# Distribution Modeling for
# Colorado SWAP Plants of Greatest Conservation Need

COLORADO NATURAL HERITAGE PROGRAM

WARNER COLLEGE
OF NATURAL RESOURCES
COLORADO STATE UNIVERSITY

*CNHP's mission is to advance the conservation of Colorado's native species and ecosystems through science, planning, and education for the benefit of current and future generations.*

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Recommended Citation:

Decker, K., J.P. Smith, J. Handwerk, G. Doyle. 2021. 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.

# 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, models of species distribution were created using information on known locations and species habitat requirements. These distribution models will be included in the conservation data sharing platform, the Colorado Conservation Data Explorer (CODEX), in order to help conserve and protect these PGCN though environmental review and conservation planning. The following objectives were met in this project:

## Objectives

1) Create distribution models for 45 of the 117 plant species listed in the Rare Plant Addendum of the SWAP (Table 1). 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, although with some loss of information.

2) Produce binary versions of the distribution models for inclusion in the Colorado Conservation Data Explorer (CODEX), being 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.

| Scientific Name | Common Name | Species Priority | Global & State Status Ranks | Federal Agency Status | % of Range in Colorado | CNHP 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 | LT | 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 |
| *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 |

| Scientific Name | Common Name | Species Priority | Global & State Status Ranks | Federal Agency Status | % of Range in Colorado | CNHP priority |
|---|---|---|---|---|---|---|
| *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 |

# Methods

## Occurrence update and review

Element occurrences for the 45 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) 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 105 new or updated Element Occurrence (EO) records were produced; the majority (85%) were from specimens dated 2000 and later, 10% represented older specimens, and 5% were from CNHP backlog files.

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 singlepart 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 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.

## 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, take into account 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. 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, however, 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, however, 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.

## Model review

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. The overall output range was classified into three tiers: unlikely (no modeled habitat), medium (values between the threshold for equal training sensitivity and specificity and 0.5, and high (0.5 or greater). 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 0.5, i.e., at least a 50% chance that the species would be present at the location according to the model. In some cases, for example if highly ranked EOs were not included in the modeled area with a 0.5 probability, the cut-off value was shifted to a lower probability to include more modeled habitat. Notes on deviations from the standard probability cut-off of 0.5 and/or clipped range extents are included in the Results section below by species. Expert review of the model for *Mimulus gemmiparus* was provided by Mark Beardsley of EcoMetrics, and his comments are included below.

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 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

Three models, for species *Oonopsis puebloensis*, *Oxybaphus rotundifolia*, and *Townsendia glabella*, required additional processing to erase values within a reservoir outline and eliminate predicted high quality but flooded habitat near high quality occurrences. This was accomplished by converting the polygon feature representing the reservoir to a raster (using the complete model raster as processing extent, snap raster, and raster analysis cell size in the Environment Settings window). Raster Calculator was then used to execute a statement of the following format to erase the reservoir from the full model: SetNull(~(IsNull("Reservoir_PolygonToRaster")),"Species_name.tif").

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 >=0.50 were classified with a value of 1. The binary raster was then clipped as specified by the reviewer. Clipping was done using an appropriate polygon shape as the clipping geometry. The final binary models with metadata will be 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, 89 Maxent model runs were made in order to produce the final 45 CODEX models. Nineteen species required only a single run to produce a satisfactory model, 17 needed a second run to incorporate corrected or additional factors, and nine species required additional runs. There was one species (*Pediocactus knowltonii*) where maximum entropy model runs failed to produce a satisfactory result and a deductive model was constructed instead, using soils, vegetation types, and climate factors matching conditions at the documented New Mexico occurrence.

Seventy-one separate environmental input layers were produced for use in this modeling effort (Appendix A), 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.

### *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 25°C (77°F). The modeled range extended 75 km (47 miles) east from nearest EO record, which seemed a reasonable extent for this under-surveyed species.

### *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.

### *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 -30°C (-22°F). 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 for CODEX was used to include additional habitat matching highly ranked EOs which were excluded at the 0.5 probability. 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.

### *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. 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.

### *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 -29C (-20F). Predicted habitat follows the known distribution around the two separated population centers.

### *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 28°C (82°F). Precipitation amounts in all seasons were also contributing factors, especially for winter and spring; totals across all seasons average nearly 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.

### *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.

### *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.

### *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). Close 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 follow the overall range of the species fairly closely.

### *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 was 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%.

### *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.

### *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. 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.

### *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 -35°C (-31°F). The classification cutoff used for CODEX was 0.45 to include more modeled habitat associated with known EO records.

### *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 39°C (102°F). 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.

### *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. Modeled habitat in Mesa and southern Garfield County were included in the final version, excluding a small area of modeled habitat in Montrose County at probabilities less than 0.5. 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.

### *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, shaley 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.

### *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.

In an expert review of this model, Mark Beardsley responded that the model looked reasonable at a broad spatial scale, although on a finer scale, the model did not always match the location of rock outcrops. In his review, Mark Beardsley suggested including landscape position as an environmental factor (mid-lower slopes with a drainage above), but this environmental input layer was not readily available. Some rock outcrops were excluded from modeled habitat, presumably based on other environmental factors, and some areas without rock outcrops were included presumably due to imprecise environmental input data.

### *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.

### *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.

### *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 connected with 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°C (-40°F). Sparse winter (driest season) precipitation and more abundant fall (wettest season) precipitation were characteristic. Modeled habitat matches the known distribution fairly closely.

### *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 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 Basinwide 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.

### *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.

### *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.

### *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 15$^{th}$, coldest winter temperatures generally not exceeding -28°C (18.4°F), and winter through summer precipitation averaging just over 27 cm (1 inch) 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.

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

The distribution of this calciphilic Colorado endemic species is similar in the main 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 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.

### *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 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.

### *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 about 5 by 3 km in the vicinity of the occurrence, on the uplands above Plateau Creek.

### *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 the known location. In Colorado, modeled areas are concentrated from south-central La Plata County to the southwestern corner of Archuleta County, generally south of Florida Mesa.

### *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°C (-40°F). Predicted habitat for this species occupies areas of slightly dryer, lower elevations and younger geologic substrates adjacent to that of *Penstemon scariosus* var. *cyanomontanus* (see below) while overlapping very little with that related species.

### *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.

### *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 fairly 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 part, 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.

### *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°C (-40°F) 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 tightly 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.

### *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.

### *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°C (-40°F). 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.

### *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).

### *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.

### *Physaria parviflora* (Piceance bladderpod), Tier 2

In common with other Piceance Basin endemics, this species is closely associated with shaley 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 35°C (95°F). 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.

### *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.

### *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 stands 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.

### *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.

### *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.

### *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.

### *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.

### *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.

# 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 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.

### Model access criteria

With the addition of the 45 species modeled in this project, modeled distribution for a total of 84 Plants of Greatest Conservation Need will be represented in the CODEX. The spatial display of the modeled distribution will not be visible to the user in CODEX; the modeled distribution will instead be used in the analysis for environmental review. Results will be returned in text or 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 all SWAP Tier 1 species have been modeled, there remain 33 SWAP Tier 2 Plants of Greatest Conservation Need lacking a species distribution model. Two SWAP Tier 2 species will need an updated model to include new element occurrence records. There are 29 of the older Tier 1 models produced as rapid assessment deductive models produced as binary surfaces; most would be improved by remodeling using better techniques.

There are an additional 30 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 of 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 Species of Concern lacking inductive species distribution models. With the exception of species species in shaded rows, all Tier 2 species have a rapid assessment deductive model.

| Scientific Name | Common Name | USFS | BLM | PGCN |
|---|---|---|---|---|
| *Aletes macdougalii* ssp. *breviradiatus* | Mesa Verde aletes | | | Tier 2 |
| *Amsonia jonesii* | Jones' bluestar | | X | |
| *Anticlea vaginatus* | Alcove death camas | | | Tier 2 |
| *Aquilegia chrysantha* var. *rydbergii* | Rydberg's golden columbine | X | X | |
| *Arabis crandallii (Boechera crandallii)* | Crandall's rockcress | | X | Tier 2 |
| *Astragalus cronquistii* | Cronquist milkvetch | | | Tier 2 |
| *Astragalus desperatus* var. *neeseae* | Elizabeth's milkvetch | | X | |
| *Astragalus detritalis* | debris milkvetch | | X | |
| *Astragalus duchesnensis* | Duchesne milkvetch | | X | |
| *Astragalus equisolensis* | Horseshoe milkvetch | | | Tier 2 |
| *Astragalus iodopetalus* | violet milkvetch | X | | Tier 2 |
| *Astragalus leptaleus* | park milkvetch | X | | |
| *Astragalus missouriensis* var. *humistratus* | Missouri milkvetch, Archuleta milkvetch | X | | Tier 2 |
| *Astragalus musiniensis* | Ferron's milkvetch | | X | |
| *Astragalus naturitensis* | Naturita milkvetch | | X | Tier 2 |
| *Astragalus piscator* | Fisher Towers milkvetch | | X | Tier 2 |
| *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 ciscoensis* | Cisco sego lily | | | Tier 2 |
| *Calochortus flexuosus* | winding mariposa lily | X | | |
| *Carex diandra* | lesser panicled sedge | X | | |
| *Chenopodium cycloides* | sandhill goosefoot | X | | |
| *Cirsium perplexans* | Adobe thistle | | | Tier 2 |
| *Cryptantha caespitosa* | tufted cryptantha | | X | |
| *Cryptantha osterhoutii* | Osterhout's cryptantha | | X | |
| *Cryptantha rollinsii* | Rollins' cryptantha | | X | |
| *Cryptogramma stelleri* | fragile rockbrake | | X | |
| *Cymopterus duchesnensis* | Uinta Basin springparsley | | X | |
| *Cypripedium parviflorum* | lesser yellow lady's slipper | X | | |
| *Delphinium ramosum* var. *alpestre* | Colorado larkspur | | | Tier 2 |
| *Delphinium robustum* | Wahatoya Creek larkspur | | | Tier 2 |

| Scientific Name | Common Name | USFS | BLM | PGCN |
|---|---|---|---|---|
| *Descurainia torulosa* | mountain tansymustard | X | | |
| *Draba graminea* | Rocky Mountain draba, San Juan whitlow-grass | | | Tier 2 |
| *Drosera anglica* | English sundew | X | | |
| *Drosera rotundifolia* | roundleaf sundew | X | | |
| *Epipactis gigantea* | stream orchid, giant helleborine | X | | |
| *Erigeron kachinensis* | Kachina daisy | | X | Tier 2 |
| *Eriogonum acaule* | singlestem buckwheat | | X | |
| *Eriogonum clavellatum* | Comb Wash buckwheat | | X | Tier 2 |
| *Eriogonum coloradense* | Colorado buckwheat | | X | Tier 2 |
| *Eriogonum contortum* | grand buckwheat | | X | |
| *Eriogonum ephedroides* | ephedra buckwheat | | X | |
| *Eriogonum exilifolium* | dropleaf buckwheat | X | | |
| *Eriogonum tumulosum* | Woodside buckwheat | | X | |
| *Eriogonum viridulum* | clay hill buckwhea | | X | |
| *Eriophorum chamissonis* | Chamisso's cottongrass | X | | |
| *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 | | |
| *Lepidium crenatum* | alkaline pepperwort | | | Tier 2 |
| *Limnorchis zothecina* | alcove bog orchid | | | Tier 2 |
| *Lomatium concinnum* | Colorado desert-parsley | | X | Tier 2 |
| *Lomatium latilobum* | Canyonlands biscuitroot | | X | |
| *Malaxis monophyllos* var. *brachypoda* | white adder's-mouth orchid | X | | |
| *Mentzelia paradoxensis* | Paradox stickleaf | | | Tier 2 |
| *Mertensia humilis* | Rocky Mountain bluebells | | | Tier 2 |
| *Neoparrya lithophila* | Bill's neoparrya | X | X | |
| *Oreocarya osterhoutii* | Osterhout cat's-eye | | | Tier 2 |
| *Parthenium ligulatum* | Colorado feverfew | | X | |
| *Pediomelum aromaticum* | aromatic Indian breadroot | | X | |
| *Penstemon harringtonii* | Harrington's beardtongue | X | X | |
| *Penstemon mensarum* | Grand Mesa penstemon | | | Tier 2 |
| *Physaria alpina* | Avery Peak twinpod | | | Tier 2 |
| *Physaria pruinosa (Lesquerella pruinosa)* | Pagosa Springs bladderpod | X | X | Tier 2 |
| *Rubus arcticus* ssp. *acaulis* | dwarf raspberry | X | | |
| *Salix arizonica* | Arizona willow | X | | Tier 2 |
| *Salix myrtillifolia* | blueberry willow | X | | |
| *Selaginella selaginoides* | club spikemoss | X | | |
| *Sisyrinchium pallidum* | pale blue-eyed grass | | X | |

| Scientific Name | Common Name | USFS | BLM | PGCN |
|---|---|---|---|---|
| *Sphaeromeria capitata* | rock tansy | | X | |
| *Sphagnum angustifolium* | sphagnum | X | | |
| *Sphagnum balticum* | Baltic sphagnum | X | | |
| *Thelypodiopsis juniperorum* | juniper tumble mustard | | | Tier 2 |
| *Thelypodium paniculatum* | northwestern thelypody | | | Tier 2 |
| *Townsendia fendleri* | Fendler's townsend-daisy | | | Tier 2 |
| *Townsendia strigosa* | hairy Townsend daisy | | X | |
| *Trichophorum pumilum* | Rolland's bulrush | | X | |
| *Trifolium dasyphyllum* ssp. *anemophilum* | Whip-root clover | | | Tier 2 |
| *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, a more detailed rock outcrop layer would be beneficial for *Mimulus gemmiparus*. 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 *Oenothera acutissima, Draba weberi,* and species of hanging garden 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 listed Piceance Basin *Physaria* species (Decker et al. 2013). Or, as with the rock outcrop layer for *M. gemmiparus*, and the CNHP-developed shale barrens layer, identify important factors which can be fairly 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.

Climatic (temperature and precipitation patterns)
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 a number of 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.

Topographic (elevation and related factors including slope, aspect, and other terrain descriptors);
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.

Biophysical (vegetation and hydrology related)
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 by 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 survey 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.

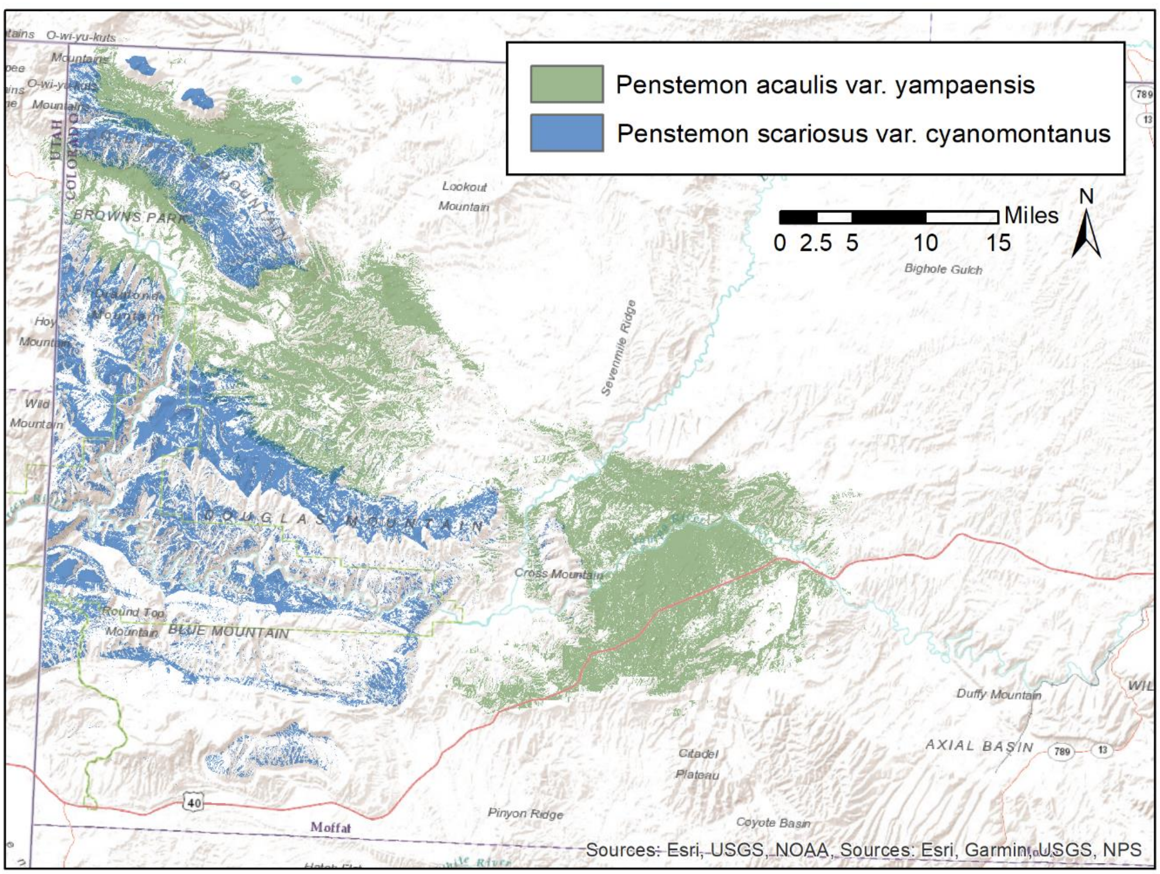

**Figure 1**. Modeled suitable habitat for two rare penstemon species in Moffat County, Colorado.

### 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. Unquestionably 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* (Appendix C).

## 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 over 70% of 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 understudied 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

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 |
|---|---|
| annual_ppt | **Environmental Input layer: Annual Precipitation**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| aprilmintemp<br>(apr_mintemp) | **Environmental Input layer: April Minimum Temperature**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| average_clay | **Environmental Input layer: Average % clay in soil**<br>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<br>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<br>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).<br><br>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**<br>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<br>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<br>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).<br>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**<br>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<br>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<br>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).<br>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. |
| avg_firstfrost | **Environmental Input layer: Average First Frost**<br>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/).<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |

| Raster name | Metadata entry |
|---|---|
| avg_lastfrost | **Environmental Input layer: Average Last Frost**<br>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/).<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| co_ned30m | **Environmental Input layer: 30m Digital Elevation Model for Colorado**<br>Source citations: U.S. Geological Survey. 2006. 30m Digital Elevation Model for Colorado. Raster digital data. http://seamless.usgs.gov/website/seamless/viewer.php<br><br>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)**<br>Scource 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<br><br>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. |
| colo_geol | **Environmental Input layer: Colorado Geology**<br>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/<br><br>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)**<br>Scource 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<br><br>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. |

| Raster name | Metadata entry |
|---|---|
| colo_nvcveg_nodev | **Environmental Input layer: National Vegetation Classification (NVC), not including developed areas**<br>Scource 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<br><br>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. |
| dist_brownspk | **Environmental Input layer: Distance to Browns Park Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Kcg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |
| dist_cutler | **Environmental Input layer: Distance to Cutler Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved.<br><br>Polygons with NAME attribute Pc were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |

| Raster name | Metadata entry |
| --- | --- |
| dist_dry_union | **Environmental Input layer: Distance to Dry Union Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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**<br>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/.<br><br>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. |
| dist_fr_hogback_shales | **Environmental Input layer: Distance to shale and sandstone units forming the Front Range (Dakota) hogback north of Colo Spgs.**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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_granitic_Yg | **Environmental Input layer: Distance to granitic rocks of 1,400-MY age group**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Yg were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |

| Raster name | Metadata entry |
|---|---|
| dist_greasewood | **Environmental Input layer: Distance to Inter-Mountain Basins Greasewood Flat ecological system**<br>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<br><br>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. |
| dist_greenriv | **Environmental Input layer: Distance to Green River Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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**<br>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<br>Colorado Division of Wildlife. 2004. Colorado Vegetation Classification Project; Statewide Mosaic. Raster digital data.<br><br>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 rasers 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 Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved.<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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_leadville | **Environmental Input layer: Distance to units containing Leadville (& Manitou) Limestone**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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 Shale in six-quad area**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved.<br><br>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_morrison | **Environmental Input layer: Distance to Morrison Fm, all units**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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 Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Kn were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |
| dist_nvcfm06c02 | **Environmental Input layer: Distance to Semi-Desert Nonvascular & Sparse Vascular Vegetation NVC formation**<br>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<br><br>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 Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Tgp were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |

| Raster name | Metadata entry |
|---|---|
| dist_pb_glac | **Environmental Input layer: Distance to Glacial drift of Pinedale and Bull Lake age**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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 occurrances**<br>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).<br><br>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. |
| dist_pem | **Environmental Input layer: Distance to Palustrine Emergent wetland types**<br>Source citation: U.S. Fish and Wildlife Service. 2016. CONUS_wet_poly_West; CO_Wetlands, National Wetlands Inventory - Version 2. Vector ditigal data, 1:12,000. https://www.fws.gov/wetlands/Data/Data-Download.html<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved.<br><br>Polygons with NAME attribute Qae were selected, exported, and used as the input feature source data for generating a Euclidian Distance raster. |

| Raster name | Metadata entry |
| --- | --- |
| dist_raton | **Environmental Input layer: Distance to Raton Fm**<br>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/<br>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<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Tkr were selected, exported, merged, and 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)**<br>Scource 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.<br><br>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_saturated | **Environmental Input layer: Distance to saturated wetlands**<br>Source citation: U.S. Fish and Wildlife Service. 2016. CONUS_wet_poly_West; CO_Wetlands, National Wetlands Inventory - Version 2. Vector ditigal data, 1:12,000. https://www.fws.gov/wetlands/Data/Data-Download.html<br><br>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<br>Scource 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<br><br>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. |

| Raster name | Metadata entry |
|---|---|
| dist_shale_barren | **Environmental Input layer: Distance to Shale Barrens**<br>Source citation: Decker, Karin. 2021. Shale Barrens of Southeastern Colorado. Vector digital data, 1:12,000. Colorado Natural Heritage Program, unpublished data.<br><br>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**<br>Scource 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<br><br>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. |
| dist_springs | **Environmental Input layer: Distance to springs**<br>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.<br><br>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_tiptwilk | **Environmental Input layer: Distance to Tipton Tongue of Green River Fm (includes Wilkins Peak member)**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>Polygons with NAME attribute Tgt were selected, exported, merged, and used as the input feature source data for generating a Euclidian Distance raster. |

| Raster name | Metadata entry |
| --- | --- |
| dist_td_kjdr | **Environmental Input layer: Distance to Dry Union fm (Td) and part of Dakota/Purgatoire/Morrison/Ralston Cr fms (Kjdr)**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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. |
| dist_troublesome | **Environmental Input layer: Distance to Troublesome Fm**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13. Units sharing boundaries across quads were dissolved.<br><br>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**<br>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/<br><br>Original ARC/INFO data was converted to ArcGIS shapefile and projected to UTM_NAD83_Zone13.<br><br>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. |

| Raster name | Metadata entry |
| --- | --- |
| dist_water | **Environmental Input layer: Distance to water**<br>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<br><br>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.<br><br>NHDFlowline: ("FType" = 460 OR "FType" = 558) AND (("FCode" = 46000 OR "FCode" = 46006) OR ("GNIS_Name" IS NOT Null))<br><br>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<br><br>NHDPoint: "FType" = 458 |
| dry_days_fall | **Environmental Input layer: Average number of days during fall (Sep-Oct-Nov) with precipitation <=5mm**<br>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/).<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental input. |
| eastness | **Environmental Input layer: Eastness (aspect)**<br>Source citation: Colorado Natural Heritage Program. 2011. Unpublished data using USGS 30m DEM. Raster digital data.<br><br>The Elevation raster was used to create an Aspect raster, which was then used to create two separate rasters representing northness and eastness.<br>northness = cos(aspect)<br>eastness = sin(aspect)<br><br>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 |

| Raster name | Metadata entry |
| --- | --- |
| frostday | **Environmental Input layer: Number of days per year with minimum temperature at or below freezing**<br>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<br><br>Daymet annual number of frost days for Colorado. Units are days. Daymet represents an average from 1980 - 1997, at 1 kilometer resolution. Raster was downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| jan_mintemp | **Environmental Input layer: January Minimum Temperature**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| LDI | Environmental Input layer: Landscape Disturbance Index (LDI)<br>Source citation: Colorado Natural Heritage Program. 2020. Landscape Disturbance Index Layer for Colorado. Raster digital data. Colorado Natural Heritage Program, Fort Collins, CO<br><br>This represents 8 individually modeled anthropogenic impacts that were then combined into a single layer. Impacts represented are:<br>* Agriculture<br>* Urban Development<br>* Oil and Gas Development<br>* Surface Mining<br>* Roads and Trails<br>* Wind turbines<br>* Solar installations<br><br>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. |

| Raster name | Metadata entry |
|---|---|
| marchmintemp | **Environmental Input layer: March minimum temperature**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| max_summertemp | **Environmental Input layer: Maximum summer temperature**<br>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/).<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| maymintemp<br>(may_mintemp) | **Environmental Input layer: May minimum temperature**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| min_wintertemp | **Environmental Input layer: Minimum winter temperature**<br>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/).<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |

| Raster name | Metadata entry |
|---|---|
| northness | **Environmental Input layer: Northness (aspect)**<br>Source citation: Colorado Natural Heritage Program. 2011. Unpublished data using USGS 30m DEM. Raster digital data.<br><br>The Elevation raster was used to create an Aspect raster, which was then used to create two separate rasters representing northness and eastness.<br>northness = cos(aspect)<br>eastness = sin(aspect)<br><br>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 |
| ppt_s1 | **Environmental Input layer: Winter Precipitation**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| ppt_s2 | **Environmental Input layer: Spring Precipitation**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| ppt_s3 | **Environmental Input layer: Summer Precipitation**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |

| Raster name | Metadata entry |
|---|---|
| ppt_s4 | **Environmental Input layer: Fall Precipitation**<br>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<br><br>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 downsampled to 30m, re-projected and snapped to be compatible with other environmental inputs. |
| relief | **Environmental Input Layer: Local Relief**<br>Source citation: Derived from U.S. Geological Survey. 2006. 30m Digital Elevation Model for Colorado. Raster digital data.<br>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**<br>Source citations: United States Forest Service. 2006. LANDFIRE Current Vegetation for Colorado. Raster digital data, 30m. http://landfire.cr.usgs.gov/viewer/viewer.html<br>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<br>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.<br>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.<br>NHDWaterbody: "FType" = 361 OR "FType" = 466 OR "FCode" = 39001 OR "FCode" = 39005 OR "FCode" = 39006<br>LandFire Current Veg: "SYSTMGRPNA" LIKE '%Riparian%' OR "SYSTMGRPNA" LIKE '%Wet% |
| shortgrass_mod2 | **Environmental Input layer: Boosted Regression Tree model of Shortgrass Prairie in Colorado.**<br>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.<br><br>This a distribution model produced using the Boosted Regression Tree method, with values representing an approximate probability of shortgrass praire occurrence at each cell. Original raster was resampled and snapped to the reference extent. |
| slope_deg | **Environmental Input layer: Slope (degrees)**<br>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**<br>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.<br><br>Images from each year were reprojected, clipped to the reference extent, and averaged. Snow persistence index represents the fraction of time that snow is present on the ground for a defined period (annual values). |
| soil_pct_org | **Environmental Input layer: Average % organic matter in soil**<br>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<br>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<br>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).<br><br>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. |
| soil_ph | **Environmental Input layer: Soil pH**<br>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<br>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<br>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).<br><br>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. |

| Raster name | Metadata entry |
|---|---|
| Soils (Pediocactus Knoltownii) | **Environmental Input layer: Soil units at and adjacent to known location of Pediocactus knoltownii**<br>Source citations: NRCS. 2012. Gridded Soil Survey Geographic (gSSURGO) Databases for Colorado and New Mexico. United States Department of Agriculture, Natural Resources Conservation Service. Available at http://datagateway.nrcs.usda.gov. November 20, 2012 (FY2013 official release).<br><br>Data for Colorado and New Mexico was downloaded. The MUPOLYGON vector files wer reprojected, merged, converted to raster, clipped to reference extent, and snapped to be compatible with other environmental inputs. This is a categorial dataset. |
| ssurgo_depth_cm | **Environmental Input layer: Soil depth**<br>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<br>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<br>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).<br><br>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**<br>Source citation: Colorado Natural Heritage Program. 2021. Unpublished data using USGS 30m DEM. Raster digital data.<br><br>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. |

## 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 really 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 specifity, 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 agree (next highest value) as moderate probability, etc.

# Appendix C: Revised model for *Eriogonum brandegeei*

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.

### *Eriogonum brandegeei* (Brandegee wild buckwheat), Tier 1

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, and are able to tolerate extreme summer temperatures 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.

# 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 output 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. 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. 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 for the period 1980-2012 to represent current climate normals. 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).

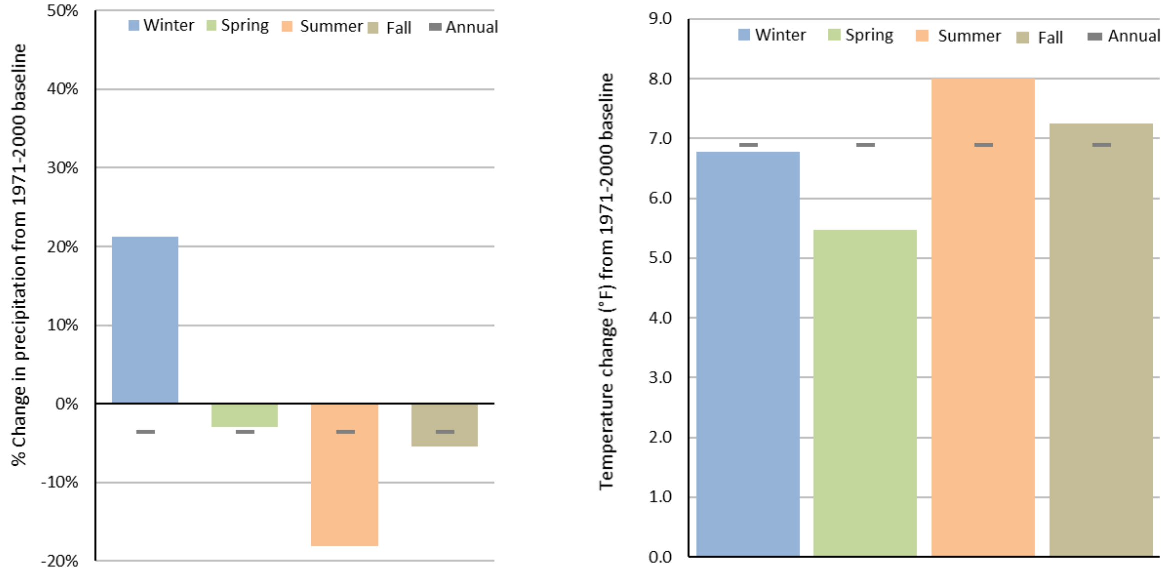


**Figure 1.** Graphs of the % change in precipitation and temperature change from baseline conditions between 1971-2000 in in the "hot and dry" scenario predicted in the hadgem2.es.1.rcp85 climate model for the 30-year period centered around 2050.

**Table 1.** Comparisons of the relative contributions of model inputs for the two "current" distribution models. The model on the left 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 downsampled to 30m. The model on the right used the hadgem2.es.1.rcp85 climate model, taking data from 1980-2012 to represent current climate normal.

**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 |
| 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 |

**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 |
| 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 |

| Variable | Percent contribution | Permutation importance |
|---|---|---|
| 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 |
|---|---|---|
| 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 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). The data is based on the average values over the period 1980-2012. 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.

**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.

This test run made clear that comparable climate change focused models of future habitat for PGCN would require a significant climate data preparation effort. 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. 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.

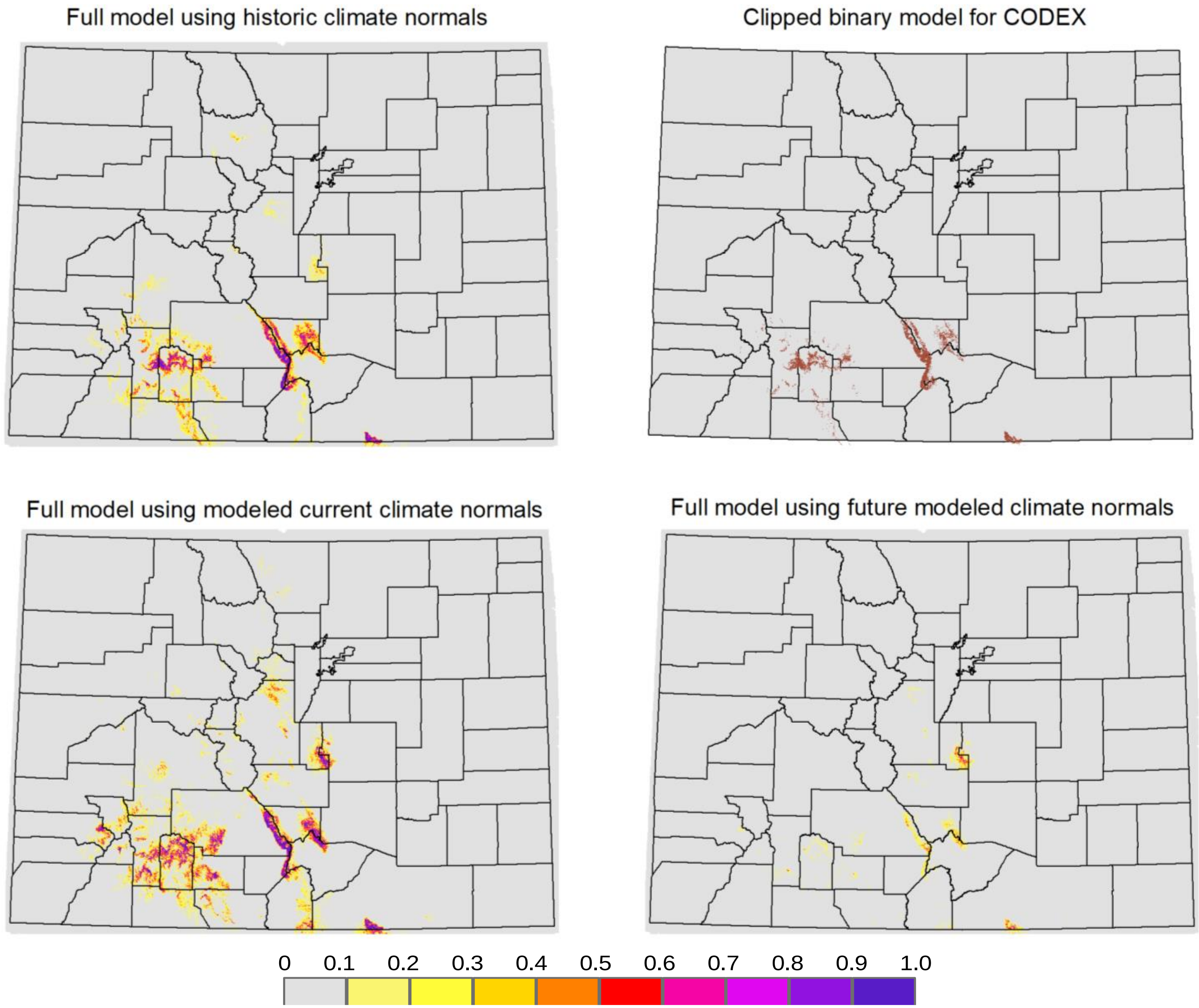


**Figure 2.** Top row: predicted model habitat using Daymet climate data, with the model on the left showing the full distribution probability (0-1) and the model on the right showing the CODEX version with probability greater than or equal to 0.5 probability. Bottom row: predicted modeled habitat using climate data from hadgem2.es.1.rcp85 climate model, with the model on the left showing conditions under the current time frame, i.e., 1980-2012, and the one on the right showing a future time frame, the 30 year period centered around 2050.