was good and the fit was suitable.

Oreocarya revealii (Gypsum Valley cat’s-eye), Tier 2

As indicated by its common name, this Colorado endemic species is a specialist of gypsum soils derived from Mancos shale. Populations are concentrated in the salt anticline valleys of Montrose, San Miguel, and Dolores counties in southwestern Colorado. Distance to Mancos shale was the most important environmental factor; other key factors were an average last frost day around May 15th, coldest winter temperatures generally not below -18.4°F (-28°C), and winter through summer precipitation averaging just over 1 inch (2.7 cm) per month. Modeled higher likelihood habitat is more-or-less restricted to the southeastern end of Paradox Valley, middle portion of Dry Creek Basin, Big Gypsum Valley, and most of Disappointment Valley. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the model was clipped to exclude habitat predicted in Delta and Montezuma Counties.

This model was reviewed by one expert reviewer, who believed the model to be reasonable, but overly broad, estimating less than 10% of the model area as being suitable habitat. The reviewer questioned the inclusion of one large, lower precision element occurrence (EO) as a model input. There are 17 documented EOs for this species in the BIOTICS database, and points from the polygons for all of them were included as inputs in the modeling process. Including points from a lower precision polygon can distort model results, but in this instance, there were sufficient points from other polygons to balance the lack of precision. Over-prediction of the habitat is largely due to the comparatively coarse scale of the environmental inputs, and lack of more relevant data.

Oxybaphus rotundifolius (Round-leaf four o'clock), Tier 2

The distribution of this calciphilic Colorado endemic species is similar to that of *Oonopsis puebloensis,* but includes additional areas southwest of Pueblo, as well as two occurrences about 90 km further south at the Pinyon Canyon Maneuver Site (PCMS) in Las Animas County. The 39 documented occurrences of this species are generally confined to the Middle Chalk and Upper Chalky shale of the Smoky Hill member of the Niobrara Formation. Distance to shale barrens was the primary contributing factor in the model; areas with a first frost in fall during the first week of October were also characteristic. Areas flooded by Pueblo Reservoir were removed from the modeled habitat. Using a cutoff of 0.275, the predicted habitat fits fairly closely with the known distribution, although a location on the eastern edge of the range in Pueblo County is not covered. Additional habitat on shale hills north of the Huerfano River, and outside the northwestern bounds of PCMS are also included.

This model was reviewed by one expert reviewer, who responded over email that the model was reasonable.

Oxytropis besseyi var. *obnapiformis* (Bessey locoweed), Tier 2

Occurrences of this species are essentially limited to Moffat County in northwestern Colorado, and adjacent areas of Utah and Wyoming. A disjunct record from the western margin of the Piceance Basin 70 km to the south has not been observed since 1978. The majority of the 22 documented occurrences are concentrated in Browns Park and to the east on similar substrates toward the Axial Basin east of Maybell. In an attempt to include several occurrences from substrates other than the Browns Park Formation, a categorical geology layer was used in the final model. Surface geology type was the most important environmental factor but predicted habitat still did not include an older occurrence record near the Wyoming border or the Piceance Basin location. This is a dry region, but the species appears to require at least 5 cm of precipitation in summer, also an important factor in the model. Outside the known distribution, a few areas of suitable habitat were predicted for Blue Mountain in Dinosaur NM, and Raven Ridge in Rio Blanco County. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, who believed the model to be good. One reviewer thought the model captured documented areas well. The second reviewer believed the model included too broad of an area. This reviewer knew of areas identified in the model where presence/absence surveys had been completed and no occupied habitat had been documented, particularly in the Hwy 318/Peck Mesa area south to the Yampa River. However, there is a historical EO known from the Peck Mesa area.

Packera mancosana (Mancos shale packera), Tier 1

This Colorado endemic species is known from a single occurrence record on the dissected plateau south of Lone Mesa in south-central Dolores County. Plants occur in a handful of scattered stands across approximately two kilometers. Although Mancos shale is characteristic of the location, the full mapped geological unit was too broad as an environmental unit, so discrete soil units supporting stands of the species were used. The presence of soil units from mapped stands was the most important factor; additional important contributing environmental factors were higher clay percent and deeper soil on flatter areas. Modeled habitat is limited to an area of about 5 by 3 km in the vicinity of the occurrence, on the uplands above Plateau Creek. A threshold value of 0.5 was used for the probability in the CODEX version of the model and full extent of the model was retained.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. This reviewer noted that the species is an obligate of a special rare type of Manco Shale which is highly eroded. The model strove to capture this using discrete soil units as inputs rather than the broader geological unit. The reviewer believed the elevational range covered by the model may be too broad both in higher and lower elevation and areas which are not Mancos Shale should be excluded from the model.

Pediocactus knowltonii (Knowlton cactus), Tier 1

This extremely rare and Federally Listed Endangered cactus is known from only a single native population in pinyon-juniper/sagebrush vegetation in northern New Mexico, just south of the Colorado border. Maxent models using a handful of points placed near the known location were unsatisfactory, so a deductive model was constructed using soil type polygons in and immediately adjacent to the occurrence. Corresponding soil units in Colorado were also selected. These were intersected with environmental factor layers to select areas where vegetation, growing season length, and annual precipitation were similar to that of the known location.

Reviewers were not satisfied with this model. Of two reviewers one ranked the model good and the other poor, but both noted the model was underfit and did not capture refined environmental inputs. Therefore, the deductive model was reconstructed using environmental inputs specified in Handwerk et al. 2017 but extended to some areas outside Southern Ute tribal lands. Inputs were vegetation type of Pinyon-Juniper Woodland or Pinyon-Juniper Sagebrush mix, elevation range of 1865-2057m (6100-6750 ft), surface geology of the San Jose Formation, and a variety of soil types (see model metadata for details).

Penstemon acaulis var. *yampaensis* (Yampa beardtongue), Tier 2

With a distribution adjacent to that of the Plateau penstemon in western Moffat County, Colorado and Daggett County, Utah, this species is documented from 31 locations in Colorado. About a third of these occurrences have not been observed within the past 30 years. The Colorado distribution ranges from north of Cold Spring Mountain southeast to the vicinity of Cross Mountain southwest of Maybell. Occurrences are typically on shaley, sandy, limestone soils derived from Browns Park Formation or the Tipton Tongue (including Wilkins Peak member) of the Green River Formation. Distance to one or both of these two substrates accounted for about 90% of the model predictive ability, and the model including both types was better constrained than models with a single type. Minor contributing factors included spring precipitation generally over 7.5 cm and extreme winter minimum temperatures not lower than -40°F (-40°C). Predicted habitat for this species occupies areas of slightly drier, lower elevations and younger geologic substrates adjacent to that of *Penstemon scariosus* var*. cyanomontanus* (see below) while overlapping very little with that related species. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, who believed the model to be either reasonable or good. The first reviewer thought the general area it encompassed was correct but knew of one location in Irish Canyon not captured by the model. The second reviewer compared recently identified occupied habitat (not yet in the BIOTICS database) to the model and did not identify large data gaps but did question the inclusion of the Vermillion Bluffs.

Penstemon degeneri (Degener beardtongue), Tier 2

This Colorado endemic is documented from 21 occurrences on rocky areas in the vicinity of the Cañon City embayment at the junction of the southern Front Range and the Wet Mountains. Substrates are derived from Precambrian age metamorphic and igneous outcrops. The model incorporating surface geology was better differentiated; distance to the aforementioned types was a primary contributing factor. Dry winters (generally less than 10 cm of precipitation) and comparatively wet summer months (16 cm or more) were also important, as was an average last frost date around the end of May. Slopes were moderate to steep. Modeled habitat extends around most of the slopes of Pikes Peak at elevations up to 8000-8500 feet (2440-2590 m) depending on aspect, extending north to the southern end of the Tarryall Mountains in Park County. Similar elevations in the Wet Mountains of central Fremont, northern Custer, and western Pueblo counties are also included. Disjunct areas modeled in central Jefferson and Park Counties were clipped out. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by two expert reviewers, who both believed the model was reasonable. One reviewer thought the model did not perform as well for higher elevations and more western locations. They knew of at least one location which was not captured by the model.

Penstemon fremontii var. *glabrescens* (Fremont's beardtongue), Tier 2

A Colorado endemic documented from 18 locations in the Piceance Basin of Rio Blanco County, this species occurs on sparsely vegetated slopes of soils derived from Green River shale. As expected, distance to Green River surface geology was the primary contributing factor in the model (52.7%). Because this unit is coarsely mapped in the available data, predicted habitat is not highly constrained; the model could be considered under fit. Shallow to moderate depth soils also played a fairly large role, contributing 26.7% to the prediction. Additional important factors were aspect (a tendency to favor more south-facing slopes) and a last frost date around the end of May. Modeled habitat was clipped to remove areas south of the boundary between Rio Blanco and Mesa counties. Remaining higher probability habitat includes scattered areas of central Moffat County, substantial area in the Piceance Basin, extending south to Garfield County with a few drainages in the Roan Plateau, and additional areas in the vicinity of the Grand Hogback to the east, and extending up nearly to the vicinity of Gypsum in the Colorado River Valley. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. The reviewer noted the model did a good job of capturing known occurrences but was skeptical of modeled habitat around Interstate 70. The reviewer also noted irrigated fields and other disturbed areas should be excluded.

Penstemon gibbensii (Gibben's beardtongue), Tier 1

This species is documented from three locations in northwestern Moffat County, and also occurs in adjacent Wyoming and Utah counties. Originally reported as occurring on soils derived from the Tertiary age Browns Park formation, it was more recently also found on the substrates of the widespread Wasatch formation. Consequently, although distance to Browns Park formation surface geology was a contributing factor in the model, the most important contribution was a general lack of summer precipitation (<6 cm). Dry winters and winter extreme low temperatures warmer than -40°F (-40°C) were also contributors. Most, but not all, habitat tends to be on south-facing exposures. Despite the lack of key substrate information, modeled habitat was fairly constrained to areas near the known locations, i.e., the floor of Browns Park and the vicinity of the junction of the Little Snake River with Powder Wash. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of modeled habitat was retained.

This model was reviewed by two expert reviewers. One wrote in an email that the model looked good. The other commented that the model may include too much habitat in the western portion of Powder Wash. Marginal suitable habitat had been identified in this area, but no occupied habitat and appropriate substrate may be restricted to sandy bluffs above the Little Snake River.

Penstemon mensarum (Grand Mesa penstemon), Tier 2

A Colorado endemic of the central west-slope higher elevations, this species is documented from 48 occurrences ranging from the southern part of the White River Plateau in Garfield County southwest to the Uncompahgre Plateau in Montrose County, but with its core distribution on and above the Grand Mesa. Habitats are open meadow areas in typical montane shrubland or woodland types of the west slope. Winter precipitation was the most important contributing factor in the model; occurrences are in areas receiving 6-14 inches (15-35 cm) of precipitation in this season. Aspen or aspen-mixed conifer forest, montane sagebrush, and oak-mixed mountain shrubland accounted for most of the biophysical setting model contribution. A variety of regional geologic substrates were picked up by the model, but the species is apparently not tightly constrained by surface geology. A threshold value of 0.5 was used for the probability in the CODEX version of the model. The model was clipped to include only predicted habitat within approximately 30 miles of known occurrences.

This model was reviewed by two botanists who had experience with this species in the field. The reviewers both believed the overall correctness of the model to be good; however, one reviewer believed the model to be underfit, overestimating the areas of occurrence, although still suggesting suitable habitat which should be checked.

Penstemon scariosus var. *albifluvis* (White River penstemon), Tier 1

Known from five occurrences in extreme western Rio Blanco County, from Raven Ridge west of Rangely south to the vicinity of Rabbit Mountain, the species is also found in adjacent Uintah County, Utah. Substrates are derived from the Parachute Creek member of the Green River shale, and distance to this surface geology type provided nearly 90% of the model information. Other important factors were soil depth and an average last frost date around the third week of May. Modeled higher probability habitat follows the documented distribution fairly closely, extending somewhat further north along Raven Ridge to the Utah border, and including an additional area south of Park Canyon at the southern end. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of modeled habitat was retained.

This model was reviewed by two expert reviewers, both who believed the model was excellent. Both thought the model captured all the appropriate habitat with correct geologic substrate and slope.

Penstemon scariosus var. *cyanomontanus* (Plateau penstemon), Tier 2

This species is documented from seven occurrences in western Moffat County, primarily on slopes of Blue Mountain to the south and Douglas Mountain to the north of the canyon of the Yampa River in Dinosaur National Monument. An additional location is known from Diamond Peak some 32 km to the north, and the range extends into adjacent Uintah County, Utah. Substrates are generally sandy, slickrock crevices, or gravel, derived from older rocks of the Uinta Mountain Group (middle Proterozoic) and adjacent Pennsylvanian age sandstone formations, but are not closely tied to a particular geologic formation. The categorical surface geology layer contributed over 50% of the information in the model; five types were important, and three additional types also supported occurrences. Other important factors included summer precipitation of at least 12.5 cm, and extreme minimum winter temperatures generally above -40°F (-40°C). Vegetation type (as biophysical setting) of pinyon-juniper or sagebrush shrubland was also a contributing factor. Modeled suitable habitat includes extensive middle elevation areas in western Moffat County, extending from Middle Mountain in the north to the slopes below Skull Creek Rim in the south. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of modeled habitat was retained.

This model was reviewed by one expert reviewer who had conducted research on the species in the field. This reviewer believed the model was reasonable.

Phacelia gina-glenneae (Troublesome phacelia), Tier 1

This Colorado endemic is known from a single large occurrence in Middle Park near Kremmling, where it is restricted to weathered volcanic ash substrates of the Troublesome Formation. Naturally, distance to this surface geology was the primary contributing factor in the model. Known stands are generally on western-facing slopes, and where summer precipitation is at least 8 cm. Similar conditions were predicted for hillsides north and east of Kremmling, additional areas extending north and south of the known location in the Troublesome Creek drainage, as well as the valley of the Colorado River, and narrow hillside areas near the junction of the Colorado and Fraser rivers at Granby (just south of the Troublesome Creek burn of 2020). A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of modeled habitat was retained.

This model was reviewed by one expert reviewer, who believed the model to be poor. They noted the model was overly broad, capturing riparian areas and areas around Granby should not be included.

Physaria alpina (Avery Peak twinpod), Tier 2

This Colorado endemic is documented from 16 occurrences in alpine turf and fellfield habitats in Park, Lake, Pitkin, and Gunnison counties. Due to its alpine nature, elevation was the most important contributing factor in the model. Extreme minimum winter temperatures reaching nearly -55°F (-48.5°C) are possible. In these alpine habitats frost can occur at any time of year, precipitation begins to fall as snow during fall months, and snow is likely to remain on the ground for more than half the year. Modeling indicated a tendency for occurrences to be on south-east facing slopes, which could mitigate harsh conditions to some degree. A threshold value of 0.5 was used for the probability in the CODEX version of the model. The model was clipped to include only predicted habitat within the range of known occurrences.

This model was reviewed by one expert botanist who believed the model to have excellent overall correctness with a suitable fit.

Physaria bellii (Bell's twinpod), Tier 2

A Colorado endemic, this species is known from 28 occurrences on hogbacks at the mountain front in Boulder and Larimer counties. These are areas where during the Laramide Orogeny the rising mountain terrain faulted and tilted overlying sedimentary layers of generally lower Cretaceous or older origin, forming the Front Range (Dakota) hogback. Occurrences range from the northern edge of Boulder city limits to the vicinity of Livermore in northern Larimer County. The species tolerates disturbance to such an extent that it is found on mine spoil piles and road cuts, as long as the substrate is derived from the appropriate rock type. Distance to shale and sandstone units forming the Front Range hogback north of Colorado Springs was the primary contributing factor in the model. The 0.5 and above model did not capture the northern extent of the range well, so the cutoff value was adjusted to 0.35. Potential habitat was truncated at the Boulder/Jefferson County border.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. The reviewer was familiar with this species on shale soils and outcrops associated with the Niobrara, Fort Hayes, and Pierre members/formations. The reviewer thought the depicted habitat area looked overly broad and should not include habitat south of Boulder Canyon.

Physaria parviflora (Piceance bladderpod), Tier 2

In common with other Piceance Basin endemics, this species is closely associated with shale soils derived from units of the Green River formation, including the Parachute Creek member surrounding the well-known Mahogany ledge oil shale zone. There are 37 locations documented in Rio Blanco, Garfield, and Mesa counties. Together, distance to Parachute Creek member (83%) and distance to Green River formation (5.3%) were the major contributing factors in the model. This species appears to have a slightly broader environmental niche than *Thalictrum heliophilum,* which has a nearly identical range. Additional model factors indicate that this species prefers the higher, cooler margins of the basin, where last frost average is in first week of June, and extreme maximum summer temperatures generally below 95°F (35°C). Modeled habitat closely tracks the presence of Parachute Creek substrates on the rim of the Piceance Basin with scattered patches on the western end of Battlement Mesa to the south across the valley of the Colorado River. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert reviewer, who believed the model to be good, tracking well with known occurrences but including too much habitat off exposed shale barrens.

Physaria pruinosa (Pagosa bladderpod), Tier 2

A narrow endemic known from northern New Mexico and southern Colorado, this species is documented from 23 occurrences in La Plata, Archuleta, and southern Hinsdale counties at lower montane elevations on the southern flank of the San Juan Mountains in Colorado. Distance to substrates derived from Mancos Shale, and high-clay soils were important contributing factors in the model. Occurrences are in areas where winter precipitation are at least 5.5 inches (14 cm) but not much higher, and last frost in spring is generally during the first week of June. The model threshold was adjusted to the equal training sensitivity and specificity (0.528) and clipped to exclude predicted habitat in San Miguel County.

This model was reviewed by one expert reviewer, who believed the model to be reasonable. The model indicates that the species could occur anywhere around the town of Pagosa Springs, and the reviewer believed this was reasonable as this species is tied to Mancos shale, which is common in the area. However, the reviewer believed the model was underfit, and an additional important factor must be missing as the species is fairly uncommon on Mancos shale. This reviewer noted heavily forested stands were included in the modeled area and this species is not found in that habitat. Also, the reviewer believed the area around the town of Chromo should be included in the model, and perhaps the lack of surveys on private land in the area hindered accurate modeling in this area.

Physaria rollinsii (Rollins twinpod), Tier 1

This Colorado endemic is known from the Gunnison Basin, with 18 documented occurrences ranging from the vicinity of Sargents at the east end, west to the upper end of the Black Canyon of the Gunnison River on dry sagebrush-dominated shrublands. This higher elevation basin is slow to warm in spring with average date of last frost around mid-June. Spring precipitation was the most important factor; winter precipitation was also a primary contributor, probably indicating a minimum tolerable winter/spring total precipitation amount for the species. Average last frost was the most important temperature factor, but other spring minimum temperature factors also contributed to the model. A tendency to occur on more south-facing aspects agrees with the idea that the species favors local conditions that may warm slightly earlier at the beginning of the growing season. Modeled habitat extends up many side drainages and ridges both north and south of the Gunnison River valley, following the distribution of sagebrush shrubland. A threshold value of 0.5 was used for the probability in the CODEX version of the model and was clipped to exclude modeled habitat in Grand County.

This model was reviewed by three expert reviewers, two who believed the model was good and one who believed it was unusable. The first reviewer noted that the model included the known location where they had observed the species. The second reviewer noted that many of the areas where they had documented the species were captured in this model, but it was not an exact match. One area east of Gunnison where the reviewer had an observation record was not included and areas of un-suitable habitat, including riparian areas of Ohio Creek and Tomichi Creek and Gambel oak woodlands (especially north of Blue Mesa Reservoir) were included in the model. The third reviewer echoed these comments but knew of locations of the species on Sapinero Mesa not included in the model and noted areas of Douglas fir, riparian areas and irrigated meadows should not be included in the model.

This model was revised in 2022, after additional data was entered into the BIOTICS database. In total, 13 EOs were updated and 15 new EOs were added with partner and specimen data in the spring of 2022. Important environmental variables in the new model included spring precipitation, May minimum temperature, and to a lesser degree, relief, and soil pH. The new model was more refined, excluding the valleys, and picking up more areas northeast of Gunnison and on Sapinero Mesa and south of the Gunnison River in general. Although improved, a lower probability cutoff of 0.205 was used for the CODEX version of the model to capture five known locations only picked up at this lower probability. The model was trimmed slightly to include modeled habitat only around the core species range.

Physaria scrotiformis (West Silver bladderpod), Tier 1

Documented from four high-elevation locations near the continental divide in San Juan and La Plata counties, this Colorado endemic is a specialist of shallow alpine substrates. Fall precipitation averaging about 29 cm was the most important factor, along with maximum summer temperatures (typically cool), and shallow, alkaline soils, of moderately rough terrain. Although the original occurrence is reported from the lower Mississippian age Leadville limestone, subsequent occurrences have been documented from younger substrates of lower Permian (Cutler Fm) or Tertiary volcanic origin that are fairly common in the San Juan Mountains. Predicted habitat is concentrated in high elevation areas of the Weminuche Wilderness Area between the Las Animas River and Vallecito Creek. Modeled habitat was truncated to include areas from southern Ouray County to northern La Plata County and adjacent western Hinsdale County, omitting areas further to the east. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by one expert botanist familiar with the species in the field, having observed two populations – one on limestone and one on volcanic tuft. This reviewer believed the overall correctness of the model was good with a suitable fit, agreeing with the mountain top habitats identified by the model.

Physaria vicina (Good-neighbor bladderpod), Tier 2

This Colorado endemic species is found primarily on soils derived from Mancos shale or adjacent sedimentary formations in southwestern Delta County, eastern Montrose County, and northern Ouray County. Two disjunct occurrences are known from the southeastern corner of Garfield County, more than 100 km (62 miles) distant from the main distribution. Distance to Mancos shale was the most important contributing factor in the model, followed by last and first frost dates (a growing season roughly between third week of May and third week of September). Winter precipitation (the driest month) was also an important factor. Modeled habitat is concentrated on rising ground above the Uncompahgre and Gunnison rivers in the vicinity of Montrose. Similar habitat ranges southeast from western Garfield County along the Grand Valley, and the opposite (southern) side of the Uncompahgre Plateau. Disjunct predicted habitat is found near the junction of the Crystal and Roaring Fork rivers on slopes above Carbondale. A threshold value of 0.25 was used for the probability in the CODEX version of the model to include more habitat to cover known locations and modeled habitat in Dolores County was clipped out.

This model was reviewed by two expert reviewers, both who believed the model was poor. The first reviewer believed most observations to be on Mancos shale and Dakota sandstone, in both pinon-juniper woodlands and sagebrush steppe plant communities in shallow to moderately deep loams. This reviewer questioned the findings near Glenwood Springs, which influenced the extent of the model, and believed many of the salt desert shrub ecological sites are not suitable habitat. The second reviewer believed the species could be associated with Pinyon-Juniper, sagebrush, and saltbushes, but that the model was too broad, and the presence of Mancos shale was not very helpful for narrowing down the search areas. This reviewer believed the species is not limited by lack of suitable habitat but is under-documented as it blooms very early in the spring and once the flowers are gone, it is indistinguishable from *Physaria acutifolia,* making it easy to overlook.

Potentilla rupincola (Rocky Mountain cinquefoil), Tier 2

This species had been previously modeled for another CNHP project. However, newly documented locations for this species made it expedient to produce a revised model to replace the original version for CODEX.

A Colorado endemic restricted to north-central Colorado, this species is documented from 34 occurrences in Larimer, Boulder, Clear Creek, and Park counties, where it is found on or near granitic outcrops and crevices. A dataset representing distance to rock outcrops in the Front Range was the primary contributing factor in the model. Most occurrences are in areas receiving 4-6 inches (10-15 cm) of summer precipitation, southern locations receive more. The montane to sub-alpine elevations where this species is found can experience extreme winter minimum temperatures as low as -39°F (-39.5°C). Modeled potential suitable habitat is most common in Larimer and Boulder counties but extends as far south as eastern Park County west of Pikes Peak. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by one expert botanist who believed the overall correctness of the model to be good. The reviewer noted the fit was suitable but questioned the model exclusion of high elevation areas just east of Virginia Dale, as there is similar geology and elevation, and it is close to known locations.

Ptilagrostis porteri (Porter feathergrass), Tier 2

A Colorado endemic closely linked to fen environments, this species is known from 31 occurrence records, ranging from south-central Lake County east to the vicinity of Woodland Park near the Teller/El Paso County border. Most occurrences are in northern Park County and adjacent Summit County, where rich fens are concentrated in drainages fed by streams originating in calcareous substrates. As expected for a fen indicator species, distance to saturated wetlands and distance to water were the most important environmental factors in the model, followed closely by April minimum temperatures well below freezing. In general, these high-elevation occurrences are cool and moist, in areas well able to support saturated soils. The modeled range was truncated to include only eastern portions of Gunnison, Pitkin, and Eagle counties, Summit, Clear Creek, Lake, Chaffee, Park and Teller counties, and small parts of Gilpin, Jefferson, Douglas, El Paso, and Fremont counties, all within 50 miles of known EOs. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by three expert reviewers, who believed the model was either reasonable, good, or poor. One reviewer believed the coverage seemed appropriate, although much of the potential habitat appears degraded and unlikely to support populations. Another reviewer believed the modeled habitat was too broad and more refined environmental inputs, which were not available, were needed to narrow predicted habitat. This reviewer expressed concern that this model could give the impression that the species is much more abundant than it actually is and that the model should contain a caveat that it is a broad, inclusive model of locations where the species may exist and should not be taken as a species distribution map. This is essentially the intent of this model, which is to be used for environmental review, and the purpose of this model is described in this report.

Puccinellia parishii (Parish’s alkali grass), Tier 2

Colorado has two documented locations of this rare grass of the southwestern US that lie about 25 km (15 miles) apart in central San Miguel and Dolores counties. Its scattered distribution is connected to its occurrence in moist, seasonally wet habitats within the surrounding arid lands. Colorado occurrences are associated with soils derived from Mancos shale or adjacent formations, and distance to Mancos shale was the most important factor in the model. Distance to palustrine emergent wetland types was also important. Sufficient winter precipitation, and a last frost date around the first of June were additional contributing conditions. Modeled suitable habitat is concentrated around the two known locations, but small scattered patches occur from southern Montrose County south to east-central Montezuma and west-central La Plata Counties. A threshold value of 0.5 was used for the probability in the CODEX version of the model and the full extent of the model was retained.

This model was reviewed by two expert reviewers, who both believed the model was poor. One reviewer was unsure of the distribution of the species in Colorado. A second reviewer thought the model was too broad and contained unsuitable habitat of areas which are not seasonally saturated. This model should be considered for eventual revision.

Salix arizonica (Arizona willow), Tier 2

This rare willow is a subalpine species of wet meadows, streamsides, and cienegas in Utah, Arizona, New Mexico, and Colorado. The three known Colorado occurrences are in southwestern Conejos County. Winter precipitation of at least 10 inches (26 cm) was the most important contributing factor in the model. Spring precipitation was also important; occurrences are in areas receiving at least 7.5 inches (19 cm) during that season. As might be expected with these precipitation patterns, snow could remain present on the ground for more than half the year. Distance to palustrine emergent wetland types, which represent the habitat in which *Salix arizonica* is found, were also an important contributing factor. Modeled suitable habitat was restricted to Conejos and Archuleta counties and a threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by a person with extensive knowledge of this species in Colorado. The reviewer chose excellent for overall correctness, although noting it is probably a little too expansive. The reviewer did suggest adding New Mexico data might possibly improve the model.

Telesonix jamesii (James telesonix), Tier 2

This species had been previously modeled for another CNHP project. However, newly documented locations for this species made it expedient to produce a revised model to replace the original version for CODEX.

This species of rocky areas is largely endemic to Colorado, although it may extend into northern New Mexico. It is documented from 35 occurrences in the Front Range of Colorado. A dataset representing distance to rock outcrops in the Front Range was the primary contributing factor in the model, as was distance to surface geology of igneous and metamorphic rocks of Precambrian age. Most locations for this species receive more than 20 inches (50 cm) of annual precipitation. Reflecting the mountainous distribution of occurrences, extreme winter low temperatures can be severe, while summer extreme maximum temperatures are generally not above 90°F (32°C). The model threshold was adjusted to 0.45 to better cover documented locations and the full extent of the model was retained.

This model was reviewed by three botanists, two of which assigned an overall correctness score, choosing good and reasonable. The first reviewer questioned the inclusion of modeled habitat between Rocky Mountain National Park and Pike's Peak and in the northern-most reaches of the model, as no occurrences have been documented in these areas, but the reviewer did believe the model portrayed reasonable locations to survey. The second reviewer noted rock outcrops were not fully included in some areas and correctly noted the model may not be able to pick up on microtopography. The third reviewer believed too much alpine habitat was represented around Pike's Peak and suggested leaving out alpine habitat and including language in the metadata that the species may occur in isolated sites in this habitat type. This reviewer also believed the model should include more habitat around Lost Creek Wilderness; although much of this area is included in modeled habitat, two known occurrences were not picked up by the model in this area.

Thalictrum heliophilum (Sun-loving meadow rue), Tier 2

This Colorado endemic is known from 33 locations in Rio Blanco, Garfield, and Mesa counties. Occurrences are generally found on moderately steep slopes and are closely tied to shaley soils derived from the Green River formation, especially the Parachute Creek member. As expected, distance to Parachute Creek member was by far the most important factor in the model, contributing over 90% of the information; slope was the next greatest contributor to the model. A slight tendency to occur on south to west facing slopes was also seen, but other environmental factors were not major contributors. Modeled habitat closely tracks the presence of Parachute Creek substrates on the southern and western portions of the Piceance Basin and the western ends of Battlement Mesa and Grand Mesa to the south across the valley of the Colorado River. The model threshold was adjusted to 0.35 to include more of a documented occurrence on Battlement Mesa. The full extent of the model was retained.

This model was reviewed by two expert reviewers, both who believed the model was either good or reasonable. based on elevation, geology, and soils. The second reviewer noted all known occurrences were included in modeled habitat but thought the model should exclude areas south of Vega State Park as it is outside of the known range and appears to be forested slopes and not open shale slopes. This area was retained in the model as the geology and slopes are accurate, but a review of aerial photography does show very few areas of barren slopes. This portion of the model was excluded in the fall of 2022.

Thelypodiopsis juniperorum (Juniper tumble mustard), Tier 2

A west-slope Colorado endemic, this species is documented from 19 occurrences in Mesa, Delta, Montrose, and Gunnison counties where it is found in typical habitats of the northern Colorado Plateau including pinyon-juniper, sagebrush, and oak-mixed mountain shrublands. Biophysical settings selected in the model were dominated by pinyon-juniper woodland and a variety of shrubland types such as oak-montane shrub, mixed salt-desert scrub, lower montane foothill shrubland, and sagebrush. Surface geology was variable, but largely formed in sedimentary units of Jurassic to Cretaceous age or overlying Quaternary substrates. Soils generally have high clay content. Slopes are generally moderate but not flat, and extreme minimum winter temperatures generally warmer than -26°F (-32°C). A threshold value of 0.5 was used for the probability in the CODEX version of the model and modeled suitable habitat was clipped to include only west-slope areas.

This model was reviewed by one expert who believed it to be reasonable but underfit, including habitat that has been altered and is unsuitable for the species. The reviewer submitted a shapefile indicating these areas, which included habitat on the north side of the Grand Valley, east of Montrose on the east side of the East Mesa, south of Hotchkiss on the Spurlin and Cottonwood Mesas, and the south east end of Disappointment Valley.

Thelypodium paniculatum (Northwestern thelypody), Tier 2

There are two poorly documented occurrences of this species from the first half of the 20th century in Colorado. Colorado occurrences would be peripheral to the central distribution of the species in Wyoming, where it is reported as a species of mesic or wet meadows and riparian areas. A deductive model was constructed, based on vegetation type and elevation. Modeled habitat included areas with elevations of 7,500-9,500 ft (2286-2895.6 m) and existing vegetation type (LANDFIRE Remap 2016) Rocky Mountain Alpine-Montane Wet Meadow, Rocky Mountain Lower Montane-Foothill Riparian Shrubland, Rocky Mountain Lower Montane-Foothill Riparian Woodland, Rocky Mountain Subalpine-Montane Mesic Meadow, Rocky Mountain Subalpine-Montane Riparian Shrubland, or Rocky Mountain Subalpine-Montane Riparian Woodland. The intersection of these two datasets was clipped to include only Moffat, northern Routt, and Jackson counties, and the lower Laramie River valley of Larimer County.

This model was reviewed by one expert who believed it to be reasonable, as the species is found in wet meadows of palustrine and riverine settings.

Townsendia fendleri (Fendler's Townsend-daisy), Tier 2

In Colorado, this species is documented from 26 locations in the south-central part of the state. Occurrences in the upper Arkansas River valley are typically on eroded badland outcrops in pinyon-juniper woodlands derived from Tertiary or Cretaceous sedimentary formations, but those in more southern stands do not share this substrate affinity. Distance to Southern Rocky Mountain Pinyon-Juniper Woodland vegetation type was the primary contributing factor in the model. The model also picked up foothill and montane grassland biophysical settings as contributing to the habitat. Fall precipitation is generally low in the range of this species, ranging from 2-3 inches (5-8 cm). A subset of occurrences in the Upper Arkansas Valley were used for modeling to decrease the influence of this more densely populated region in model results. The model threshold was adjusted to 0.25 to better cover documented locations. Modeled suitable habitat was clipped to exclude areas west or south of Poncha Pass at the north end of the San Luis Valley.

This model was reviewed by two botanists familiar with the species in the field, who both believed the overall correctness to be good. The first reviewer believed the inclusion of a wide area around Salida/Poncha Springs/Buena Vista in a variety of habitats to be correct for this species. The second reviewer thought the model was suitable for surveys in potential habitat but may include too broad of an area.

Townsendia glabella (Gray's Townsend-daisy), Tier 2

This endemic of southwestern Colorado is documented from 22 locations, nine of which are considered historic (not observed during the past 30 years). Although reported as occurring on "the Smokey Hill member of Mancos shale", geologic sources warn that the difficulty of mapping units corresponding to Niobrara formation members in the Mancos shale between the Dakota Sandstone/Burro formation and the Mesa Verde group in this part of Colorado is extreme. Consequently, the species was modeled using distance to units of the Mancos shale as this substrate is currently mapped on 1x2 degree maps for the area. In addition to distance to Mancos shale surface geology, moderately deep soils with comparatively high clay content at elevations generally below 7550 ft (2300 m) were characteristic. May minimum temperatures above freezing may also contribute an important isoline in the distribution. Modeled higher probability suitable habitat omits some historical occurrence records and was clipped to limit the final extent to Montezuma, La Plata and Archuleta counties. A threshold value of 0.5 was used for the probability in the CODEX version of the model.

This model was reviewed by three expert reviewers, who assigned the overall correctness as good, reasonable, or poor. The first reviewer believed the model was coarse and should exclude wetlands and the town. This reviewer would like to see the model be more closely aligned with platy shale barrens. A second reviewer agreed that this model was too broad, picking up area in the forest with shale geology but not shale soils. The third reviewer agreed that this model was underfit and included more areas of unsuitable habitat than suitable. This reviewer noted habitat should be limited to the oyster beds of the Smoky Hill member of Mancos Shale.

Trifolium dasyphyllum ssp. *anemophilum* (Whip-root clover), Tier 2

This species is currently only documented in Colorado from a single occurrence in Weld County; it is primarily known from the Laramie Range in Wyoming. A deductive model was constructed from soil types only (NRCS 2012) and limited to Weld and Logan counties. Soil map units selected to represent the habitat were Ustic Torriorthents-Rock outcrop complex, 9 to 40 percent slopes (MU Key 95166) and Badland (MU Key 95101).

This model was reviewed by two experts. The first, based in Wyoming, replied that the model is not in alignment with any aspect of the Wyoming distribution. The species in that state is found in an elevation range between 7000-8920 feet, and in Colorado at 5400 feet. The second botanist, based in Colorado, believed the modeled habitat correctly matched the habitat in Colorado where the species occurs and ranked the model as good for overall correctness, given it is based on very limited occurrence data in Colorado. This reviewer believed soil type was a good choice of an important variable for this deductive model.

Discussion

Coverage and use of available species models

The Colorado Natural Heritage Program tracks roughly 540 plant species, with 117 of these, the Plants of Greatest Conservation Need, ranked globally critically imperiled (G1) or imperiled (G2). These species are at risk throughout their range and under threat of extinction. Pressures on these species include oil and gas development, recreation, and suburban or exurban development. Many of these species are under-surveyed and little is known about their life history and environmental needs. This project defines both mapped locations of potentially suitable habitat and identifies environmental drivers to give a better understanding of species most important needs.

Models produced during this project are suitable for use in identifying field survey target areas, and for landscape scale spatial analysis or to aid in management of and avoidance of impacts to the species. Because the primary use of these models in CODEX is to assist landowners and managers in identifying which species of concern are most likely to occur in an area of interest, we were not concerned that models would be overly constrained by using known typical substrates as primary input, as long as predicted habitat did not exactly outline individual occurrences. Binary versions are easily exported to .kml/.kmz format for use in Google Maps and Google Earth and are smaller files for use on other GIS devices.

For some species, a few element occurrence (EO) records were excluded from use in habitat modeling. Excluded records were typically very old historical or extant EOs, and those with low spatial precision (mapped as covering very large spatial areas). This exclusion can result in such locations falling outside high probability modeled habitat. Our modeling process aims to define areas of most likely habitat for the species, not simply to buffer all known EO locations. Higher probability modeled areas include habitats with environmental conditions most similar to the greatest number of known occurrences and may exclude EOs which do not meet these criteria. These EOs, therefore, will fall within lower probability areas of the model. We recognize that the binary model in CODEX may exclude some documented occurrences of the species; however, our intent is to delineate areas most likely to harbor the species, striking a balance of including the most similar areas near documented locations while not excluding additional reasonable habitat.

With the addition of the 81 species modeled in this project, modeled distribution for a total of 115 Plants of Greatest Conservation Need are represented in the CODEX. The spatial display of the modeled distribution is visible to the user in CODEX with a signed data sharing agreement and the modeled distribution will be used in the analysis for environmental review for all users, where results will be returned in tabular form. The models used in CODEX will be a binary version (yes/no) of the full probability model delivered to CNAP which includes a likelihood from 0-1 over the modeled area. Full spatial models have been delivered to CNAP for use in species surveys or other conservation work. Portions of these full spatial models could be shared with agency partners with a signed data-sharing agreement and with CNAP permission as needed.

Additional modeling needs

Although nearly all SWAP Tier 1 and 2 species have been modeled, there remain two SWAP Tier 2 Plants of Greatest Conservation Need lacking a species distribution model (Table 2). We chose not to model these species at this time due to unresolved taxonomic issues. There are also 26 of the older Tier 1 models created as rapid assessment deductive models produced as binary surfaces; most would be improved by remodeling using better techniques. CNHP continuously re-evaluates species rankings as new species are described, known species are revised, or additional occurrences found, so these totals are likely to change over time. New occurrence records are regularly submitted to or requested by CNHP. This data can be checked against existing models and used to determine when a new model is needed. In addition, several of the models produced during this project could benefit from additional work to identify more useful model inputs that might improve the predictive ability of the model. Many of these were identified in the expert review process, which was completed for Round I models in the fall of 2021 and for Round II models in the fall of 2022. In some cases, a lack of information about the species' environmental niche and/or a lack of robust occurrence data hindered model development, making further model revisions difficult until more information is obtained. Table C-4 details a list of species to consider for future model revisions, prioritized from reviewer comments. This table also notes modeling suggestions and existing data gaps limiting model revisions. All reviewer input will be considered in future revisions. During this project, nine species distribution models were revised in 2022 based on model reviewer feedback and another six models had minor edits made during review for CODEX processing. For a discussion of model review results and potential processes to improve models, see Future data development section below and Appendix C.

There are an additional 28 BLM sensitive species in Colorado not included in SWAP that lack models, and 23 USFS Region 2 sensitive species occurring in Colorado not included on either the SWAP or BLM list that have not been modeled (Table 2). There are also perhaps 110 or so fully tracked G3 (rounded rank) species without special status which could be modeled if occurrence data is available.

Finally, all our models would benefit from some form of ground-truthing. Because statistically rigorous model validation is highly cost/labor intensive, field verification efforts should be encouraged for crews who are surveying a particular area and are able to check survey locations with GPS against the predicted habitat to confirm presence or absence.

Table 2. Colorado special status plant species lacking species distribution models.

Scientific Name	Common Name	USFS	BLM	PGCN
Amsonia jonesii	Jones' bluestar		X	
Aquilegia chrysantha var. *rydbergii*	Rydberg's golden columbine	X	X	
Astragalus detritalis	debris milkvetch		X	
Astragalus duchesnensis	Duchesne milkvetch		X	
Astragalus leptaleus	park milkvetch	X		
Astragalus musiniensis	Ferron's milkvetch		X	
Astragalus proximus	Aztec milkvetch	X		
Astragalus ripleyi	Ripley's milkvetch	X	X	
Astragalus sesquiflorus	sandstone milkvetch		X	
Botrychium campestre	Iowa moonwort, prairie moonwort	X		
Botrychium lineare	Narrowleaf grape fern			Tier 2
Calochortus flexuosus	winding mariposa lily	X		
Carex diandra	lesser panicled sedge	X		
Chenopodium cycloides	sandhill goosefoot	X		
Cryptantha caespitosa	tufted cryptantha		X	
Cryptantha osterhoutii	Osterhout's cryptantha		X	
Cryptogramma stelleri	fragile rockbrake		X	
Cymopterus duchesnensis	Uinta Basin springparsley		X	
Cypripedium parviflorum	lesser yellow lady's slipper	X		
Descurainia torulosa	mountain tansymustard	X		
Drosera anglica	English sundew	X		
Drosera rotundifolia	roundleaf sundew	X		
Epipactis gigantea	stream orchid, giant helleborine	X		
Eriogonum acaule	singlestem buckwheat		X	
Eriogonum contortum	grand buckwheat		X	
Eriogonum ephedroides	ephedra buckwheat		X	
Eriogonum exilifolium	dropleaf buckwheat	X		
Eriogonum tumulosum	Woodside buckwheat		X	
Eriogonum viridulum	clay hill buckwheat		X	
Eriophorum chamissonis	Chamisso's cottongrass	X		

Scientific Name	Common Name	USFS	BLM	PGCN
Frasera paniculata	tufted frasera		X	
Gentianella tortuosa	Cathedral Bluff dwarf gentian		X	
Gilia (Aliciella) stenothyrsa	Uinta Basin gilia		X	
Ipomopsis aggregata ssp. *weberi*	scarlet gilia	X		Tier 2
Kobresia simpliciuscula	simple bog sedge	X		
Lomatium latilobum	Canyonlands biscuitroot		X	
Malaxis monophyllos var. *brachypoda*	white adder's-mouth orchid	X		
Neoparrya lithophila	Bill's neoparrya	X	X	
Parthenium ligulatum	Colorado feverfew		X	
Pediomelum aromaticum	aromatic Indian breadroot		X	
Penstemon harringtonii	Harrington's beardtongue	X	X	
Rubus arcticus ssp. *acaulis*	dwarf raspberry	X		
Salix myrtillifolia	blueberry willow	X		
Selaginella selaginoides	club spikemoss	X		
Sisyrinchium pallidum	pale blue-eyed grass		X	
Sphaeromeria capitata	rock tansy		X	
Sphagnum angustifolium	sphagnum	X		
Sphagnum balticum	Baltic sphagnum	X		
Townsendia strigosa	hairy Townsend daisy		X	
Trichophorum pumilum	Rolland's bulrush		X	
Triteleia grandiflora	largeflower triteleia	X		
Utricularia minor	lesser bladderwort	X		
Viola selkirkii	Selkirk's violet	X		

Future data development

Additional or improved data

For species which proved difficult to model satisfactorily, more detailed environmental data layers could help refine modeled habitat. For example, an expanded detailed rock outcrop layer was developed for be *Mimulus gemmiparus*, but also proved useful for two other species. More challenging to produce, a high-quality dataset depicting areas where groundwater comes to the surface (small seeps and springs) would be useful for *M. gemmiparus* as well as *Oenothera acutissima, Draba weberi, Erigeron kachinensis* and other species of hanging garden or alcove environments. Production of these and similar enhanced data layers was outside of the scope of this project.

Environmental inputs used in this project can be grouped into a few basic types:

<u>Substrate (geologic and soil factors)</u>

Substrate datasets are derived from ground-based mapping, and the original data is often quite old. There is essentially only a single soils dataset available, which has been revised and manipulated, but retains much of the coarseness of the original effort. Surface geology has somewhat better quality, but available data is often incomplete within a species range. Statewide maps digitized from original hand-drawn publications are the primary source of coverage at a regional or national scale. Many smaller areas (1:24000 to 1:500000 scale quads) have been mapped, but not all are available in digital format, and those that have been digitized are often not edge matched with adjoining quads.

For some future models that cover a limited range, it may be worthwhile to digitize particular geologic units from fine-scale mapping within a limited study area, as was done for the two federally listed Piceance Basin *Physaria* species (Decker et al. 2013). Or, as with the rock outcrop layer for *Mimulus gemmiparus*, and the CNHP-developed shale barrens layer, identify important factors which can be quickly mapped from aerial imagery over large areas.

New soils data is unlikely to be readily available in the foreseeable future and would be difficult to map. Modelers should keep an eye out for new interpretations of the older data that might prove useful.

<u>Climatic (temperature and precipitation patterns)</u>
Climate datasets are plentiful; the ways in which precipitation and temperature models can be partitioned into time slices ranging from minutes to millennia seem endless, and several different observational datasets have been used in climate modeling (e.g., tree-ring or midden data in addition to historical observations). It is important, however, to remember that full coverage datasets are interpolated from point observations, and elevation is a primary component of the process. Areas of complex topography, including much of western Colorado, have highly variable patterns of precipitation, making accurate interpolation difficult. Microclimatic patterns will remain nearly impossible to model over large areas for the foreseeable future.

<u>Topographic (elevation and related factors including slope, aspect, and other terrain descriptors)</u>
Topographic datasets are generally derived from the Digital Elevation Model and are consequently highly correlated with each other and with climate models. If a particular topographic pattern associated with a species distribution can be identified and quantified, additional datasets can be generated with comparative ease. Many researchers develop new algorithms to calculate topographic indices, and these are widely available online.

<u>Biophysical (vegetation and hydrology related)</u>
Landcover mapping of widespread vegetation types is typically done by classification of aerial or satellite imagery. Available statewide vegetation datasets have acceptable accuracy at landscape scales but are very often incorrect at the very fine scale level pertinent to small plant populations. Similarly, small-patch vegetation types (e.g., wetlands) are poorly mapped by satellite image classification, and are best represented by hand-mapped polygons on high resolution aerial imagery, or ground-based mapping. Categorical versions of landcover datasets are useful to identify association with particular vegetation types or patterns of occurrence on the landscape that can then be addressed with additional data development.

Most hydrologic data is developed and distributed through the National Hydrography Dataset and related products. The very large vector digital datasets can be challenging to manipulate, and errors in the data are common. Again, this data is acceptable at landscape scales but may not reflect actual conditions near rare plant populations in a useful way.

Disturbance (both natural and anthropogenic)

A single dataset incorporating many types of anthropogenic disturbance was used during this project, and individual disturbance types could be broken out of the index if needed. Natural disturbances such as fire, flooding, drought, and so forth are typically addressed through their effects on landcover or hydrologic patterns.

An ever-present challenge in modeling rare plant species is the relative size of the plant itself in comparison with the resolution and precision of environmental data. Our models were produced using a resolution of 30 x 30 m cells. For some species, the entire known population could fit in a single cell this size. For regional species-of-concern surveys and landscape-scale planning, this is an adequate resolution. However, further refinement of local habitat extent is frequently desired for locations where management decision will affect potential habitat. In such instances, our models can serve as a baseline for re-running a restricted area model using data at a finer resolution (e.g., 10 m cells) that will help resource managers narrow the area of interest. Of course, the production of 10 m resolution data does not mean that values at a particular point on the ground are more accurate than those of coarser data. Any model is only as good as its poorest input. Finer interpolation of values measured at selected points will never replace the expert botanist's search image in the real world but can suggest that areas never before considered as suitable might be worth a look.

In general, modelers should always consider how to represent micro-habitat factors that are important to individual species at a landscape scale. The distance-to-substrate is one such method. Discussions between the modeler and botanists or others familiar with the species are central to the model development process.

Refined models

Although many species were modeled with a single run, nearly all species would be better served with one or more additional model iterations; the initial run often suggests environmental factors that might be improved with additional data. Most rare plant species are little studied, so interpretation of multiple model results could also point to important, but previously unsuspected, factors controlling a species' distribution. For example, the modeled pattern of immediately adjacent but rarely overlapping local habitat between *Penstemon acaulis* var. *yampaensis* and *Penstemon scariosus* var. *cyanomontanus* in Moffat County (Figure 1) is an interesting ecological insight at a scale not often considered by botanists. Elevational separation between these two penstemon species means that *Penstemon scariosus* var. *cyanomontanus* experiences higher, generally cooler, and slightly wetter conditions in comparison with its near neighbor *P. yampaensis*, found in lower, drier habitat where temperature extremes are slightly more pronounced.

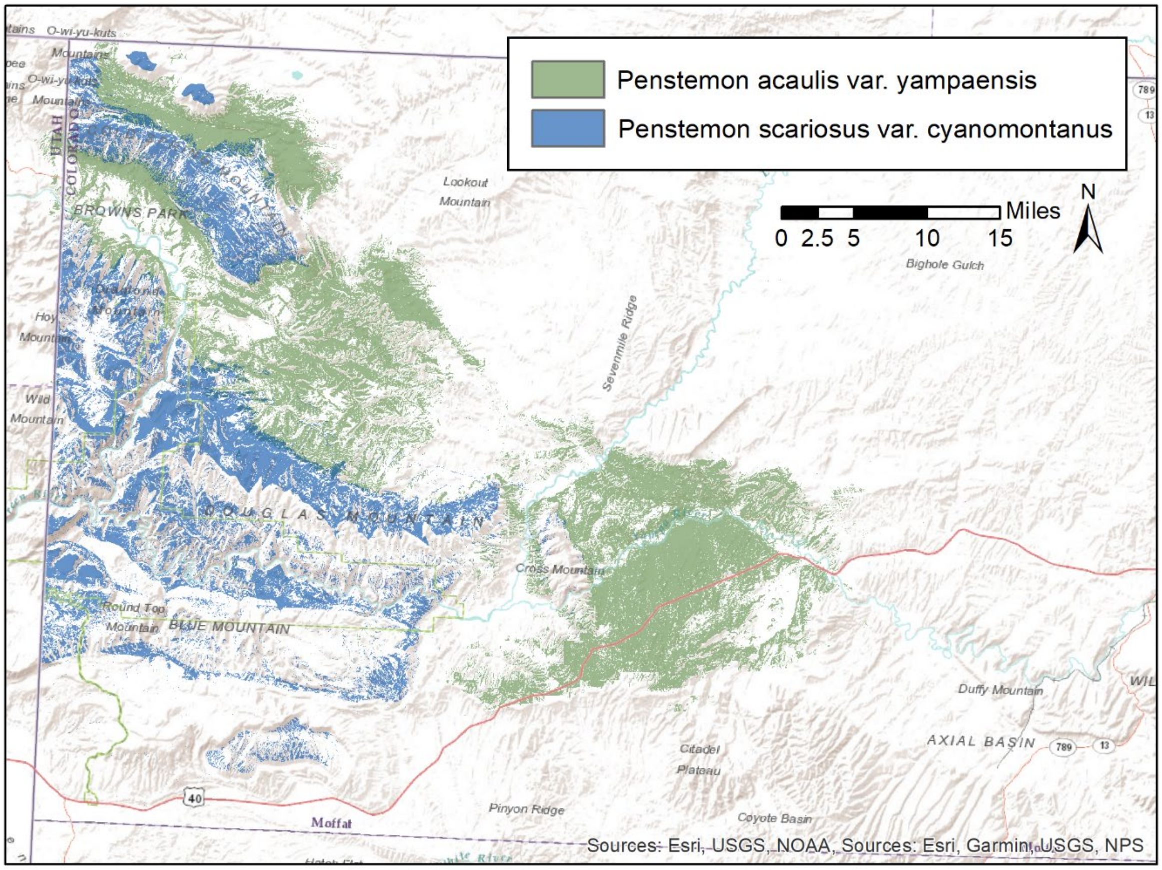

Figure 1. Modeled suitable habitat for two rare penstemon species in Moffat County, Colorado.

Future conditions

Climate change is an immediate concern in the management of rare plant species. Previous evaluations of Colorado's individual rare plant species vulnerability to changing climatic conditions have largely concluded that virtually all are highly vulnerable (CPW 2015, CNHP 2015). These vulnerability assessments were produced using generalized techniques that were not able to assess more detailed species-specific information. Conditions are changing, and it would be expedient to generate models of species distribution under future conditions. Maxent includes options for using projected future climate data that can be used to investigate the effects of changing climate on species distributions. A test of the procedure for making a projected model was completed for *Draba smithii* and used to evaluate five additional species (Appendix D).

Conclusion

During this project, CNHP staff developed an efficient and repeatable method for producing high quality predictive habitat models for rare plant species in Colorado. Many of the environmental input layers at the statewide level developed for this effort can be used in future modeling efforts. We now have a much better idea of what it takes to develop a collection of models, factors that might make modeling a single species difficult, and where cost-savings from production of multiple models can be realized. With the addition of these models into CODEX, the modeled distribution for almost all the plant species listed as Plants of Greatest Conservation Need will be represented in the statewide conservation data sharing platform, improving environmental review. The binary models, along with the full probability models provided to CNAP, will aid in the conservation of these species through their use in prioritizing and planning for conservation activities. Colorado's Plants of Greatest Conservation Need are critically under-studied and under-surveyed. This modeling work amplifies our knowledge, building upon decades of field work preserved in CNHP's database, and advances our understanding of species habitat.

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Appendix A: Data sources

Table 1. Data layers used as environmental input factors in Maxent and deductive models.

Raster names are as shown in model result outputs and metadata. Metadata entry gives the full layer name, source or sources, and a brief explanation of data processing and interpretation.

Raster name	Metadata entry
aprilmintemp (apr_mintemp)	**Environmental Input layer: April Minimum Temperature** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Minimum Temperature; April. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet Monthly Minimum Temperature in April for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
average_clay	**Environmental Input layer: Average % clay in soil** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Values are supplied for each of 11 standard soil levels, down to 2.5m. Values of 0 are really NoData. Non-zero values were averaged from layers 1 - 6 as a proxy for percent clay composition down to 60cm soil depth. Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.

Raster name	Metadata entry
average_sand	**Environmental Input layer: Average % sand in soil** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Values are supplied for each of 11 standard soil levels, down to 2.5m. Values of 0 are really NoData. Non-zero values were averaged from layers 1 - 6 as a proxy for percent sand composition down to 60cm soil depth. Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.
average_silt	**Environmental Input layer: Average % silt in soil** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Values are supplied for each of 11 standard soil levels, down to 2.5m. Values of 0 are really NoData. Non-zero values were averaged from layers 1 - 6 as a proxy for percent silt composition down to 60cm soil depth. Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.

Raster name	Metadata entry
avg_firstfrost	**Environmental Input layer: Average First Frost** Source citations: Thornton, PE, MM Thornton, BW Mayer, N Wilhelmi, Y Wei, RB Cook. 2012. Daymet: Daily surface weather on a 1km grid for North America,1980-2012. Acquired online (http://daymet.ornl.gov/) on 02/20/2014 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/doi:10.3334/ORNLDAAC/Daymet_V2 via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). Daymet Daily surface weather for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 2012, at 1 kilometer resolution. The earliest (Julian) day of each year during summer/fall on which the minimum temperature was <= 0°C was averaged. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
avg_lastfrost	**Environmental Input layer: Average Last Frost** Source citations: Thornton, PE, MM Thornton, BW Mayer, N Wilhelmi, Y Wei, RB Cook. 2012. Daymet: Daily surface weather on a 1km grid for North America,1980-2012. Acquired online (http://daymet.ornl.gov/) on 02/20/2014 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/doi:10.3334/ORNLDAAC/Daymet_V2 via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). Daymet Daily surface weather for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 2012, at 1 kilometer resolution. The latest (Julian) day of each year during spring/summer on which the minimum temperature was <= 0°C was averaged. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
co_ned30m	**Environmental Input layer: 30m Digital Elevation Model for Colorado** Source citations: U.S. Geological Survey. 2006. 30m Digital Elevation Model for Colorado. Raster digital data. http://seamless.usgs.gov/website/seamless/viewer.php Raster was re-projected, clipped to the Colorado state boundary extent with a minimum border of 8.5km, and used as base extent and snap reference for all environmental inputs.
colo_bps	**Environmental Input layer: Biophysical Settings (BPS)** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Biophysical Settings. LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov BPS represents the vegetation system that may have been dominant on the landscape prior to Euro-American settlement. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. This is a categorial dataset.

Raster name	Metadata entry
colo_evt	**Environmental Input layer: Existing Vegetation Type (EVT)** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type. LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov EVT represents the current distribution of the terrestrial ecological systems classification, developed by NatureServe for the western hemisphere, through 2016. A terrestrial ecological system is defined as a group of plant community types (associations) that tend to co-occur within landscapes with similar ecological processes, substrates, and/or environmental gradients. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. This is a categorial dataset.
colo_geol	**Environmental Input layer: Colorado Surface Geology** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Shapefile was converted to a 30m raster, using the CELL_CENTER cell assignment type, and snapped to be compatible with other environmental inputs. Formation name abbreviation was retained. This is a categorical dataset.
colo_nvc_veg	**Environmental Input layer: National Vegetation Classification (NVC)** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. National Vegetation Classification (NVC). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov National Vegetation Classification (NVC) represents the current distribution of vegetation groups within the U.S. National Vegetation Classification System ([version 2.0] http://usnvc.org/). Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. This is a categorial dataset.
colo_nvcveg_nodev	**Environmental Input layer: National Vegetation Classification (NVC), not including developed areas** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. National Vegetation Classification (NVC). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov National Vegetation Classification (NVC) represents the current distribution of vegetation groups within the U.S. National Vegetation Classification System ([version 2.0] http://usnvc.org/). Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells with attributes of Developed-Low Intensity, Developed-Medium Intensity, Developed-High Intensity, and Developed-Roads were reclassified to NoData. This is a categorial dataset.

Raster name	Metadata entry
dist_30plus_slope	**Environmental Input layer: Distance to slopes of more than 30 degrees** Source citation: Colorado Natural Heritage Program. 2021. Unpublished data using USGS 30m DEM. Raster digital data. Slope in degrees raster (derived from U.S. Geological Survey. 2006. 30m Digital Elevation Model for Colorado) was reclassified to identify cells greater than or equal to 30 degrees. Cells meeting this criteria were used as the input for generating a Euclidian Distance raster.
dist_badlands	**Environmental Input layer: Distance to Intermountain Basins Cliff Scree & Badland Sparse Vegetation** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. National Vegetation Classification (NVC). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov National Vegetation Classification (NVC) represents the current distribution of vegetation groups within the U.S. National Vegetation Classification System ([version 2.0] http://usnvc.org/). Original raster data was re-projected, then clipped and snapped to be compatible with other environmental inputs. This dataset was then reclassified to retain NVC_NAME = Inter-Mountain Basins Cliff Scree & Badland Sparse Vegetation, while all other types were classified as NoData. This raster was then used as the input feature source data for generating a Euclidian Distance raster.
dist_brownspk	**Environmental Input layer: Distance to Browns Park Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tbp were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_carlgrhngran	Environmental Input layer: **Distance to Carlile Shale, Greenhorn Limestone, and Graneros Shale** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Kcg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_copl_pj	**Environmental Input layer: Distance to Colorado Plateau Pinyon-Juniper Woodland vegetation type vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Distance to Colorado Plateau Pinyon-Juniper Woodland were used as the input feature source data for generating a Euclidian Distance raster.
dist_cutler	**Environmental Input layer: Distance to Cutler Formation** Source citation: Originator: Day, W.C., Green, G.N., Knepper, D.H., and Phillips, R.C. 2000. Spatial Geologic Data Model for the Gunnison, Grand Mesa, Uncompahgre National Forests Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and the Colorado Parts of the Grand Junction, Moab, and Cortez 1° x 2° Geologic Maps. Vector digital data, 1:250,000. U.S. Geological Survey. https://pubs.usgs.gov/of/1999/ofr-99-0427/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved. Polygons with NAME attribute Pc were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_dry_union	**Environmental Input layer: Distance to Dry Union Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Td were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_fault	**Environmental Input layer: Distance to fault** Source citation: Green, G.N., 1992, CO_Geology_Faults, The Digital Geologic Map of Colorado in ARC/INFO Format. Vector digital data, 1:500,000.U.S. Geological Survey Open-File Report 92-0507A-O, 9 p. and 14 magnetic disks; online at http://pubs.usgs.gov/of/1992/ofr-92-0507/. Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13 and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_fr_hogback_shales	**Environmental Input layer: Distance to shale and sandstone units forming the Front Range (Dakota) hogback north of Colo Spgs.** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Kc, Kpl, KJdr, KJds, P&if, @Pll, @&lf, @Pjs were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_fr_outcrops	**Environmental Input layer: Distance to Front Range Rock Outcrops, third (expanded) version (150m)** Source citation: Decker, Karin. 2021. Rock outcrops in the Front Range, but not including the mountain front hogbacks. Vector digital data. Approximately 1:15,000. Colorado Natural Heritage Program, unpublished data. Points marking the approximate location of (primarily granitic) rock outcrops were digitized using high (but variable) resolution World Imagery from Environmental Systems Research Institute (ESRI) and checked against Google Earth views as needed. The point shapefile was buffered to 150m radius, with overlaps dissolved, and used as the input feature source data for generating a Euclidian Distance raster.
dist_granitic_Yg	**Environmental Input layer: Distance to granitic rocks of 1,400-MY age group** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Yg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_greasewood	**Environmental Input layer: Distance to Inter-Mountain Basins Greasewood Flat ecological system** Source citation: US Geological Survey. 2011. GAP/LANDFIRE National Terrestrial Ecosystems. Raster digital data. http://gis1.usgs.gov/csas/gap/viewer/land_cover/Map.aspx Original raster data was re-projected, then clipped and snapped to be compatible with other environmental inputs. This dataset was then reclassified to retain Ecolsys_LU = Inter-Mountain Basins Greasewood Flat, while all other types were classified as NoData. This raster was then used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_greenriv	**Environmental Input layer: Distance to Green River Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_herb_riparian	**Environmental Input layer: Distance to combined WGP floodplain and herbaceous riparian** Source citations: US Geological Survey. 2011. GAP/LANDFIRE National Terrestrial Ecosystems. Raster digital data. http://gis1.usgs.gov/csas/gap/viewer/land_cover/Map.aspx Colorado Division of Wildlife. 2004. Colorado Vegetation Classification Project; Statewide Mosaic. Raster digital data. Original raster data was re-sampled, re-projected then clipped and snapped to be compatible with other environmental inputs. The GAP dataset was then reclassified to retain Ecolsys_LU = Western Great Plains Floodplain, while all other types were classified as NoData. The CDOW dataset was reclassified to retain CLASS_NM = Herbaceous Riparian. The two rasters were added, and all non-zero values retained. This raster was then used as the input feature source data for generating a Euclidian Distance raster.
dist_hermosa	**Environmental Input layer: Distance to Hermosa Formation** Source citation: Originator: Day, W.C., Green, G.N., Knepper, D.H., and Phillips, R.C. 2000. Spatial Geologic Data Model for the Gunnison, Grand Mesa, Uncompahgre National Forests Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and the Colorado Parts of the Grand Junction, Moab, and Cortez 1° x 2° Geologic Maps. Vector digital data, 1:250,000. U.S. Geological Survey. https://pubs.usgs.gov/of/1999/ofr-99-0427/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved. Polygons with NAME attribute Ph, Php, and Phu were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_ignmet_xy	**Environmental Input layer: Distance to Igneous and Metamorphic Rocks of Precambrian Age** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Xb, Xfh, Xq, Yp, Yg, Xg, Xm, or Yxg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_IMB_mont_SB	**Environmental Input layer: Distance to Inter-Mountain Basins Montane Sagebrush Steppe vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Inter-Mountain Basins Montane Sagebrush Steppe were used as the input feature source data for generating a Euclidian Distance raster.
dist_IMB_sage	**Environmental Input layer: Distance to Inter-Mountain Basins Big Sagebrush Shrubland vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Inter-Mountain Basins Big Sagebrush Shrubland were used as the input feature source data for generating a Euclidian Distance raster.
dist_kc_tc	**Environmental Input layer: Distance to the Colorado Group and Coalmont Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Kc and Tc were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_leadville	**Environmental Input layer: Distance to units containing Leadville (& Manitou) Limestone** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute M_, MD, MD_, MDO, and O_ were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_mancos	**Environmental Input layer: Distance to Mancos Shale** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Km were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_mancos_sixqd	**Environmental Input layer: Distance to Mancos Formation in six quad area** Source citation: Originator: Day, W.C., Green, G.N., Knepper, D.H., and Phillips, R.C. 2000. Spatial Geologic Data Model for the Gunnison, Grand Mesa, Uncompahgre National Forests Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and the Colorado Parts of the Grand Junction, Moab, and Cortez 1° x 2° Geologic Maps. Vector digital data, 1:250,000. U.S. Geological Survey. https://pubs.usgs.gov/of/1999/ofr-99-0427/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved. Polygons with NAME attribute Km were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_mixed_forest	**Environmental Input layer: Distance to mixed conifer forests vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland, Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland, or Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland were used as the input feature source data for generating a Euclidian Distance raster.
dist_morrison	**Environmental Input layer: Distance to Morrison Formation, all units** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute J@mc, Jm, Jmc, Jmce, Jme, Jmj, Jmr, Jmre, Jms, Jmse, Jmw, or Jmwe were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_niobrara	**Environmental Input layer: Distance to Niobrara Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Kn were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_nlcd_shrub	**Environmental Input layer: Distance to Shrub/Scrub and Woody Wetlands landcover type** Source citation: National Land Cover Database 2011 (NLCD) 2011. Multi-Resolution Land Characteristics Consortium (MRLC) dataset. https://data.nal.usda.gov/dataset/national-land-cover-database-2011-nlcd-2011 Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as NLCD_2011 = Shrub/Scrub or Woody Wetlands were used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_nvcfm06c02	**Environmental Input layer: Distance to Semi-Desert Nonvascular & Sparse Vascular Vegetation NVC formation** Source citation: US Geological Survey. 2011. GAP/LANDFIRE National Terrestrial Ecosystems. Raster digital data. http://gis1.usgs.gov/csas/gap/viewer/land_cover/Map.aspx Original raster data was re-projected, then clipped and snapped to be compatible with other environmental inputs. This dataset was then reclassified to retain Formation = Semi-Desert Nonvascular & Sparse Vascular Vegetation (06.C.02), while all other types were classified as NoData. This raster was then used as the input feature source data for generating a Euclidian Distance raster.
dist_parachute	**Environmental Input layer: Distance to Parachute Creek member of Green River Formation** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tgp were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_pb_glac	**Environmental Input layer: Distance to Glacial drift of Pinedale and Bull Lake age** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Qd were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_pacman_soils	**Environmental Input layer: Distance to soils with Packera mancosana occurrences** Source citations: NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Soil units with SSURGO attributes MUKEY 507319, 507229, 502153, 501969 were selected and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_pem	**Environmental Input layer: Distance to Palustrine Emergent wetland types** Source citation: U.S. Fish and Wildlife Service. 2016. CONUS_wet_poly_West; CO_Wetlands, National Wetlands Inventory - Version 2. Vector digital data, 1:12,000. https://www.fws.gov/wetlands/Data/Data-Download.html Polygons with attributes beginning with PEM were selected (query: Like PEM%) and used as the input feature source data for generating a Euclidian Distance raster.
dist_qae	**Environmental Input layer: Distance to Quaternary alluvium and eolian deposits** Source citation: Originator: Day, W.C., Green, G.N., Knepper, D.H., and Phillips, R.C. 2000. Spatial Geologic Data Model for the Gunnison, Grand Mesa, Uncompahgre National Forests Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and the Colorado Parts of the Grand Junction, Moab, and Cortez 1° x 2° Geologic Maps. Vector digital data, 1:250,000. U.S. Geological Survey. https://pubs.usgs.gov/of/1999/ofr-99-0427/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved. Polygons with NAME attribute Qae were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_raton	**Environmental Input layer: Distance to Raton Formation** Source citations: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Green, G.N., and Jones, G.E. 1997. The Digital Geologic Map of New Mexico in ARC/INFO Format. Vector digital data, 1:500,000. U.S. Geological Survey. http://pubs.usgs.gov/of/2005/1351/data/NMgeol_dd.zip Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tkr were selected, exported, merged, and used as the input feature source data for generating a Euclidian Distance raster.
dist_RM_aspen	**Environmental Input layer: Rocky Mountain Aspen Forest and Woodland vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Rocky Mountain Aspen Forest and Woodland were used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_RM_oakshrub	**Environmental Input layer: Distance to Rocky Mountain Gambel Oak-Mixed Montane Shrubland vegetation type** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Rocky Mountain Gambel Oak-Mixed Montane Shrubland were used as the input feature source data for generating a Euclidian Distance raster.
dist_rock_outcrops2	**Environmental Input layer: Distance to Rock Outcrops, second version (180m)** Source citation: Decker, Karin. 2021. Rock outcrops in general range of Mimulus gemmiparus. Vector digital data. Approximately 1:15,000. Colorado Natural Heritage Program, unpublished data. Points marking the approximate location of granitic rock outcrops were digitized using high (but variable) resolution World Imagery from Environmental Systems Research Institute (ESRI) and checked against Google Earth views as needed. The point shapefile was converted to a 180m raster and used as the input feature source data for generating a Euclidian Distance raster.
dist_saltbush	**Environmental Input layer: Distance to Intermountain Shadscale-Saltbush Scrub or Intermountain Dwarf Saltbush-Sagebrush Scrub** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. National Vegetation Classification (NVC). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov National Vegetation Classification (NVC) represents the current distribution of vegetation groups within the U.S. National Vegetation Classification System ([version 2.0] http://usnvc.org/). Original raster data was re-projected, then clipped and snapped to be compatible with other environmental inputs. This dataset was then reclassified to retain NVC_NAME = Intermountain Shadscale-Saltbush Scrub or Intermountain Dwarf Saltbush-Sagebrush Scrub, while all other types were classified as NoData. This raster was then used as the input feature source data for generating a Euclidian Distance raster.
dist_sandstone	**Environmental Input layer: Distance to sandstone lithology** Source citation: Horton, J.D., San Juan, C.A., and Stoeser, D.B, 2017, The State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States (ver. 1.1, August 2017): U.S. Geological Survey Data Series 1052, 46 p., https://doi.org/10.3133/ds1052. The State Geologic Map Compilation (SGMC) Geodatabase of the Conterminous United States (ver. 1.1, August 2017) - SGMC_Geology. Colorado polygons are based on Tweto 1979, with additional classification fields added. Original downloaded polygon data was reprojected to UTM NAD83, zone 13, and clipped to the project extent. Polygons with MAJOR1 attribute = Sandstone were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_saturated	**Environmental Input layer: Distance to saturated wetlands** Source citation: U.S. Fish and Wildlife Service. 2016. CONUS_wet_poly_West; CO_Wetlands, National Wetlands Inventory - Version 2. Vector digital data, 1:12,000. https://www.fws.gov/wetlands/Data/Data-Download.html Polygons with attributes Palustrine Emergent Saturated (PEMB) and Palustrine Scrub-Shrub Saturated (PSSB) were selected and used as the input feature source data for generating a Euclidian Distance raster.
dist_sg_bps	**Environmental Input layer: Distance to Western Great Plains Shortgrass Prairie BPS** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Biophysical Settings. LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov BPS represents the vegetation system that may have been dominant on the landscape prior to Euro-American settlement. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as BPS Name = Western Great Plains Shortgrass Prairie were used as the input feature source data for generating a Euclidian Distance raster.
dist_shale_barren	**Environmental Input layer: Distance to Shale Barrens** Source citation: Decker, Karin. 2021. Shale Barrens of Southeastern Colorado. Vector digital data, 1:12,000. Colorado Natural Heritage Program, unpublished data. Polygons were digitized using high (but variable) resolution World Imagery from Environmental Systems Research Institute (ESRI) and checked against 1 x 2-degree geology quad maps (georeferenced tif images). Shale barren polygons were hand-drawn in ArcGIS 10.4 (ESRI 2015) by the photo-interpreter based on the best estimation of sparsely vegetated boundaries and used as the input feature source data for generating a Euclidian Distance raster.
dist_shortgrass	**Environmental Input layer: Distance to Great Plains Shortgrass Prairie** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. National Vegetation Classification (NVC). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov National Vegetation Classification (NVC) represents the current distribution of vegetation groups within the U.S. National Vegetation Classification System ([version 2.0] http://usnvc.org/). Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as NVC Name = Great Plains Shortgrass Prairie were used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_springs	**Environmental Input layer: Distance to springs** Source citation: Ledbetter, Jeri D., MGIS, Lawrence E. Stevens, PhD, Abraham Springer, PhD, and Benjamin Brandt, MGIS. 2014. Springs Inventory Database. Online Database. Springs and Springs-Dependent Species Database. Vers. 1.0. Springs Stewardship Institute, springsdata.org. Original kml data was converted to ArcGIS geodatabase and points were projected to UTM_NAD83_Zone13. Points were used as the input feature source data for generating a Euclidian Distance raster.
dist_srm_pj	**Environmental Input layer: Distance to Southern Rocky Mountain Pinyon-Juniper Woodland** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Southern Rocky Mountain Pinyon-Juniper Woodland were used as the input feature source data for generating a Euclidian Distance raster.
dist_tiptwilk	**Environmental Input layer: Distance to Tipton Tongue of Green River Formation (includes Wilkins Peak member)** Source citations: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tgt were selected, exported, merged, and used as the input feature source data for generating a Euclidian Distance raster.
dist_td_kjdr	**Environmental Input layer: Distance to Dry Union Formation (Td) and part of Dakota/Purgatoire/Morrison/Ralston Creek formations (Kjdr)** Source citations: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Td and KJdr were selected, exported, merged, and used as the input feature source data for generating a Euclidian Distance raster.

Raster name	Metadata entry
dist_troublesome	**Environmental Input layer: Distance to Troublesome Formation** Source citations: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Tt were selected, exported, merged, and used as the input feature source data for generating a Euclidian Distance raster.
dist_tuff2	**Environmental Input layer: Distance to selected Tertiary volcanic tuffs** Source citation: Originator: Day, W.C., Green, G.N., Knepper, D.H., and Phillips, R.C. 2000. Spatial Geologic Data Model for the Gunnison, Grand Mesa, Uncompahgre National Forests Mineral Resource Assessment Area, Southwestern Colorado and Digital Data for the Leadville, Montrose, Durango, and the Colorado Parts of the Grand Junction, Moab, and Cortez 1° x 2° Geologic Maps. Vector digital data, 1:250,000. U.S. Geological Survey. https://pubs.usgs.gov/of/1999/ofr-99-0427/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved. Polygons with NAME attribute Tbm, Tev, Tfg, Theb, Tq, and Tur were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_tvolc_sel	**Environmental Input layer: Distance to selected Tertiary volcanic formations in south-central Colorado** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Taf, Tbb, Tiql, Tpl were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_tuff_combo	**Environmental Input layer: Minimum distance to either selected Tertiary volcanic tuffs or selected Tertiary volcanic formations in south-central Colorado** The two above inputs (dist_tuff2 and dist_tvolc_sel) were combined by taking the minimum distance value.

Raster name	Metadata entry
dist_wasatch_all	**Environmental Input layer: Distance to Wasatch Formation units in northwest Colorado** Source citation: Tweto, Ogden. 1979. Geologic map of Colorado. Vector digital data, 1:500,000. U.S. Geological Survey. ftp://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-92-0507/ Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Polygons with NAME attribute Twn, Twc, Tw, Two were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster.
dist_water	**Environmental Input layer: Distance to water** Source citation: U.S. Geological Survey. 2010. High Resolution National Hydrography Dataset. File-based geodatabase, vector digital data 12,000 - 24,000. http://nhd.usgs.gov/index.html USGS High Resolution National Hydrography Dataset (NHD) for Colorado was queried for permanent water (polygon, line, and point). Results were converted to 30m raster and a distance raster calculated. NHDFlowline: ("FType" = 460 OR "FType" = 558) AND (("FCode" = 46000 OR "FCode" = 46006) OR ("GNIS_Name" IS NOT Null)) NHDWaterbody: "FCode" = 39000 OR "FCode" = 39004 OR "FCode" = 39009 OR "FCode" = 39010 OR "FCode" = 39011 OR "FCode" = 39012 OR "FCode" = 43600 OR "FCode" = 43617 OR "FCode" = 43618 OR "FCode" = 43621 NHDPoint: "FType" = 458
dry_days_fall	**Environmental Input layer: Average number of days during fall (Sep-Oct-Nov) with precipitation <=5mm** Source citations: Thornton, PE, MM Thornton, BW Mayer, N Wilhelmi, Y Wei, RB Cook. 2012. Daymet: Daily surface weather on a 1km grid for North America,1980-2012. Acquired online (http://daymet.ornl.gov/) on 02/20/2014 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/doi:10.3334/ORNLDAAC/Daymet_V2 via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). Daymet Daily surface weather for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 2012, at 1 kilometer resolution. The number of days during the period covering September, October, and November where precipitation was less than or equal to 5mm was averaged. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental input.

Raster name	Metadata entry
eastness	**Environmental Input layer: Eastness (aspect)** Source citation: Colorado Natural Heritage Program. 2011. Unpublished data using USGS 30m DEM. Raster digital data. The Elevation raster was used to create an Aspect raster, which was then used to create two separate rasters representing northness and eastness. northness = cos(aspect) eastness = sin(aspect) Values range from -1 to +1. Northness will take values close to 1 if the aspect is generally northward, close to -1 if the aspect is southward, and close to 0 if the aspect is either east or west. Eastness behaves similarly, except that values close to 1 represent east-facing slopes. For more information: http://ordination.okstate.edu/envvar.htm
frostday_yr	**Environmental Input layer: Number of days per year with minimum temperature at or below freezing** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Frost days annual. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet annual number of frost days for Colorado. Units are days. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
gapveg	**Environmental Input layer: Distance to Semi-Desert Nonvascular & Sparse Vascular Vegetation NVC formation** Source citation: US Geological Survey. 2011. GAP/LANDFIRE National Terrestrial Ecosystems. Raster digital data. http://gis1.usgs.gov/csas/gap/viewer/land_cover/Map.aspx Categorical dataset with values representing ecological system types.
geol_sgmc_maj1	**Environmental Input layer: First-listed major lithology of geologic unit** Source citation: Horton, J.D., San Juan, C.A., and Stoeser, D.B, 2017, The State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States (ver. 1.1, August 2017): U.S. Geological Survey Data Series 1052, 46 p., https://doi.org/10.3133/ds1052. The State Geologic Map Compilation (SGMC) Geodatabase of the Conterminous United States (ver. 1.1, August 2017) - SGMC_Geology. Original downloaded data was reprojected to UTM NAD83, zone 13, and clipped to the project extend, then converted to 30 m raster using the "MAJOR1" field as grid value, snapped to be compatible with other environmental inputs. Colorado polygons are based on Tweto 1979, with additional classification fields added.

Raster name	Metadata entry
jan_mintemp	**Environmental Input layer: January Minimum Temperature** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Minimum Temperature; April. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet Monthly Minimum Temperature in January for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
LDI	**Environmental Input layer: Landscape Disturbance Index (LDI)** Source citation: Colorado Natural Heritage Program. 2020. Landscape Disturbance Index Layer for Colorado. Raster digital data. Colorado Natural Heritage Program, Fort Collins, CO This represents 8 individually modeled anthropogenic impacts that were then combined into a single layer. Impacts represented are: * Agriculture * Urban Development * Oil and Gas Development * Surface Mining * Roads and Trails * Wind turbines * Solar installations Each individual layer has its own relevant weight and decay function type (see Supplemental Information). The individual impact layers are then additively combined to produce an overall disturbance layer. The weights are scaled to produce a final range where scores => 500 are High impact.
marchmintemp	**Environmental Input layer: March minimum temperature** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Minimum Temperature; May. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet Monthly Minimum Temperature in March for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.

Raster name	Metadata entry
max_summertemp	**Environmental Input layer: Maximum summer temperature** Source citations: Thornton, PE, MM Thornton, BW Mayer, N Wilhelmi, Y Wei, RB Cook. 2012. Daymet: Daily surface weather on a 1km grid for North America,1980-2012. Acquired online (http://daymet.ornl.gov/) on 02/20/2014 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/doi:10.3334/ORNLDAAC/Daymet_V2 via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). Daymet Daily surface weather for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 2012, at 1 kilometer resolution. The highest temperature during the period including June, July, and August for each year was averaged. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
maymintemp (may_mintemp)	**Environmental Input layer: May minimum temperature** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Minimum Temperature; May. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet Monthly Minimum Temperature in May for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
min_wintertemp	**Environmental Input layer: Minimum winter temperature** Source citations: Thornton, PE, MM Thornton, BW Mayer, N Wilhelmi, Y Wei, RB Cook. 2012. Daymet: Daily surface weather on a 1km grid for North America,1980-2012. Acquired online (http://daymet.ornl.gov/) on 02/20/2014 from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://dx.doi.org/doi:10.3334/ORNLDAAC/Daymet_V2 via the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). Daymet Daily surface weather for Colorado. Units are degrees Celsius. Daymet represents an average from 1980 - 2012, at 1 kilometer resolution. The lowest temperature during the period including December, January, and February for each year was averaged. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.

Raster name	Metadata entry
northness	**Environmental Input layer: Northness (aspect)** Source citation: Colorado Natural Heritage Program. 2011. Unpublished data using USGS 30m DEM. Raster digital data. The Elevation raster was used to create an Aspect raster, which was then used to create two separate rasters representing northness and eastness. northness = cos(aspect) eastness = sin(aspect) Values range from -1 to +1. Northness will take values close to 1 if the aspect is generally northward, close to -1 if the aspect is southward, and close to 0 if the aspect is either east or west. Eastness behaves similarly, except that values close to 1 represent east-facing slopes. For more information: http://ordination.okstate.edu/envvar.htm
pct_copl_pj	**Environmental Input layer: Percent of Colorado Plateau Pinyon-Juniper Woodland vegetation type within 150m** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Colorado Plateau Pinyon-Juniper Woodland were used as the input feature source data for a moving window analysis (focal statisticsm SUM) to count the number of 30m cells within a circular distance of 150m were of this vegetation type. The sum was divided by the number of cells within the window (81) to obtain a percentage grid.
pct_imb_mont_sage	**Environmental Input layer: Percent of Inter-Mountain Basins Montane Sagebrush Steppe vegetation type within 150m** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Inter-Mountain Basins Montane Sagebrush Steppe were used as the input feature source data for a moving window analysis (focal statisticsm SUM) to count the number of 30m cells within a circular distance of 150m were of this vegetation type. The sum was divided by the number of cells within the window (81) to obtain a percentage grid.

Raster name	Metadata entry
pct_IMB_sage	**Environmental Input layer: Percent of Inter-Mountain Basins Big Sagebrush Shrubland vegetation type within 150m** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Inter-Mountain Basins Big Sagebrush Shrubland were used as the input feature source data for a moving window analysis (focal statisticsm SUM) to count the number of 30m cells within a circular distance of 150m were of this vegetation type. The sum was divided by the number of cells within the window (81) to obtain a percentage grid.
pct_mixed_forest	**Environmental Input layer: Percent of mixed conifer forest vegetation type within 150m** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland, Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland, or Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland were used as the input feature source data for a moving window analysis (focal statisticsm SUM) to count the number of 30m cells within a circular distance of 150m were of this vegetation type. The sum was divided by the number of cells within the window (81) to obtain a percentage grid.
pct_RM_aspen	**Environmental Input layer: Rocky Mountain Aspen Forest and Woodland vegetation type within 150m** Source citation: LANDFIRE, Earth Resources Observation and Science Center (EROS), U.S. Geological Survey. 2020. Existing Vegetation Type (EVT). LANDFIRE Remap 2016, CONUS. Raster digital data. www.landfire.gov Existing Vegetation Type represents complexes of plant communities representing NatureServe's terrestrial Ecological Systems classification. Data for continental US was downloaded, reprojected, clipped to reference extent, and snapped to be compatible with other environmental inputs. Cells attributed as EVT_Name = Rocky Mountain Aspen Forest and Woodland were used as the input feature source data for a moving window analysis (focal statisticsm SUM) to count the number of 30m cells within a circular distance of 150m were of this vegetation type. The sum was divided by the number of cells within the window (81) to obtain a percentage grid.

Raster name	Metadata entry
ppt_s1	**Environmental Input layer: Winter Precipitation** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Total Precipitation. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet total precipitation (centimeters) for December, January, & February for Colorado were totaled to represent average winter precipitation. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
ppt_s2	**Environmental Input layer: Spring Precipitation** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Total Precipitation. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet total precipitation (centimeters) for March, April, & May for Colorado were totaled to represent average winter precipitation. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
ppt_s3	**Environmental Input layer: Summer Precipitation** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Total Precipitation. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet total precipitation (centimeters) for June, July, & August for Colorado were totaled to represent average winter precipitation. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
ppt_s4	**Environmental Input layer: Fall Precipitation** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Total Precipitation. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet total precipitation (centimeters) for September, October, & November for Colorado were totaled to represent average winter precipitation. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.

Raster name	Metadata entry
ppt_yrly	**Environmental Input layer: Total Annual Precipitation** Source citation: Peter E. Thornton, National Center for Atmospheric Research. 2002. Daymet: Climatological Summaries for the Conterminous United States, 1980-1997. Monthly Total Precipitation. Raster digital data, 1 km resolution. http:\\www.daymet.org Daymet total precipitation (centimeters) for all months for Colorado were totaled to represent average annual precipitation. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was down sampled to 30m, re-projected and snapped to be compatible with other environmental inputs.
relief	**Environmental Input Layer: Local Relief** Source citation: Derived from U.S. Geological Survey. 2006. 30m Digital Elevation Model for Colorado. Raster digital data. A measure of surface roughness. Created from 30m DEM for Colorado by using FocalRange command: FOCALRANGE(coelev30, Circle, 16, DATA)
riparian_dist	**Environmental Input Layer: Distance to wetland/riparian area** Source citations: United States Forest Service. 2006. LANDFIRE Current Vegetation for Colorado. Raster digital data, 30m. http://landfire.cr.usgs.gov/viewer/viewer.html U.S. Geological Survey. 2010. High Resolution National Hydrography Dataset. File-based geodatabase, vector digital data 12,000 - 24,000. http://nhd.usgs.gov/index.html There is not a complete statewide dataset for wetland or riparian areas. Using available partial datasets (NWI, CDOW riparian) may just bias to mapped areas. Decided to try using NHD & LandFire as described below, but this is known to be an imperfect solution. USGS High Resolution National Hydrography Dataset (NHD) for Colorado and USFS LandFire Current Vegetation were queried for wetland and riparian areas. Results were converted to 30m raster, and a distance raster calculated. NHDWaterbody: "FType" = 361 OR "FType" = 466 OR "FCode" = 39001 OR "FCode" = 39005 OR "FCode" = 39006 LandFire Current Veg: "SYSTMGRPNA" LIKE '%Riparian%' OR "SYSTMGRPNA" LIKE '%Wet%
shortgrass_mod2	**Environmental Input layer: Boosted Regression Tree model of Shortgrass Prairie in Colorado.** Source citation: Fink, Michelle. 2014. Final model of Shortgrass Prairie for use in Colorado Wildlife Action Plan Enhancement: Climate Change Vulnerability Assessment. Colorado Natural Heritage Program, unpublished 30m raster digital data. This a distribution model produced using the Boosted Regression Tree method, with values representing an approximate probability of shortgrass prairie occurrence at each cell. Original raster was resampled and snapped to the reference extent.
slope_deg	**Environmental Input layer: Slope (degrees)** Source citation: Colorado Natural Heritage Program. 2011. Unpublished data using USGS 30m DEM. Raster digital data.

Raster name	Metadata entry
snow_persistence	**Environmental Input layer: Snow Persistence Index** Source citation: Hammond, J. C., F. A. Saavedra, S. K. Kampf (2017). MODIS MOD10A2 derived snow persistence and no data index for the western U.S., HydroShare, https://doi.org/10.4211/hs.1c62269aa802467688d25540caf2467e Raster digital data. Images from each year were reprojected, clipped to the reference extent, and averaged. Values are the percent of year where snow is on the ground.
soil_pct_org	**Environmental Input layer: Average % organic matter in soil** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Values are supplied for each of 11 standard soil levels, down to 2.5m. Values of 0 are really NoData. Non-zero values were averaged from layers 1 - 6 as a proxy for percent clay composition down to 60cm soil depth. Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.

Raster name	Metadata entry
soil_ph	**Environmental Input layer: Soil pH** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Soil pH values are supplied for each of 11 standard soil levels, down to 2.5m. Values of 0 are really NoData. Non-zero pH values were averaged from layers 1 - 6 for this project. Note - a mathematical mean is not technically the appropriate way to lump multiple pH values, but we are restricted by how the data were originally recorded. Surface pH alone was not seen as sufficient information, so we averaged the values of the first 6 layers as a proxy for actual total pH down to 60cm soil depth. Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.
soil_type	**Environmental Input layer: Soil type (Map Unit)** Source citations: NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). In deductive models, map units were selected as appropriate, merged, and converted to 30m raster as required.

Raster name	Metadata entry
ssurgo_depth_cm	**Environmental Input layer: Soil depth** Source citations: Miller, D.A. and R.A. White. 1998. A Conterminous United States Multi-Layer Soil Characteristics Data Set for Regional Climate and Hydrology Modeling. Data derived from Natural Resources Conservation Service (NRCS) State Soil Geographic database (STATSGO). Tabular digital data. http://www.essc.psu.edu/soil_info/index.cgi?soil_data&conus NRCS. 1994. State Soil Geographic (STATSGO) data base for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Database for Colorado. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release). Depth to bedrock (field ROCKDEPM) is a single value per soil polygon. Units are centimeters. Note that a value of 152 really means >= 152 cm and a value of 0 is really NoData (occurs on Water polygons only). Due to the coarse scale of STATSGO (NRCS 1994) and the incomplete nature of SSURGO (NRCS 2012) in Colorado, all soil inputs used in CODEX PGCN models were based on the combined STATSGO-SSURGO version. Tabular data was joined to the combined STATSGO-SSURGO vector digital dataset for Colorado and exported as a 30m raster.
ter_rough_index	**Environmental Input layer: Terrain Ruggedness Index** Source citation: Colorado Natural Heritage Program. 2021. Unpublished data using USGS 30m DEM. Raster digital data. The Elevation raster was used to create an index of terrain ruggedness reflecting the difference in elevation between neighboring cells. R script provided by Michelle Fink, CNHP.

Table 2. Climate Projection Specific Data Sources

These inputs were only used for the models discussed in Appendix D.

Raster name	Metadata entry
s1_pr_cnrm_cm5_tif	**Environmental Input layer: Winter total precipitation under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The total modeled precipitation, in mm, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s1_pr_hadgem2_es_tif	**Environmental Input layer: Winter total precipitation under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The total modeled precipitation, in mm, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s1_tmean_cnrm_cm5	**Environmental Input layer: Winter mean temperature under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The mean of monthly minimum and maximum temperatures, in degrees Celsius, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s1_tmean_hadgem2_es	**Environmental Input layer: Winter mean temperature under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The mean of monthly minimum and maximum temperatures, in degrees Celsius, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s1_tmin_cnrm_cm5	**Environmental Input layer: Winter minimum temperature under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The minimum temperature, in degrees Celsius, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.
s1_tmin_hadgem2_es	**Environmental Input layer: Winter minimum temperature under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The minimum temperature, in degrees Celsius, for the months January, February, and December of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s2_pr_cnrm_cm5_tif	**Environmental Input layer: Spring total precipitation under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The total modeled precipitation, in mm, for the months March, April, and May of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s2_pr_hadgem2_es_tif	**Environmental Input layer: Spring total precipitation under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The total modeled precipitation, in mm, for the months March, April, and May of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.
s2_tmin_cnrm_cm5_tif	**Environmental Input layer: Spring minimum temperature under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The minimum temperature, in degrees Celsius, for the months March, April, and May of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s2_tmin_hadgem2_es_tif	**Environmental Input layer: Spring minimum temperature under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The minimum temperature, in degrees Celsius, for the months March, April, and May of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s3_pr_cnrm_cm5_tif	**Environmental Input layer: Summer total precipitation under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The total modeled precipitation, in mm, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.
s3_pr_hadgem2_es_tif	**Environmental Input layer: Summer total precipitation under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The total modeled precipitation, in mm, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s3_tmax_cnrm_cm5_tif	**Environmental Input layer: Summer maximum temperature under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The maximum temperature, in degrees Celsius, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s3_tmax_hadgem2_es_tif	**Environmental Input layer: Summer maximum temperature under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The maximum temperature, in degrees Celsius, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.
s3_tmin_cnrm_cm5_tif	**Environmental Input layer: Summer minimum temperature under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The minimum temperature, in degrees Celsius, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s3_tmin_hadgem2_es_tif	**Environmental Input layer: Summer minimum temperature under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The minimum temperature, in degrees Celsius, for the months June, July, and August of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
s4_pr_cnrm_cm5_tif	**Environmental Input layer: Autumn total precipitation under the 'Warm and Wet' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- The total modeled precipitation, in mm, for the months September, October, and November of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.
s4_pr_hadgem2_es_tif	**Environmental Input layer: Autumn total precipitation under the 'Hot and Dry' climate scenario** Source citations: Fink, M., K. Decker, R. Rondeau, and L. Grunau. 2019. Adaptation in the face of environmental change: supporting information for Colorado BLM. Colorado Natural Heritage Program, Colorado State University, Fort Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O'Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- The total modeled precipitation, in mm, for the months September, October, and November of the same calendar year. The 'current' dataset is a 30 year average centering on the year 1985 and the future projected is a 30 year average centering on the year 2050. The two datasets have the same name due to model projection requirements. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. Monthly, downscaled data for each year was averaged, re-projected, clipped, and snapped to the same cell-size as all other model inputs.

Raster name	Metadata entry
wyo_ww	**Environmental Input layer: Habitat suitability model for *Artemisia tridentata ssp. wyomingensis* under the 'Warm and Wet' climate scenario** Source citations: Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford, and T. Schulz. 2017. Sagebrush Landscape: Upper Gunnison River Basin, Colorado: Social-Ecological Climate Resilience Project. North Central Climate Science Center, Ft. Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave, M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin. 2011. The CNRM-CM5.1 global climate model: description and basic evaluation, Climate Dynamics, vol. 40(9): 2091-2121. DOI:10.1007/s00382-011-1259-y --- This model was created for Rondeau et al. (2017) using the same climate datasets as for this project and is used here as a climate-projected proxy for the pct_IMB_mont_sage input of the original species model. The 'Warm and Wet' climate scenario is based on the CNRM-CM5.1 global climate model under RCP 4.5. The *wyomingensis* models were spatially restricted to non-zero values of the pct_IMB_mont_sage dataset and snapped to the same cell-size as all other model inputs. The 'current' and 'future' datasets have the same name due to model projection requirements.

Raster name	Metadata entry
wyo_hd	**Environmental Input layer: Habitat suitability model for *Artemisia tridentata ssp. wyomingensis* under the 'Hot and Dry' climate scenario** Source citations: Rondeau, R., B. Neely, M. Bidwell, I. Rangwala, L. Yung, K. Clifford, and T. Schulz. 2017. Sagebrush Landscape: Upper Gunnison River Basin, Colorado: Social-Ecological Climate Resilience Project. North Central Climate Science Center, Ft. Collins, Colorado. Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis and R. Nemani. 2013. Downscaled Climate projections suitable for resource management, Eos Trans. AGU, 94(37), 321. Data available at https://www.nasa.gov/nex (Accessed 02/07/2017). Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., Hughes, J., Jones, C. D., Joshi, M., Liddicoat, S., Martin, G., O’Connor, F., Rae, J., Senior, C., Sitch, S., Totterdell, I., Wiltshire, A., and Woodward, S. 2011. Development and evaluation of an Earth-system model HadGEM2, Geosci. Model Dev. Discuss., 4, 997–1062, doi:10.5194/gmdd-4-997-2011. --- This model was created for Rondeau et al. (2017) using the same climate datasets as for this project and is used here as a climate-projected proxy for the pct_IMB_mont_sage input of the original species model. The 'Hot and Dry' climate scenario is based on the HADGEM2-ES global climate model under RCP 8.5. The *wyomingensis* models were spatially restricted to non-zero values of the pct_IMB_mont_sage dataset and snapped to the same cell-size as all other model inputs. The 'current' and 'future' datasets have the same name due to model projection requirements.

Appendix B: Basic modeling methods

Element Occurrence or location processing

- For each species use a single-species shapefile output from BIOTICS (or other source)
- Use the Multipart to Singlepart tool to separate all polygons (this interim step not kept)
- Use the Feature to Point tool to convert the polygons to centroid points (check the "Inside" box), and name the shapefile something like: sppname_pts.shp
- Use the Add XY Coordinates to generate location data for each point (don't use X Y fields already there from the polygon shapefile, since they belong to a single EO).
- Open the sppname_pts.dbf file in Excel
- Check for low-precision/very old EO records – these may need to be left out of the modeling dataset
- Copy SNAME and POINT_X, POINT_Y info into a three-column multispecies .csv file, omitting old, low-precision points, although you might keep these if consistent with range of other points. Generally anything older than 1970 could be left out. The csv spreadsheet should look something like the example below, with as many rows for each species as there are good locations. Species names can be as they would normally appear, including ssp. or var. Make sure your XY coordinates are all in the same spatial reference as your environmental grids (e.g., NAD83 Zone 13)

SNAME	X	Y
Species1 Name	277935.1488	4184812.83
Species1 Name	282537.3615	4191508.725
Species2 Name	228874.062	4168829.166

Environmental data processing

- All grids must share a common projection, extent, cell size, and alignment, and be in the same folder
- I typically use the 30m elevation grid as my reference grid, but just be sure to always use the same reference grid, and make sure it covers the full extent of the study area.
- The Maxent software requires ASCII grid files, but other modeling methods can use ESRI grids or geotiff (geotiff preferred, since it is smaller and easier to work with)
- Use the settings under Environments (either under Geoprocessing menu or use the button at the bottom of the raster to ASCII conversion tool) to set processing extent, snap to grid, output cell size to the reference grid. Be sure environments are correct each time an input processing step is run.
- For categorical variables such as soil type, geology type, vegetation type, it is much better to use a "distance to a particular type" instead of the categories themselves, so try to narrow down one or a few types. Use the Euclidian Distance tool with a shapefile as the input feature to generate the distance to X grid.

Maxent modeling

- Unzip the Maxent files in location on your computer (not on the network, unless using modeling server)
- Make sure you have java installed

- To open Maxent, double click the maxent.bat file
- Browse to the location of samples .csv file, and folder of environmental layers files (ascii rasters)
- Select one species in the left-hand window and select appropriate environmental layers in the right window. Be sure to specify if a layer is categorical instead of continuous (default).
- If you always use the same location for environmental layers, model runs will be faster after the first time because Maxent makes a cache of layer info. Every time a new layer is used, it will have to write that into the cache.
- Check boxes on right side (create response curves, make pictures…, do jackknife), OK to use auto features - left side box. If there are plenty of points (like more than 100 or so, you could, under settings at the bottom, put in a number like 10 to 25 in the Random test percentage box. This gives a better estimate of model fit. For these rare species models, it isn't necessary.
- **Use the default asc output, the other ones don't work in ArcMap**
- Note that all climate variables (precipitation and temperature) are highly correlated with elevation, so I sometimes omit the elevation grid
- Specify the output directory, leave projection layers field blank (this is for projecting under future conditions, e.g., climate change)
- See this pdf for help with Maxent settings P:\CNAP_2021_2025\CODEX PGCN Models\references\modeling\a_maxent_model_v7.pdf
- When ready, click the run button in lower left. Program will let you know if there is a problem with any inputs. One or two layers i.e., soil_pH have "no data" in some areas such as the reservoirs, so OK to just say ignore and suppress additional warnings
- A run will probably take an hour or two, depending on if data is all cached.
- If you want to do another run, make a new Maxent folder (e.g., maxent2) so as not to overwrite the previous run.

Model results

- It is best to set ArcMap to not automatically turn on added layers (Customize > ArcMap Options > General tab, uncheck box "Make newly added layers visible by default"
- Add the .asc file that is in your Maxent folder for that species to an ArcMap .mxd
- Convert the .asc to a .tif raster using Conversion tools > To Raster > ASCII to Raster. Specify .tif for the output raster, and use FLOAT for output data type
- Classify the tif raster under symbology tab - yes to calculate statistics first
- Potentially keep everything above 0.50; botanists to review, determine final extent
- Initial cutoffs used were orange= Equal training sensitivity and specificity, red= 0.50+

Post review processing

- To "erase" an area (i.e., reservoir), make a polygon of the feature to be erased, and convert it to a raster, using the complete model raster as processing extent, snap raster, and raster analysis cell size in environment settings. In raster calculator, use a statement like this to set reservoir cells to "NoData": SetNull(~(IsNull("EchoCynRes_PolygonToRaster")),"Townsendia_glabella.tif"). This is now the new full model. Now reclassify according to desired cutoff and export for CODEX model, use additional range clip if needed.
- For CODEX binary version, classify the full model into two display classes, then reclassify this so that everything not kept (e.g., cells <0.50, and areas of NoData) becomes NoData, and cells above cutoff = 1. Then clip this binary if needed.
- For clipping with non-rectangular shape, check the "Use input features for clipping geometry" box

- To make a shape incorporating an elevation contour, use Contour (spatial analyst tools / surface) on a classified elevation grid, then draw a boundary polygon and use this in feature to polygon to get the contour portion. Then select appropriate part and export as clip shape.

Deductive models

- Maxent can be used to investigate the contribution of selected variables to predictive ability in a model, but if results are unsatisfactory, a deductive model may be needed.
- Deductive models are constructed by combining grids of the various factors, using the "envelope" of applicable conditions (e.g., elevation between 5000 and 9000 ft).
- To identify the envelope or range for each factor, use the Extract Values to Points tool to intersect species location points with each environmental raster input. Values will be output in a new column in the new output shapefile
- When you have the values for each factor, use the Raster Calculator with CON statements, or the Reclassify tool (after setting the display classes) to pull out the ranges (values outside the range of interest should become NoData, values in range 1). Add the binary rasters together in Raster Calculator, then Reclassify again. For a binary result, use the highest value as 1, everything else becomes NoData. Or you may want to keep areas where all but one factor agrees (next highest value) as moderate probability, etc.

Appendix C: Expert review of SDM for rare plant species

Introduction

In the past two decades, the popularity and accessibility of species distribution modeling has increased dramatically (Franklin 2013, Guisan et al. 2013, Zurell et al. 2020). Accessible computing equipment, a proliferation of predictive algorithms, and user-friendly interfaces have made it possible for nearly anyone with access to spatial data to produce a predictive distribution model for a species of interest, regardless of their knowledge of the species and its habitat. This is in stark contrast to previous times when species distribution maps were produced by one or more specialists, using extensive field knowledge of "their" species, a paper map, and an indelible marker. These early "models" were easily converted to digital format, and often remain the most useful representation of where a particular species can be expected to occur.

The growth of species distribution modeling has resulted in countless digital models, covering various areas, but often only occasionally tested in the field. A primary validation of any distribution model is that it permits the discovery of previously unknown occurrences. Standard statistics used to assess the quality of a model (for example, the widely reported Area under the Receiver Operating Curve or AUC), do not necessarily tell us much about whether the model is good in the field. Field validation is expensive, time consuming, and can even be dangerous when predicted habitat is in difficult terrain. A somewhat more accessible evaluation technique is the expert review performed by those who have observed the modeled species in the field.

In the course of this project to produce models for use in conservation planning, we solicited expert review from regional botanists/ecologists in a uniform format. Models were produced for 81 of the Plants of Greatest Conservation Need as specified in the 2015 Colorado State Wildlife Action Plan. These distribution models are included in the conservation data sharing platform, the Colorado Conservation Data Explorer (CODEX), to help conserve and protect these species though environmental review and conservation planning. As such, the modeling process was focused on producing products that kept a balance between predicting too much suitable habitat to be reasonable in field survey, and models that too closely fit already documented locations.

Our objectives are to report on the results of the review process, identify sources of reviewer dissatisfaction with models, recognize corrective actions that can be taken to address reviewer comments, and recommend best practices for future reviews.

Methods

Reviews were solicited from botanists active currently or in the past in Colorado and adjacent states, on the basis of having some familiarity with a particular species. Reviewers were affiliated with a variety of local, state, and federal agencies, universities, regional herbaria, and/or the Colorado Native Plant Society or Colorado Natural Heritage Program. An online survey google form with a combination of radio button choices and fields for text comment was used in combination with a binary model draft displayed on ArcGIS Online, both viewable in an internet browser (supplementary material). CNHP botanists made an effort to remind reviewers to fill out the survey, and to clarify unclear survey responses. In a few instances, reviewers chose to respond by email, and their answers were entered into appropriate columns to the extent that could be determined from the email content. Not all reviewers completed all questions. The questions asked in the google form are shown in Table C-1.

Table C-1. Questions included in the Google Form for expert model review, Round I. Questions with an * were included in the google form for Round II review.

Question	Response Type	Choices
What is your name?	Short answer	
What is your email address?	Short answer	
Which species did you review?	Short answer	
Briefly describe your familiarity with the species and areas where you have observed it.	Long answer	
Overall correctness	Multiple Choice	Un-usable, Poor, Reasonable, Good, Excellent
Please add any comments to justify the overall score which you chose.	Long answer	
Fit	Multiple Choice	Underfit (model covers too broad of an area), Overfit (model covers too narrow of an area), Suitable
Please add any comments to justify the fit which you chose.	Long answer	
Distribution	Multiple Choice	Should include additional areas, Should exclude certain areas, Suitable
Please add any comments to justify the distribution which you chose.	Long answer	
Do you have a shapefile or circled map image of the area you believe should be included or excluded? If so, please email to jp.smith@colostate.edu	Multiple Choice	Yes, No
Additional Comments	Long answer	
*May we identify you in the final report as an expert reviewer of this species?	Multiple Choice	Yes, No

Responses were tabulated in a spreadsheet that preserved all online entries. Categorical responses were tallied, and comments were summarized into five general categories of dissatisfaction with the model:

<u>Comment summary category definitions</u>

Too broad / widespread: The model area was perceived as including too much area outside the current documented range of the species

Has incorrect inclusions: The model area included unsuitable habitat types to a degree that prompted comment (e.g., riparian areas included for an upland species, reservoirs as habitat)

Missing known occurrences: The area within modeled suitable habitat did not cover one or more documented locations for the species

Data refinement desired: The reviewer suggested an environmental factor that appeared to be omitted from the model, or a more fine-scaled representation of included data

Reviewer unclear on model purpose: The reviewer expected the model to show detailed microhabitat at a scale much finer than that of the model resolution, or expected the modeled area to conform closely to only known occurrence locations

Results

Thirty-nine individual botanists reviewed a total of 47 models created in Round I of this project, for a total of 75 reviews. Individuals reviewed from one to eight species models, depending on the extent of their expertise. As expected, model review detail and useful feedback was variable both within and between reviewers. Over 80% of reviews concluded that the model in question was in the "Reasonable" or higher level of overall correctness. Ten models were assigned Poor, and two were labeled Unusable. The majority of rankings fell within the three middle Overall Correctness categories from Poor to Good (Table C-2). As reviews were submitted, we realized that it would have been advisable to better define evaluation parameters, and to adequately describe the purpose and use of the models. Reviewer comments indicated that model characteristics making a model unusable to one reviewer might be acceptable to a different reviewer. In some instances, the disinclination of a reviewer to make use of the standard review form (replying instead by email) detracted from the utility of their response.

The overall goal of the review process was for each reviewer to compare a model of predicted suitable habitat against their personal knowledge of a species and its habitat. Although reviewers in Round I had all observed their reviewed species, there was considerable variation in the level of experience needed to make useful comparisons between an external GIS model and the internal "model that I carry in my head with regard to this species." There was naturally variation in amount of reviewer experience in locating and identifying the species in the field; some reviewers discovered and described the species, others had seen it only a single time, but most reviewers had at least moderate experience with the species. Reviewer experiences were highly variable in how recently the species or its habitat had been observed. Some reviewers had surveyed during the most recent field season, others had not seen the species for one or more decades. Although their most recent observation date was not usually reported by reviewers as part of this survey, it appeared from responses that agency personnel and those with a particular investment (i.e., discoverers/publishers) are those most likely to be making frequent and recent surveys. Finally, individual biases and beliefs about what a model "should" be were apparent in many responses. This information is difficult to quantify, but should be useful in guiding future review efforts, and illuminating potential areas where communication can be improved.

Categorized reviewer comments revealed that even models ranked Good or Excellent might have room for improvement. In general, reviewers were most likely to indicate that a model was too broad or included too much unsuitable habitat (Table C-2). The inclusion of unsuitable habitat in predicted areas was the second most frequent comment type.

Table C-2. Tally of reviewer comments by comment summary category and overall model correctness score for Round I of expert botanist solicitation.

	Excellent	Good	Reasonable	Poor	Unusable	% of total reviews
Too broad / widespread		3	11	5	2	31%
Has incorrect inclusions	1	5	6	4	1	25%
Missing known occurrences		2	4	1	1	12%
Data refinement desired	1	3	6	3		19%
Reviewer unclear on model purpose			1	5	2	12%

In the first round of review, the five Overall Correctness categories were presented without definitions. For some reviewers, a misunderstanding about what would make a model poor or unusable required a follow-up between CNHP botanists and the reviewer to clarify. This experience shows that those soliciting model review may need to educate botanical experts on how/why models are produced, and work to clarify review expectations. For instance, the ranking categories should be well defined (e.g., Table C-3 below).

Table C-3. Suggested definitions for use in model review.

Overall Correctness Category	Definition
Five-category method	
Excellent	Model covers occurrences, appears to narrow down suitable habitat area well, given coarseness of available data, indicates convincing areas for survey.
Good	Model covers occurrences, contains some areas of unsuitable/unlikely habitat, but these do not dominate and could be omitted, indicates plausible areas for survey.
Reasonable	Model covers most good occurrences, may include significant unsuitable area, but could be trimmed, indicates some likely areas for survey.
Poor	Model misses some important occurrences, includes large unsuitable areas, generally does not represent species habitat, but may indicate additional likely areas for survey.
Unusable	Model misses many occurrences, is no better than random survey, does not agree with reviewer beliefs about the species, indicates additional areas that are thought to be highly improbable.

In the second round of expert review of the project, the model review form included the above definitions in Table C-3. The model review form also included the following project explanation at the beginning:

> These models were created for CODEX (Colorado's Conservation Data Explorer), a free web-based mapping and environmental review tool hosted by CNHP (https://codex.cnhp.colostate.edu/). The intent of these models is to facilitate conservation and protection of these species though environmental review and conservation planning. Models

are a broad, inclusive representation of locations recommended for survey where suitable habitat may exist. Due to modeling limitations, some unsuitable habitat may be included.

In the second round of expert botanist review solicitation, 18 individual botanists reviewed a total of 32 models created primarily in Round II of this project, for a total of 42 additional reviews. Individuals reviewed from one to eight species models, depending on the extent of their expertise. Over 80% of reviews concluded that the model in question was in the Good or Reasonable category of Overall Correctness. Only one model was assigned Poor, and three were labeled Excellent; none were labeled Unusable.

In spite of the variable responses from reviewers, the exercise did produce important feedback that was used to revise some models. Nine models were revised based on feedback and one additional model from 2010 was revised based on the availability of new data; these were for *Aletes humilis*, *Descurainia kenheilii*, *Cirsium perplexans*, *Draba smithii*, *Erigeron kachinensis*, *Lupinus crassus*, *Nuttallia densa*, *Pediocactus knowltonii, Physaria rollinsii,* and *Thalictrum heliophilum*. The most easily implemented revisions were removing portions of predicted habitat too far outside the known range when a botanist indicated that they had surveyed unsuccessfully for the species in that area or believed this extent to be incorrect (e.g., *Draba smithii. Cirsium perplexans, Nuttalia densa, Thalictrum heliophilum*), or removing obviously incorrect habitat areas (e.g., reservoirs) from modeled habitat (e.g., *Aletes humilis*). The model for *Pediocactus knowltonii* was completely redone using a deductive model based on reviewer comments. For other species, models were run again using updated occurrence data and trying additional environmental inputs to address reviewer comments.

Revisions not able to be completed under this scope of this project, including those that would be too complex to implement at this point or involving other data inputs not yet available were noted and flagged for revision in future work (Table C-4). In some cases, models which received a poor review were thought to reflect a lack of information about the species environmental niche (*Oreocarya reveallii*) or lack of occurrence data due the species being potentially overlooked (*Physaria vicina*) or a species was thought to be evolutionarily young and had not yet expanded into all potential habitat (*Ipomopsis ramosa*) or available input data were too coarse, inaccurate, or otherwise unable to reflect the natural complexities of environmental conditions (*Eriogonum brandegeei, Eriogonum coloradense, Penstemon degeneri*). All reviewer input, even if no solutions were suggested, will be considered in future revisions.

Table C-4. Species to consider for future model revisions, prioritized from reviewer comments. Modeling suggestions from the reviewer and/or CNHP botanist are given along with existing data gaps identified by CNHP botanist and modeler.

Species	Comments
Mentzelia paradoxensis	Include gypsum soils (if available) and vegetation type (barrens) as model inputs
Physaria pruinosa	Poor coverage in SE corner; include vegetation type (barrens) as a model input
Townsendia glabella	Include the oyster bed layer of the Smoky Hill member of Mancos shale (would need to be digitized) and vegetation type (barrens) as model inputs
Cleome multicaulis	Exclude irrigated farmlands and urban areas from the model; include existing vegetation type as a model input or model post-processing
Penstemon fremontii var. *glabrescens*	Exclude irrigated farmlands; include existing vegetation type as a model input or model post-processing

Physaria parvifora	Exclude habitat other than shale barrens; include additional species occurrence data since original modeling, include existing vegetation type as model input, or model post-processing
Phacelia gina-glennaeae	Exclude unsuitable habitat; species will be subsumed into *P. formosula* (NatureServe 2023) - re-model using up-to-date species concept, include existing vegetation cover as model input, or model post-processing
Packera mancosana	Too broad of an elevational range and not restricted to Mancos shale geology; include refined geology as an input (would need to be digitized)
Eriogonum brandegeei	Model did not perform well around Cañon City; lack of occurrence data in this area makes modeling difficult
Aliciella sedifolia	Model should be limited to around 13,000 feet; more refined environmental inputs needed
Eriogonum coloradense	Model missing atypical habitat; more surveys needed in these areas to add occurrence data as an input
Penstemon acaulis var. *yamapensis*	More occurrence data needed to refine this model
Penstemon degeneri	Model did not represent high elevation or western occurrences well
Oreocarya revealii	More information about species environmental niche required
Physaria vicina	More occurrence data required
Puccinellia parishii	Exclude habitat which is not seasonally saturated; refined environmental inputs needed
Lygodesmia doloresensis	Model missing eastern edge of the range; more surveys needed in this area
Eriogonum pelinophilum	More detailed geology required for fine scale modeling across the species range (would need to be digitized)

Discussion

Through more detailed evaluation of reviewer comments, we were able to identify and assign sources of model dissatisfaction to several entities, namely, the review process, the modeling process, or the data (Table C-5). We also identified potential corrective actions that can be implemented to improve the review process and more detailed explanation of the model purpose and intended use was included in the second round of expert model review. Although some sources of model concern arising from data cannot be corrected, improved communication with regard to model process and objective together with the realities of geo-spatial data, are likely to improve the utility of the review processes for all involved.

Table C-5. Source of model dissatisfaction

Concern	Potential corrective actions
Review process	
Reviewer expects model to show microhabitat	More detailed explanation of purpose and intended use of model
Reviewer expects model to be tightly constrained to vicinity of known locations (i.e., to “show the range”)	More detailed explanation of purpose and intended use of model; work to implement a cost-effective method of either selecting small portions of statewide environmental datasets, or else constraining background samples to be nearer known occurrences. The goal of this effort would be to eliminate distant and dissimilar areas from model construction.

Concern	Potential corrective actions
Reviewer expects wants finer scale model	Detailed explanation of realities of data availability; or work with modeler to develop better inputs
Modeling process	
Lack of experience with modeling technique and/or data preparation	Work with, hire/retain experienced modelers; train additional staff
Insufficient bio-eco-geo knowledge to permit interpretation of inputs and draft results	Modeler works closely with botanist, ecologist, etc. to determine appropriate inputs
Data - Occurrences	
Missing occurrences	Locate and add additional occurrences; request data from reviewer; consult with field botanists who may have unsubmitted records
Occurrences poorly mapped	Improve mapping if possible; remove or down-weight poorly mapped occurrences
Too few occurrences	Deductive model based on specimen information, re-do model if additional occurrences found
Some clusters of occurrences in well surveyed areas dominate model results	Subset and/or weight occurrences
Data - Environmental covariates	
Desired input not available	Explain realities of data availability, try to identify surrogate
Desired input not available across species range	Detailed explanation of realities of data availability, try to identify surrogate data, or constrict model area
Scale too coarse or shows too widespread predicted distribution	Constrict model area, down sample data
Predicted area includes too much unsuitable habitat	Find data that better represents key factors, down sample data, cut unsuitable areas from final model
Many highly correlated inputs	Correlation analysis considered in selection of inputs
Errors or unexpected patterns in data layer produce unlikely results	Check validity of original data and preparation process; omit this covariate
Distribution not driven by any known covariate	More research on species requirements needed

Tradeoffs between model production costs and validation efforts are a crucial consideration in the often under-funded sphere of rare species conservation. Most species distribution models have a statistical evaluation of some sort, ideally with a separate, independent set of test points that have not been used to create (train) the model. In our work modeling the predicted distribution of rare plant species, we typically do not have enough location points to justify withholding a useful percentage from model construction. While it is clearly ineffective to hold out one or two of ten points for testing, there are no recognized standards for when and how many points to hold out as a test percentage. With ample time and funding, this question could be researched, but support is generally wanted for more essential tasks such as field survey and conservation efforts. Consequently, we take comparative note of statistics such as AUC that compare the performance of the model against the combined set of training and background points, but do not regard them as high-quality model evaluation tools in this situation.

Field validation can be statistically rigorous, with spatially balanced randomly generated sample points enabling statistical evaluation. This type of exercise is often prohibitively expensive and time consuming, unless the species is a well-funded conservation target. Less rigorous, informal field validation is more realistic, and should be employed whenever possible. In this scenario field biologists have access to the model (either in the field or in the office after collecting accurate location data) and can report success or failure of model at a visited location. Success and failure can take several meanings here. A clear validation is if the target species is in fact found at a predicted location. However, the species absence at a location that otherwise appears highly suitable is not always a failure. Possible reasons for the absence include:

- the species is mobile or only seasonally apparent and was missed during the field visit
- the species could become established in the location, but has not dispersed to the area (for various reasons), or was formerly present but extirpated by anthropogenic activity
- the habitat is in fact unsuitable, and could not support the species if it has ever dispersed to the area

Our goal is to test whether the model is useful for our objective, not whether it is correct, however that is defined (Pearson 2010). Expert review of species distribution models can act as an informal post hoc field validation, similar to the in-office post field-visit scenario, but with more variable results, depending on the experience and model evaluation skill of the expert. Our experience with expert review indicates that our rare plant models are acceptable tools and representative of on-the-ground conditions. In addition, the cost-benefit balance, together with the network-building effect and iterative nature of the model production-review-revision process can lead to a synergistic effect that benefits both the species of greatest conservation need and those who study them.

A quick search turned up several hundred to a few thousand publications on the topics of boundary organizations and knowledge co-production in conservation, land management, and climate change response. A special issue of Frontiers in Ecology and Evolution (Enquist et al. 2017) featured a series of articles about the emerging field of translational ecology (TE) wherein boundary-spanning organizations are depicted as key players in the translational process between scientists (especially academia) and stakeholders (land management agencies, etc.). Clearly there is widespread feeling that researchers and practitioners could benefit from stronger ties. This has led to a proliferation of discussion about boundary spanners at the science/policy divide, boundary objects (physical objects or tools providing a common point of reference among stakeholders), evidence bridges (facilitating knowledge exchange between researchers and practitioners), and related concepts (Morisette et al. 2017, Gustafsson and Lidskog 2018, Salafsky et al. 2019, Kadykalo et al. 2021).

There is, however, little recognition of the value of the vertical communication and long-term network building that greatly reduce boundary effects. TE is a delightful concept, but the authors seem unaware of several networked organizations that have traditionally (albeit quietly) filled this role in conservation and ecological decision making, particularly in the US. The members of the NatureServe network (state Natural Heritage Programs, Conservation Data Centers, etc.) have a decades-long history of acting as evidence bridge organizations between university or agency scientists and a variety of stakeholders, including local, state, tribal, and federal land managers, non-governmental environmental advocacy, conservation organizations, political entities, local educators, “amateur” field observers, and more.

Furthermore, Natural Heritage Program (NHP) staff typically embody a pool of both extensive field-based ecological knowledge as well as trusted long-term stakeholder relationships in their state or region. Program staff often possess biological knowledge and field experience that spans decades, providing the ability to discern trends in the biodiversity of an area. Staff may serve as recovery team or technical committee members for a particular taxa or group of taxa, as well as being members and leaders of local or regional stakeholder groups. NHPs serve as training grounds for qualified ecologists (botanists, zoologists, etc.) who may later take agency positions, and often provide training for agency personnel and other stakeholders. NHPs are well positioned to get all parties to the table, being connected with researchers and practitioners, as well as other boundary-spanning groups. NHPs preserve the tradition of natural history but have also adapted to current conservation trends and issues. The fact that we were able to elicit expert reviews from so many individual botanists is a remarkable demonstration of the value of our program’s partnership-building expertise.

In the case of rare species, especially those of less glamorous taxa, it can be a challenge to find experts who are able to evaluate a distribution model. This loss of expert knowledge is ongoing and difficult to mitigate against in a quickly changing world but provides an important source of useful (although often denigrated) evidence in conservation. The same holds true for indigenous community expertise as well.

There are opportunities for all involved in the practice or funding of botany and plant ecology to facilitate the preservation and ongoing maintenance of expert knowledge. Staff of agencies and conservation organizations can work to instill the enthusiasm for field work and support upcoming botanists and ecologists on the track to subject-matter expertise while experts in senior or career positions can mentor younger colleagues to pass on both their field knowledge and other observations about a species. Academic modelers can and should move beyond highly technical explanations and learn to communicate the basic modelling process and concepts in plain English, following the advice of E.B. White that “No one can write decently who is distrustful of the reader's intelligence, or whose attitude is patronizing.” In the end, any single species distribution model cannot be all things to all users but can play a role in facilitating and sustaining networks of conservation practice.

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Appendix D: Projected suitable habitat under potential future climate conditions

Climate model basics

General circulation models (global climate models) or GCM are computer models that simulate how various physical processes interact in the atmosphere, oceans, and landmasses to produce world-wide climate patterns. GCMs are used for all types of investigation into climate behavior, both short and long term. These models are tested to see how well they predict past conditions. Global scale models use a three-dimensional grid of large cells (on the order of 1 x 2 degrees – about 16 of which cover Colorado).

Dozens of modelling groups (centers) around the world use GCMs under various scenarios to predict what climate conditions might be like in the future. Scenarios represent the complex relationship between the socioeconomic forces driving greenhouse gas and aerosol emissions and the levels to which those emissions would climb during the 21st century. In more recent model efforts, scenarios are called Representative Concentration Pathways (RCP). Models are set up with known historic conditions in 1950, and run without additional correction to 2100, using input specifications (scenario or RCP values) about how greenhouse gases will change under global circulation patterns.

Each model run produces complex multidimensional output (a global 3-dimensional climate grid over time). The data we use is typically available in NetCDF format. Extensive data manipulation is required to convert the NetCDF datasets into the various monthly, seasonal, and annual rasters of precipitation or temperature that we use in species distribution models. Following standard practice in weather data, climate data is typically averaged over a 30-year “normal” period for comparison with new observations or future projections.

Because all models have their particular biases, it is important to predict future species distribution by using two separate “slices” of the same 150-year model dataset (model space), one representing the recent past (historic normal), and the other representing the projected future normal for a particular period. This controls for model bias and allows us to have confidence that the observed change is due to scenario conditions, not a difference resulting from using two models.

Test model of predicted future distribution for *Draba smithii*

From prior climate change related project work, CNHP had available a selection of processed seasonal precipitation and temperature statewide datasets (Fink et al. 2019). Unfortunately, a complete set of rasters equivalent to climate inputs used in the PGCN distribution modeling was not available. We were able to match seasonal precipitation, and to substitute average high for summer and fall for maximum summer temperature, and average low temperature for winter and spring to approximate winter minimum temperature. The values used in modeling are averages of the variables over the 30-year period. Frost date and other climate datasets were not available without significant additional computations. This climate data was based on the hadgem2.es.1.rcp85 climate model from the NEX-DCP30 bias corrected downscaled (800 m) dataset, prepared by the Climate Analytics Group and NASA Ames Research Center using the NASA Earth Exchange, and distributed by the NASA Center for Climate Simulation (Thrasher et al. 2013) for the period 1970-2000 to represent current climate normal. The original HadGEM2-ES GCM was performed at the Met Office Hadley Centre, Exeter, UK (Collins et al. 2011).

This is a model that shows a hot and dry future climate for most of Colorado, with an average annual reduction in precipitation of 4% and increase average temperature of nearly 7°F (Figure 1.). Projected future normal values were for the 30-year period centered around 2050 (i.e., 2035-2065 from the complete 150-year model dataset).

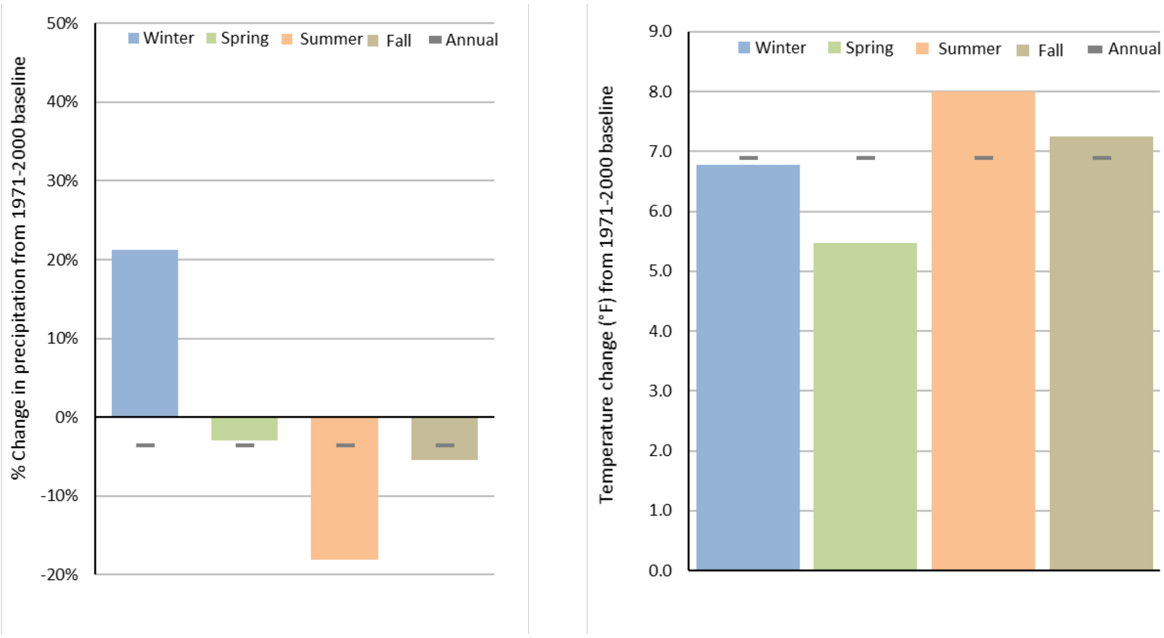

Figure 1. Graphs of the % change in precipitation and temperature change from baseline conditions between 1971-2000 in the "hot and dry" scenario predicted in the hadgem2.es.1.rcp85 climate model for the 30-year period centered around 2050.

Table 1. Comparisons of the relative contributions of model inputs for the two "current" distribution models. The model on the left is the model created to represent the species distribution in CODEX. This model used Daymet data. Daymet data is interpolated from historic weather observations (weather station locations) and represents an average from 1980 - 1997, at 1 kilometer resolution; the raster was down sampled to 30m. The model on the right used the hadgem2.es.1.rcp85 climate model, taking data from 1970-2000 to represent current climate normal. Variable descriptions are presented in Appendix B.

Daymet current model

Variable	Percent contribution	Permutation importance
dist_tvolc_sel	23.1	8.5
ter_rough_index	19.1	0.6
ppt_s1	14.6	5.7
ppt_s3	12.7	40.8
max_summertemp	8.4	1.2
co_ned30m	5.4	0.1
ppt_s4	3.3	24.8
slope_deg	2.8	0

hadgem2.es.1.rcp85 current model

Variable	Percent contribution	Permutation importance
dist_tvolc_sel	24.1	39.6
ter_rough_index	22.1	0.5
ppt3_hd	13.8	7.8
co_ned30m	11.2	0
ppt1_hd	8.2	10.4
ppt4_hd	4.7	24.4
dist_ignmet_xy	3.6	6
eastness	2.7	0.8

Variable	Percent contribution	Permutation importance
dist_ignmet_xy	2.6	1.6
northness	1.9	0.3
may_mintemp	1.4	2.7
ppt_s2	1.4	11.4
eastness	1.1	0.3
avg_lastfrost	0.9	0.1
average_clay	0.8	1.2
min_wintertemp	0.1	0.3
average_sand	0.1	0.2
ssurgo_depth_cm	0.1	0.1
apr_mintemp	0	0
average_silt	0	0
avg_firstfrost	0	0

Variable	Percent contribution	Permutation importance
northness	2.3	0.4
tmax4_hd	1.9	3.2
ssurgo_depth_cm	1.4	1
slope_deg	1.4	0
tmin1_hd	1.1	0.3
ppt2_hd	1	2.5
average_clay	0.3	0.6
average_silt	0.2	2.3
tmax3_hd	0.1	0.1
average_sand	0	0
tmin2_hd	0	0

The figure below (Figure 2) illustrates the predicted model habitat produced during this project using Daymet climate data (top row) and predicted habitat using the hot and dry model, the hadgem2.es.1.rcp85 climate model (bottom row).

The top left shows the full Maxent model with probabilities from 0-1. Climate data used in this model included seasonal precipitation, April and May mintemp, avg first and last frost, max summertemp and min wintertemp. This climate data was based on Daymet monthly data, which is interpolated from historic weather observations (weather station locations). For reference, the top right is the clipped binary model of high probability habitat (cut off was 0.5) which will be used in CODEX.

The bottom left is the full Maxent model for the current (recent past) distribution but using the “model space” period of the hot and dry model, the hadgem2.es.1.rcp85 climate model. Overall statewide patterns of predicted suitable habitat are similar between the two “current” full Maxent models. Differences between the top and bottom left maps are due primarily to the different temperature datasets used to represent climate. Non-climate inputs were the same as in the top left full model.

Bottom right shows the full Maxent model using the hadgem2.es.1.rcp85 climate model for the 30-year period centered around 2050 (i.e., 2035-2065 from the complete 150-year model dataset). Non-climate inputs were unchanged. Although predicted higher probability habitat remains in a few key locations (vicinity of Pikes Peak, Sangre de Cristos and Wet Mountains, Raton pass), future predicted habitat is severely diminished under hot and dry future conditions.

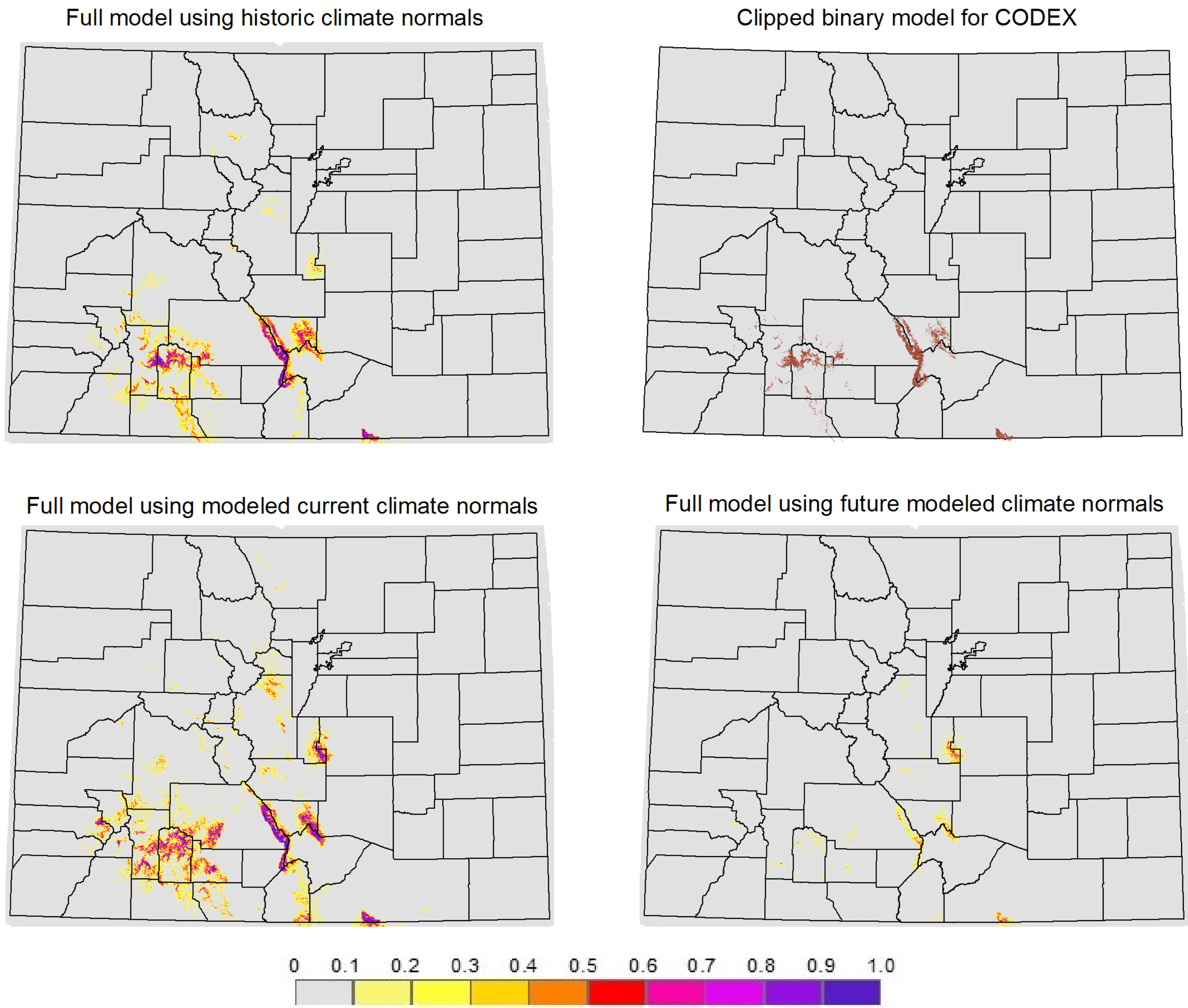

Figure 2. *Draba smithii* species distribution models. Top row: predicted model habitat using Daymet climate data, with the model on the left showing the full distribution probability (0-1) and the model on the right showing the CODEX version with probability greater than or equal to 0.5 probability. Bottom row: predicted modeled habitat using climate data from hadgem2.es.1.rcp85 climate model, with the model on the left showing conditions under the current time frame, i.e., 1970-2000, and the one on the right showing a future time frame, the 30-year period centered around 2050.

Application of Methodology to Additional Species

Building upon the pilot work with *Draba smithii*, five additional species were chosen as target species to project suitable habitat under potential future climate conditions. These were *Astragalus microcymbus, Astragalus osterhoutii, Eutrema penlandii, Frasera coloradensis* and *Ipomopsis polyantha*. Several criteria were considered in choosing the species of interest. The species needed to have a recently created species distribution model, either through this project or with other project funding. Secondly, climate factors should have been important factors in the modeling of the species' distribution. The final selection aimed to choose species across a range of habitats, regions of the state, and species of priority for the USFWS and CNAP. All the Plants of Greatest Conservation Need listed in the 2015 SWAP have a conservation action listed to model potential habitat/range shifts in response to projected climate changes, and almost all PGCN are considered extremely vulnerable to climate change (CPW 2015). However, within the climate change vulnerability analysis in the SWAP, the evaluated increased risk of certain factors which feed into the climate change vulnerability analysis does vary. Of these, *Eutrema penlandii* was ranked with a greatly increased (GI) vulnerability for the physiological hydrological niche and *Ipomopsis polyantha* and *Frasera coloradensis* both had a GI vulnerability for historical hydrological niche. The physiological hydrological niche is defined as a species dependence on a narrowly defined precipitation/hydrologic regime that may be vulnerable to loss or reduction with climate change. The historical hydrologic niche measures large-scale precipitation variation that a species has experienced in recent historical times; in the case of a greatly increased vulnerability, a species has experienced a very small precipitation variation in the past 50 years.

For these five species, two climate models were used to investigate the potential future distribution of these species under a Hot and Dry climate scenario (hadgem2.es.1.rcp85, described above) and a Warm and Wet scenario (cnrm-cm5.rcp45, original GCM performed by the Centre National de Recherches Météorologiques, Toulouse, FR [Voldoire et al. 2011]). Two time periods were used for comparison: a historical time period (1971-2000, average 1985) and future, 2035 – 2065, centered on 2050). Climate conditions in Colorado for the Hot and Dry climate scenario are described above in Figure 1. The Warm and Wet climate scenario differs by an overall increase in precipitation and a lower overall increase in temperature of about 3.7 °F (Figure 3). As noted with *Draba smithii* above, CNHP had available a selection of processed seasonal precipitation and temperature statewide datasets from prior climate change related project work at these two representative concentration pathways (Fink et al. 2019).

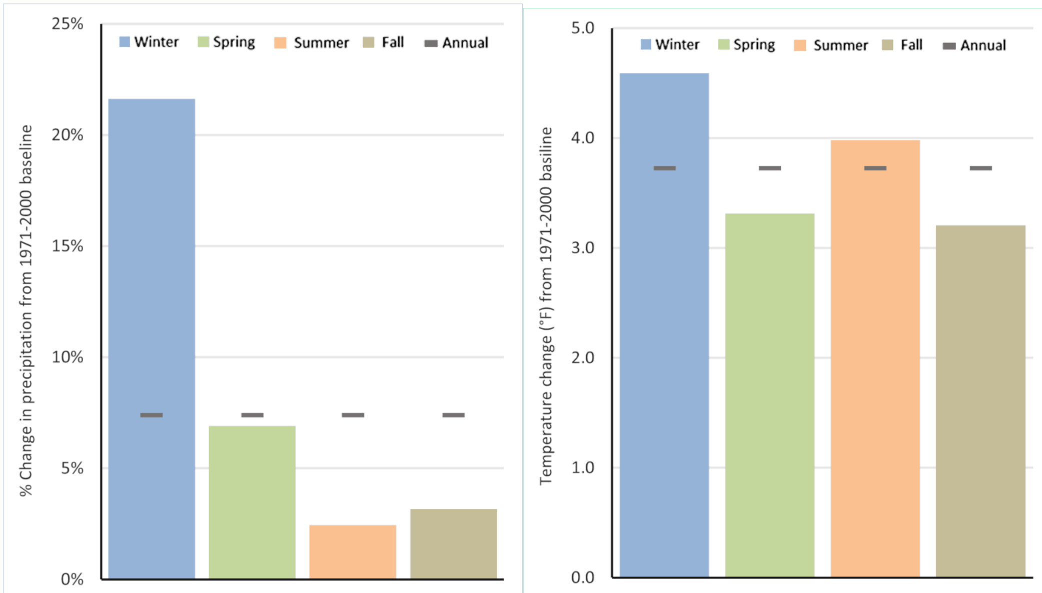

Figure 3. Graphs of the % change in precipitation and temperature change from baseline conditions between 1971-2000 in the "warm and wet" scenario predicted in the cnrm-cm5.rcp45 climate model for the 30-year period centered around 2050.

Because the variables readily available did not match the variables used in the CODEX models, comparisons were made only between historical and future climate projections and not compared to CODEX models. These comparisons were used to identify areas which were persistent (areas where bioclimatic conditions are currently suitable and will be suitable in the future), emergent (areas where bioclimatic conditions are not currently suitable but will be suitable in the future), threatened (areas where bioclimatic conditions are currently suitable but only barely suitable in the future with a sharply declining trend) and lost (areas where bioclimatic conditions are currently suitable but will not be suitable in the future). These change categories were originally developed in Fink et al. (2019) for a different modeling algorithm and much wider-ranging plant species with better known ranges than are being modeled here, so some adjustments to the methodology were necessary. The basic concept is to compare how habitat suitability for each species is projected to change not only over time but also in relation to the species' current occupied range.

However, because the current occupied range of these species is not fully understood, the CODEX models (still only representing habitat suitability, but using known climate data) were used as a proxy for occupied range. Two model value thresholds were calculated in order to categorize differences between current and future models; a "low cut" derived from the mean of the sensitivity = specificity threshold calculated for the Hot and Dry and Warm and Wet current climate models, and a "high cut" calculated as the top 20-percentile of current climate model values that occur within the binary threshold used in the CODEX models, again averaged over the Hot and Dry and Warm and Wet scenarios. Model values below the "low cut" are regarded as unsuitable habitat, while values at or above the "high cut" are assumed to be occupied habitat. Thus, the model change categories were defined as shown in Table 2.

Table 2. Determination of Change Category value ranges.

Category	Definition	Future - Current values
Lost	Suitable in Current, not in Future	between -1 and [high cut] - 1 if Future < [low cut]
Threatened	Suitable in Current, still barely Suitable in Future, but with sharply declining trend.	between -1 and [high cut] - 1 if Future >= [low cut]
Persistent	Suitable in Current, Suitable in Future	between [high cut] - 1 and 1 - [high cut]
Emergent	Not suitable in Current, Suitable in Future	between 1 - [high cut] and 1

The following maps illustrate potential changes in suitable habitat (within the constraints of the modeled space) for the species under two climate scenarios. This demonstrates how the environmental conditions upon which these species depend may shift. These models do not account for biological factors, such as the adaptive capacity of a species or human behavior, which may influence species persistence.

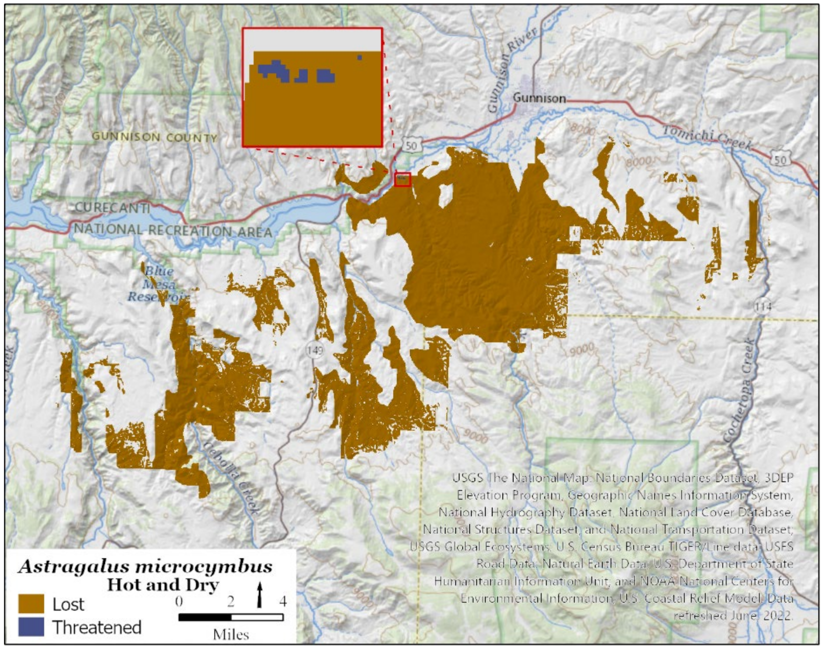

Figure 4. Modeled future habitat suitability for *Astragalus microcymbus* under the Hot and Dry climate scenario.

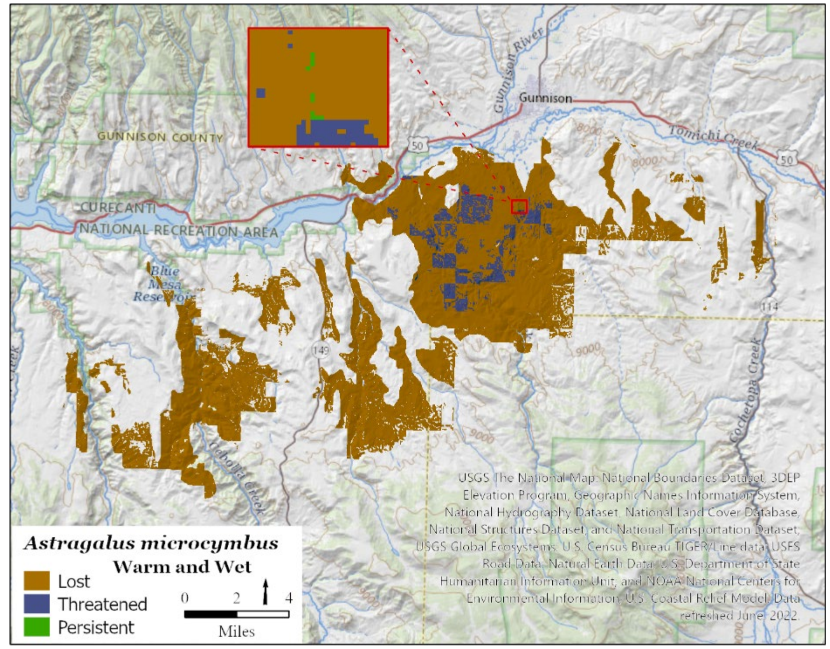

Figure 5. Modeled future habitat suitability for *Astragalus microcymbus* under the Warm and Wet climate scenario.

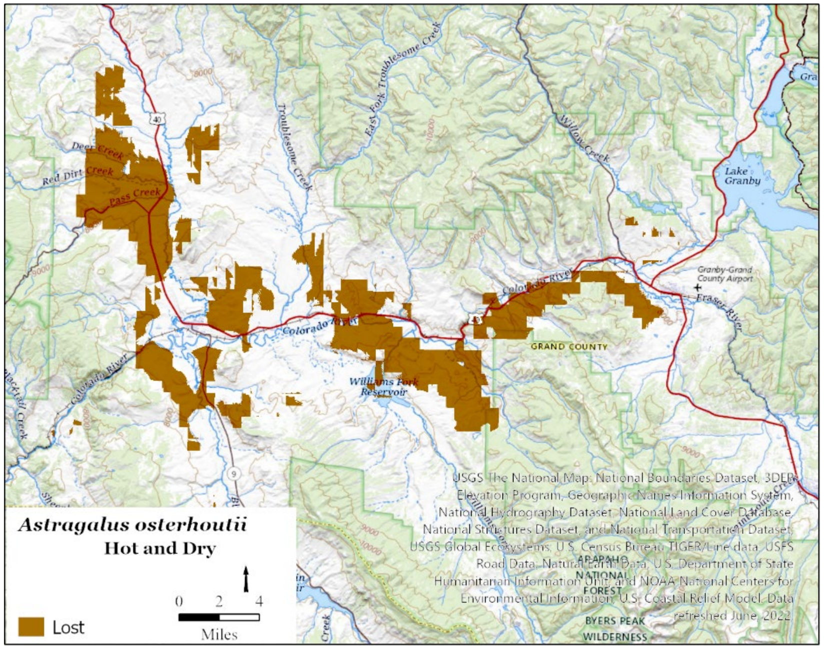

Figure 6. Modeled future habitat suitability for *Astragalus osterhoutii* under the Hot and Dry climate scenario.

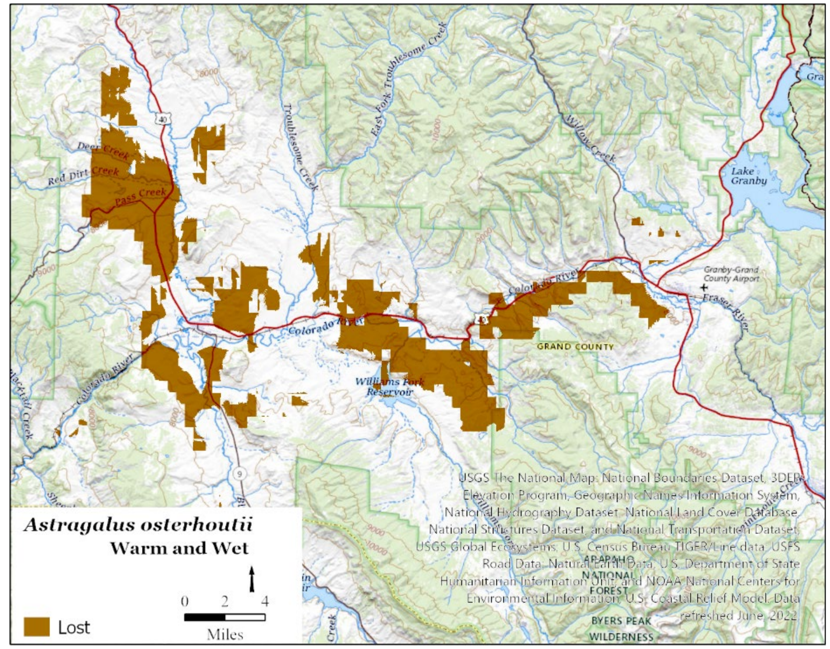

Figure 7. Modeled future habitat suitability for *Astragalus osterhoutii* under the Warm and Wet climate scenario.

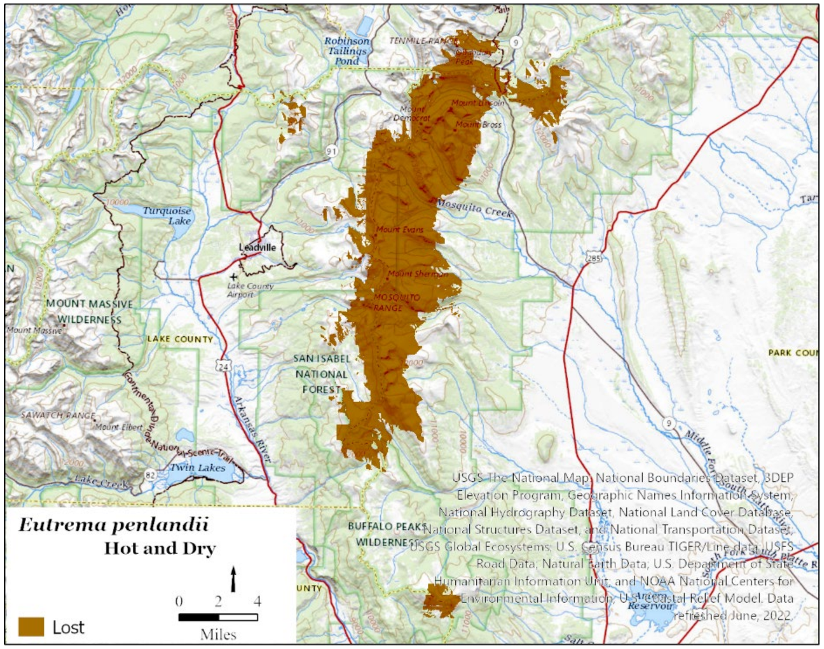

Figure 8. Modeled future habitat suitability for *Eutrema penlandii* under the Hot and Dry climate scenario.

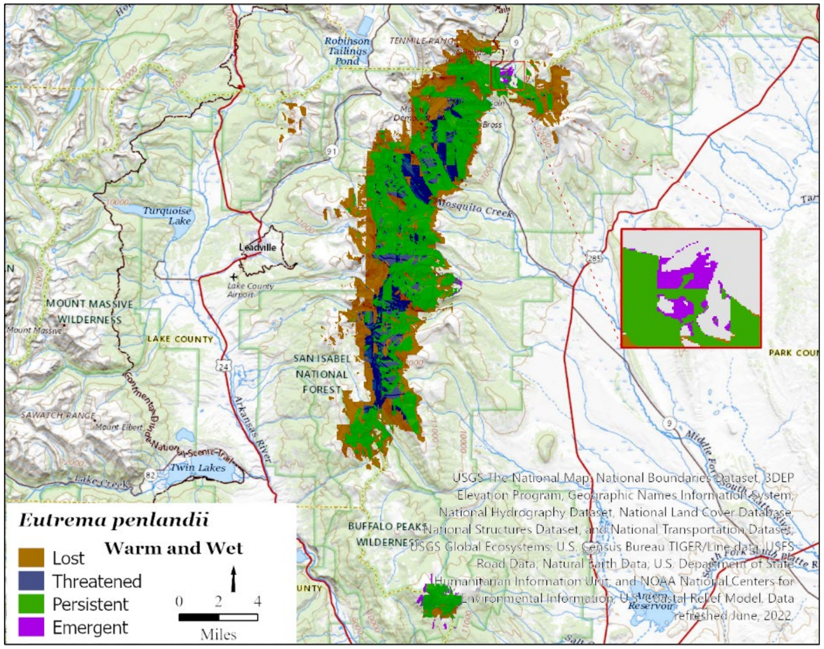

Figure 9. Modeled future habitat suitability for *Eutrema penlandii* under the Warm and Wet climate scenario.

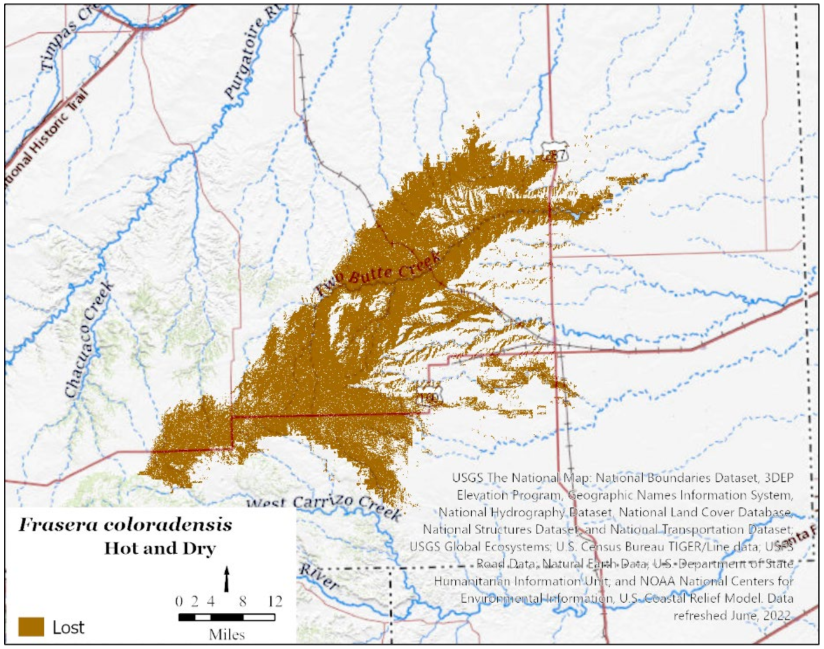

Figure 10. Modeled future habitat suitability for *Frasera coloradensis* under the Hot and Dry climate scenario.

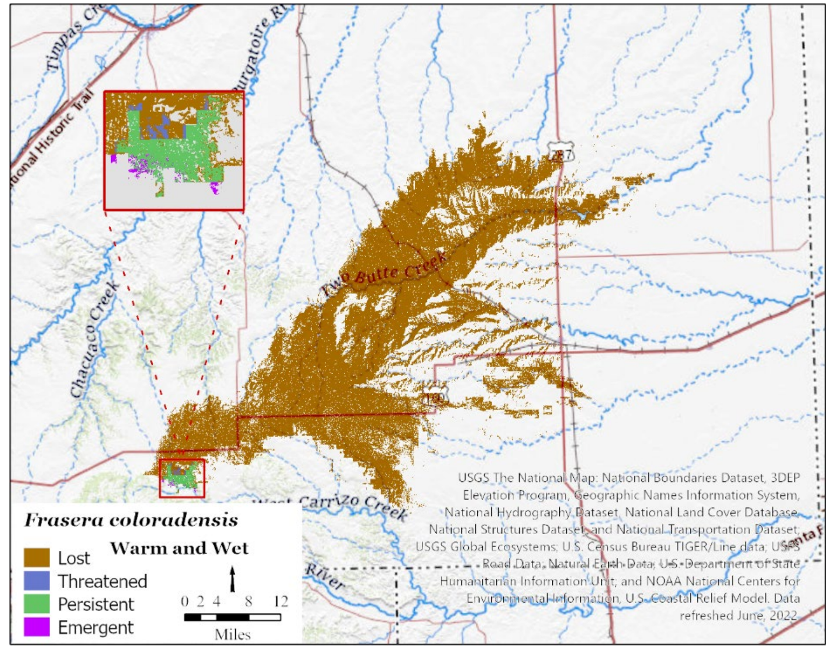

Figure 11. Modeled future habitat suitability for *Frasera coloradensis* under the Warm and Wet climate scenario.

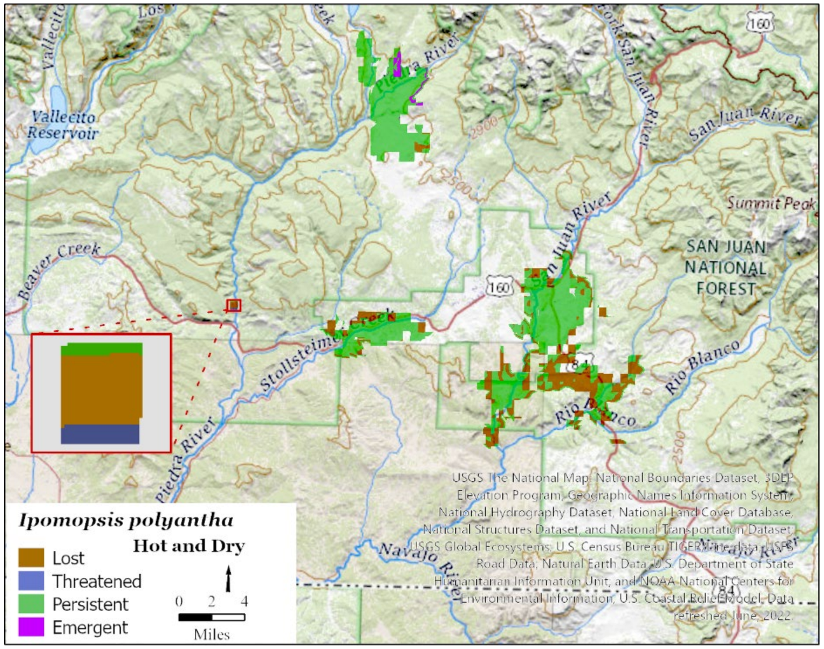

Figure 12. Modeled future habitat suitability for *Ipomopsis polyantha* under the Hot and Dry climate scenario.

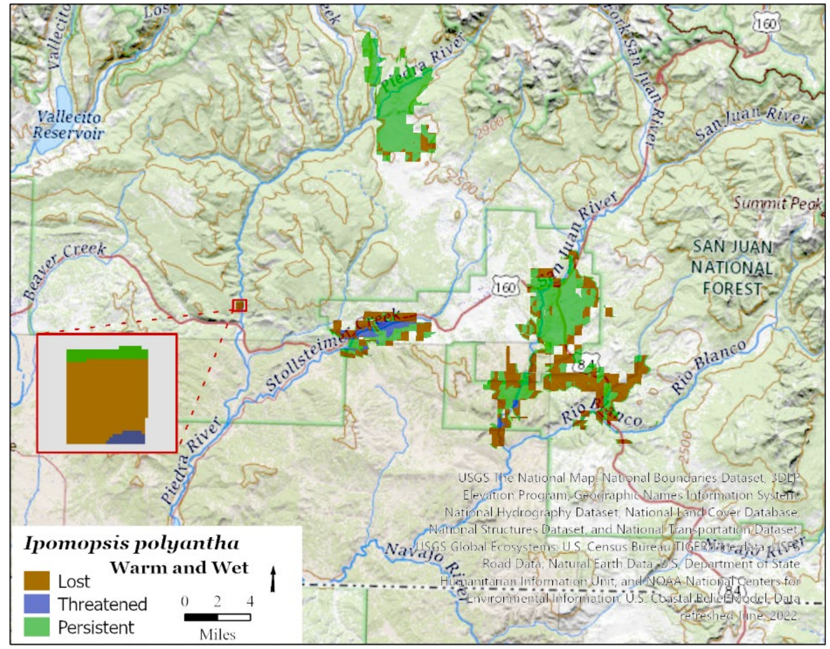

Figure 13. Modeled future habitat suitability for *Ipomopsis polyantha* under the Warm and Wet climate scenario.

Astragalus microcymbus is a sagebrush obligate species narrowly restricted to the Gunnison Basin (CNHP 2022). For this species, suitable habitat is predicted to be almost completely lost under the Hot and Dry scenario, and almost completely threatened or lost under the Warm and Wet scenario, with only a small area predicted to be persistent (Figures 4, 5). The most important variables in the maxent model under the Hot and Dry climate scenario were co-occurrence of *Artemisia tridentata* spp. *wyomingensis*, distance to Igneous and Metamorphic rocks of Precambrian age, and percent organic matter in the soil. For the Warm and Wet scenario, the first two top variables were the same, but the third was winter minimum temperature.

Astragalus osterhoutii is a species restricted to a 15-mile range near the town of Kremmling in Middle Park, found on seleniferous, brown-gray soils and often growing with sagebrush or on barrens. This species is federally listed as Endangered under the Endangered Species Act (CNHP 2022, USFWS 2022). For this species, habitat suitability is predicted to be completely lost under both the Hot and Dry and Warm and Wet scenarios (Figures 6, 7). The most important variables in the maxent model under both the Hot and Dry and Warm and Wet climate scenarios were distance to the Colorado Group and Coalmont Formation geology, minimum winter temperature, and spring precipitation.

Eutrema penlandii is an alpine species endemic to a 40-kilometer stretch of the Continental Divide in the Mosquito Range. This species is found in fens, usually associated with perennial snow melt and is federally listed as Threatened under the Endangered Species Act (CNHP 2022, USFWS 2022). For this species, habitat suitability is predicted to be completely lost under the Hot and Dry scenario; however, under the Warm and Wet scenario, much of the currently suitable habitat is persistent, with predicted loss on the edges of the range at lower elevations (Figure 8, 9). The most important variables in the maxent model under the Hot and Dry climate scenario were the distance to the Leadville formation, spring minimum temperature and winter precipitation respectively. For the Warm and Wet climate scenario, the most important variables were distance to the Leadville formation, mean winter temperature, and spring minimum temperature.

Frasera coloradensis is a Colorado endemic known only from the shortgrass prairie in the southeast corner of Colorado, growing in low sandy/sandstone breaks in grasslands, mixed prairie breaks or open pinyon-juniper woodlands (CNHP 2022). For this species, habitat suitability is predicted to be completely lost under the Hot and Dry scenario. Under the Warm and Wet scenario, there is only a small percentage of habitat remaining persistent and an even smaller area showing up as emergent in the southwest corner of the species range (Figures 10, 11). However, except for the southwest corner of the model under the Warm and Wet scenario, the future projected increases in summer temperatures by these models are so far outside of the historical conditions that they are considered to be novel conditions, and therefore, the model should be interpreted with low confidence. Unfortunately, presence-only models such as these perform poorly when projected onto novel conditions (Cory et al. 2013).

Ipomopsis polyantha is a narrow endemic found around Pagosa Springs on Mancos Shale associated with barrens and Ponderosa pine woodlands. This species is federally listed as Endangered under the Endangered Species Act (USFWS 2022). For this species, habitat suitability is projected to decline less under the Hot and Dry scenario versus the Warm and Wet scenario, which is an opposite result than expected (Figures 12, 13). This appears to be due to the model response to spring precipitation. Lower spring precipitation is favored consistently for all models, including the original model completed for CODEX under a different project. Seven runs of this model, trying different environmental factors, were completed, but the original model with this response appeared to be the closest to the accepted CODEX model. Biologically, it seems counterintuitive that lower spring precipitation would be associated with an increase in suitability of habitat; in the field botanists have observed a large flush of seedlings following a wet spring. It is therefore reasonable to conclude that this is again a limitation of Presence Only models. If the species only occurs in drier areas, the Maxent algorithm is constrained in its projections. Alternatively, this counterintuitive result may be due to the influence of microclimate, which is not accounted for in this model. Botanists in the field have observed higher densities of this species at the toe of slopes, near irrigation ditches or other areas where moisture may be retained. It is possible that this species is adapted to a microclimate which may change under a hotter and drier climate scenarios, but this change could not be accounted for in this model. Finally, another interesting result with this model was the prediction of species distribution north of Pagosa Springs, including an area of unoccupied but designated critical habitat on national forest lands surrounding the Piedra River. This area was not included in the model results for the original model created in CODEX. This area remains persistent in both the Hot and Dry and Warm and Wet climate scenarios.

Conclusion

Most distribution models for rare species, including those produced for this project, are based on recent historic climate conditions, and focused on identifying survey areas, in hopes of increasing our knowledge of the species range and population levels. Species distribution models intended to facilitate the development of adaptation strategies in response to rapidly changing environmental conditions must instead focus on changes in patterns of precipitation and temperature within a species range. The delineation of a species' climate envelope and evaluation of current population stressors, together with predicted degree of change in the near future, can provide direction for a variety of adaptive management strategies.

In this project, projections of suitable habitat under future climate scenarios were created using existing climatic input variables created for a 2019 project modeling a wide-ranging conservation element. Using readily available data allowed us to create these models quickly, but it limits our choice of climatic variables, how they are calculated, the GCM-RCP scenarios and the downscaling method. These projects suggest potential changes in suitable habitat (within the constraints of the modeled space) for the species under future climate scenarios, but the development of location-specific adaptation strategies based on these models should be done with caution. Future work to refine these models should include the creation of climatic input variables specific to rare plants using downscaled climate data currently seen as the most reliable , which could require a significant investment of time and money.

As expected for most rare and restricted-range species, Colorado's Plants of Greatest Conservation Need are nearly all highly vulnerable to changing environmental conditions, since they are apparently already adapted to narrow environmental niches. Of the species investigated under this effort all, except for *Ipmoposis polyantha*, are long-lived perennial species which may have a slower response to changing environmental conditions. For these long-lived perennial species, the climate projection models, especially under the Hot and Dry scenario, predicted almost a complete loss of suitable habitat. The pace of environmental change is fueling pressure to develop faster methods for identifying climate niche specialization and adaptive capacity, instead of relying on lengthy common garden studies and decades-long demographic monitoring. Adaptive management strategies for these species could be guided by species-specific, model-based investigation of climate constraints and tolerances.

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