Pocket gopher (*Thomomys talpoides*) soil disturbance peaks at mid elevation and is associated with air temperature, forb cover, and plant diversity

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Supplementary Material

**Table S1.** GPS coordinates and elevation of each site within a transect.

| Peak       | Latitude (°) | Longitude (°) | Elevation (m) |
|------------|--------------|---------------|---------------|
| Avery      | 38.86548     | -106.91236    | 2711          |
| Avery      | 38.86523     | -106.91238    | 2812          |
| Avery      | 38.95136     | -106.98636    | 2896          |
| Avery      | 38.96224     | -106.98546    | 2982          |
| Avery      | 38.96594     | -106.98281    | 3135          |
| Avery      | 38.97142     | -106.98428    | 3192          |
| Avery      | 38.97529     | -106.97827    | 3347          |
| Avery      | 38.92741     | -106.97823    | 3455          |
| Avery      | 38.98407     | -106.97021    | 3655          |
| Cinnamon   | 38.88163     | -106.96172    | 2749          |
| Cinnamon   | 38.89727     | -106.97899    | 2799          |
| Cinnamon   | 38.93460     | -107.01078    | 2932          |
| Cinnamon   | 38.94540     | -107.02822    | 3025          |
| Cinnamon   | 38.96168     | -107.03091    | 3181          |
| Cinnamon   | 38.96189     | -107.03879    | 3223          |
| Cinnamon   | 38.97018     | -107.02955    | 3366          |
| Cinnamon   | 38.99111     | -107.06497    | 3416          |
| Cinnamon   | 38.99356     | -107.06754    | 3579          |
| Cinnamon   | 38.99463     | -107.06913    | 3665          |
| Cinnamon   | 38.99495     | -107.07043    | 3726          |
| Hunters Hill | 38.84759   | -106.81964    | 2824          |
| Hunters Hill | 38.90366   | -106.78383    | 3060          |
| Hunters Hill | 38.92538   | -106.77776    | 3171          |
| Hunters Hill | 38.92596   | -106.79232    | 3249          |
| Hunters Hill | 38.92683   | -106.79105    | 3322          |
| Hunters Hill | 38.92963   | -106.78896    | 3430          |
| Hunters Hill | 38.93297   | -106.78699    | 3531          |
| Hunters Hill | 38.93762   | -106.78742    | 3629          |
| Hunters Hill | 38.94084   | -106.78776    | 3724          |
| Hunters Hill | 38.94595   | -106.78773    | 3827          |
| Ruby       | 38.86430     | -107.03173    | 2822          |
| Ruby       | 38.85617     | -107.06954    | 2945          |
| Ruby       | 38.86447     | -107.10579    | 3055          |
| Ruby       | 38.87421     | -107.10598    | 3128          |
| Ruby       | 38.88382     | -107.11328    | 3199          |
| Ruby       | 38.89454     | -107.11722    | 3333          |
| Ruby       | 38.90226     | -107.11630    | 3447          |
Table S2. There was significant spatial autocorrelation in five out of the six predictor variables. For each predictor, Moran’s I estimates the amount of spatial autocorrelation for a given predictor, such that high values indicate high spatial autocorrelation. Each Moran’s I is accompanied by a standard deviation estimate (SD) and a p-value.

| Predictor         | Moran’s I    | SD             | p-value   |
|-------------------|--------------|----------------|-----------|
| Forb:grass        | 0.06548605   | 0.04408553     | 0.0674    |
| Inverse Simpsons’| 0.09267314   | 0.04680174     | 0.0212    |
| Sine aspect       | 0.1270489    | 0.04701599     | 0.0025    |
| Cosine aspect     | 0.1463025    | 0.04624237     | 0.0005    |
| Soil depth        | 0.2016100    | 0.04644518     | <0.0001   |
| MAT               | 0.3085896    | 0.04684599     | <.00001   |
**Supplementary Methods S1- Climate interpolation detailed methodology and results**

All code and data associated with this document are available upon request to Joshua Lynn (jslynn@unm.edu) or Jennifer Rudgers (jrudgers@unm.edu).

**METHODS**

*Data compilation*

We compiled climate data from 29 weather stations in Gunnison and Pitkin Counties, Colorado (Table S3, Fig. S1). Slope, elevation, and aspect for each station were obtained from USGS digital elevation models (DEM; Dollison 2010), based on the station's reported latitude and longitude. Weather stations varied in the period of record, therefore, while the data are useful for interpolating climate means, we do not recommend using them to interpolate values for a given year, without investigating the level of basin-wide coverage in that time period. More recent years will have complete coverage.

Daily data are available in the file: *allclimatedata_oct2016.csv*

*Climate yearly summaries*

We gap-filled missing data only for days that were flanked on both sides by available data, and did so by taking the average of the single prior day and single subsequent day. We then calculated annual summaries of climate variables over each water year (1 Oct - 30 Sep). For the calculation of average summer temperature, we excluded four outlier observations <0°C from Porphyry Creek (station 25) during 1989. The mean cumulative growing degree days (GDD) was determined over the period of 1 Jun - 30 Sep using a base temperature of 0°C (Frank and Hofmann 1989). GDD is particularly useful because it provides an integrated measure of temperature combined with the length of the growing season. Mean annual precipitation (MAP) and mean snow depth (MSD) were calculated for each water year over the full period of record of each weather station (Table S3). Because snow depth is highly locally variable, we urge caution in interpolating snow depth data to new sites. Our process excluded data that may be compromised by missing observations due to temporary equipment failures. We used GDD and snow depth data from a station × water year combination only if <5% of days in a given water year were missing data. We used annual precipitation data only if <10% of days in a given water year were missing data, under the assumption that this decision could be less conservative than for temperature or snow depth because many days have zero precipitation, and MAP is a cumulative, rather than average, metric.

R script to create the yearly summaries: *GunnisonBasinYearlyMet.R*

Yearly data summary produced by this script: *GunnisonBasinYearlyMet.csv*

*Slope, aspect, elevation from Digital Elevation Models*

For each meteorological station and each site for which we wished to predict climate, we determined the median value of slope, aspect, and elevation from “The National Map” DEMs, provided by the USGS (Dollison 2010). All GIS analyses were performed in QGIS (QGIS Development Team 2017). DEMs were used to create layers containing slope and aspect data.
for the region (*r.slope.aspect*; GRASS Development Team 2017). Coordinates for the weather station were then given a circular buffer area with a radius of 10m (*Fixed distance buffer* tool; GRASS Development Team 2017). Slope, elevation and aspect values for each weather station were taken as the median for the buffer area, with aspect converted to radians.

**DEM data for each weather station:** GunnisonBasinDEM.csv

Fig. S1. Map of weather stations in Gunnison and Pitkin Counties, Colorado, used for climate interpolation.

### Climate regression models

To determine coefficients to interpolate climate for locations of biological observations that lacked weather stations, we used model selection procedures based on the second order Akaike Information Criterion (*AICc*), following Anderson (2008) and Burnham and Anderson (2002). This method predicts each climate variable from the best combination of elevation, slope, and aspect according to the minimum *AICc*, which discounts for model complexity and corrects for bias due to sample size. Aspect was included in models as sine (aspect) + cosine (aspect) to account for the circularity in this metric. The sine of aspect represents the east-west gradient (1=east), and the cosine of aspect accounts for north-south variation (1=north). We initially tested each climate variable for significant nonlinearities against elevation, slope, and aspect, and detected none. We therefore used linear equations to interpolate climate for each location of biological data collection. We also examined models that included latitude and
longitude; however, these predictors were weak, and should not have a directional influence at the small spatial scale of the Upper Gunnison Valley Basin (I. Rangwala, pers. comm.).

The set of eight candidate models included all predictors (1 model: elevation + slope + sin(aspect)+cos(aspect)), all sets of two predictors (3 models), single predictors alone (3 models), and the null model, which included only random effects. All linear mixed effect models included the random effects of station identity and water year to account for the lack of independence of observations from the same location or same time period (lmer function in lme4 package, R Core Team 2016). We tested all models for assumptions of normality of residuals and homogeneity of variances, and used outlier exclusions (<9 observations per variable) to meet model assumptions rather than imposing transformations on the data that would alter interpretability.

When the best model included multiple predictors, we examined correlations among the predictors and tested for possible multicollinearity using the vif function in car; we found no violation of multicollinearity. When models were similar in AICc (delta < 2) we selected the model with more predictors and higher $R^2$ to increase resolution of the prediction. We obtained marginal and conditional likelihood $R^2$ for the best candidate models using the sem.model.fits function in the piecewiseSEM package implemented in R (Lefcheck 2015; Nakagawa and Schielzeth 2013, R Core Team 2016). Marginal $R^2$ describes the proportion of variance explained by the fixed factors alone, whereas conditional $R^2$ describes the proportion of variance explained by both the fixed and random factors. We used likelihood ratio $X^2$ tests to evaluate the statistical significance of individual predictors within the best model.

**R script to build regression models:** [GunnisonBasinInterpolation.R](#)

**Climate interpolation**

To predict average yearly climate variables for a new set of sites, we used the predict function in R stats package. For each climate variable, we generated two prediction models. The first included the random effects of site and year to account for non-independence of observations at those scales and generate year-specific predictions (p1). The second returns the average predicted value, without random effects in the model (p2). Standard errors of predictions are not easily computed because of the difficulty in incorporating uncertainty in the variance parameters, and we have not tackled the uncertainty issue.

**R script for prediction is at the end of:** [GunnisonBasinInterpolation.R](#)

**RESULTS**

Coefficients from the best model for each climate variable appear in Table S4. Datasets differed in coverage over the range of elevation, slope, and aspect (Table S3). Even though predictions were linear, we caution predicting outside of this range, especially at the highest elevations, where weather station data were most limited.

Temperature variables strongly declined with elevation, with a marginally positive influence of slope. Mean yearly minimum temperature was not explained by any predictors; the
null model had the lowest $AIC_c$. Thus, minimum temperatures should not be interpolated using this dataset. Minimum temperatures in Gunnison, CO (2420 m) are often lower than those at higher elevation, which may explain the lack of influence of elevation for this variable.

Precipitation variables consistently increased with elevation, but some also had relationships with slope and aspect. Mean annual precipitation was primarily influenced by elevation, with equivalently weak influences of both north-south and east-west axes of aspect. This pattern was likely driven by the higher snow depths in west-facing sites and the higher summer precipitation in south-facing sites.

Mean snow depth increased with elevation, and west-facing slopes had deeper snow, with no significant influence of the north-south gradient of aspect. Slope had no meaningful influence on mean snow depth, but because of the location of weather station sites, coverage did not include slopes > 30. Given the local-scale variability of snow depth, we suggest using caution when interpolating that variable, despite the relatively high marginal $R^2$.

Mean summer precipitation increased with elevation, slope, and in south-facing sites [cosine (aspect)]. However, the low marginal $R^2$ (Table S4) and high variability suggests using caution when interpolating this variable to other sites using our models.

**Significant contributors (for Acknowledgements):**

*If you use these data or their products, please acknowledge:* Melanie Kazenel acquired and gap-filled the climate dataset and constructed initial models. Joshua Lynn and Jennifer Rudgers conducted statistical analyses in consultation with Imitaz Rangwala (University of Colorado, Boulder) and Shannon Sprott (Rocky Mountain Biological Laboratory). This work was funded by NSF DEB#1354972.

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Nakagawa, S., and H. Schielzeth. 2013. A general and simple method for obtaining $R^2$ from generalized linear mixed-effects models. Methods in Ecology and Evolution 4(2): 133-142. DOI: 10.1111/j.2041-210x.2012.00261.x
### Table S3

Locality information of weather stations from which climate data were aggregated, along with data collection period of record and data source (RMBL = Rocky Mountain Biological Laboratory, NRCS = USDA Natural Resources Conservation Service, SCENIC = Southwest Climate and Environmental Information Collaborative). Elevation is given in m. Slope and aspect data were not available for Bison Lake; it was excluded from analyses.

| Station Name                  | Number | Elevation | Latitude  | Longitude  | Record       | Source   |
|-------------------------------|--------|-----------|-----------|------------|--------------|----------|
| Billy Barr                    | 1      | 2917      | 38.9631   | -106.9933  | 2011-2015   | RMBL     |
| Bison Lake                    | 11     | 3316      | 39.7649   | -107.3568  | 1987-2015   | NRCS     |
| Brumley                       | 12     | 3231      | 39.0877   | -106.5417  | 1981-2015   | NRCS     |
| Butte                         | 13     | 3097      | 38.8943   | -106.9530  | 1982-2015   | NRCS     |
| Chapman Tunnel                | 14     | 3082      | 39.2622   | -106.6293  | 2008-2015   | NRCS     |
| Cochetopa Pass                | 15     | 3054      | 38.1628   | -106.5988  | 2005-2015   | NRCS     |
| Crested Butte                 | 6      | 2702      | 38.8739   | -106.9769  | 1981-2015   | NRCS     |
| Crested Butte 6.2N            | 7      | 3292      | 38.9603   | -106.9908  | 2006-2015   | SCENIC   |
| Gunnison 6.6N                 | 8      | 2420      | 38.6391   | -106.9408  | 2010-2015   | SCENIC   |
| Independence Pass             | 16     | 3231      | 39.0754   | -106.6117  | 1982-2015   | NRCS     |
| Ivanhoe                       | 17     | 3170      | 39.2920   | -106.5492  | 1993-2015   | NRCS     |
| Judd Falls                    | 2      | 3004      | 38.9417   | -106.9731  | 2010-2015   | RMBL     |
| Kettle Ponds                  | 3      | 2860      | 38.5941   | -106.9731  | 2010-2015   | RMBL     |
| Kiln                          | 18     | 2926      | 38.3172   | -106.6145  | 1981-2015   | NRCS     |
| Marble 0.5NNW                 | 9      | 2565      | 39.0791   | -107.1906  | 2011-2015   | SCENIC   |
| McClure Pass                  | 19     | 2896      | 39.1290   | -107.2881  | 1981-2015   | NRCS     |
| Mexican Cut                   | 4      | 3412      | 39.0283   | -107.0636  | 2010-2015   | RMBL     |
| Nast Lake                     | 20     | 2652      | 39.2972   | -106.6069  | 1987-2015   | NRCS     |
| North Lost Trail              | 21     | 2804      | 39.0781   | -107.1439  | 1986-2015   | NRCS     |
| Overland Reservoir            | 22     | 2999      | 39.0906   | -107.6347  | 1990-2015   | NRCS     |
| Park Cone                     | 23     | 2926      | 38.8200   | -106.5897  | 1981-2015   | NRCS     |
| Park Reservoir                | 24     | 3036      | 39.0464   | -107.8741  | 1981-2015   | NRCS     |
| Porphyry Creek                | 25     | 3280      | 38.4888   | -106.3397  | 1981-2015   | NRCS     |
| Saint Elmo                    | 26     | 3213      | 38.6998   | -106.3680  | 2008-2015   | NRCS     |
| Sargents Mesa                 | 27     | 3514      | 38.2856   | -106.3707  | 2010-2015   | NRCS     |
| Schofield Pass                | 28     | 3261      | 39.0152   | -107.0488  | 1986-2015   | NRCS     |
| Snodgrass                     | 5      | 3396      | 38.9331   | -106.9861  | 2010-2015   | RMBL     |
| Taylor Park Colorado          | 10     | 3173      | 38.9078   | -106.6017  | 1989-2015   | SCENIC   |
| Upper Taylor                  | 29     | 3243      | 38.9908   | -106.7542  | 2010-2015   | NRCS     |
Table S4. Coefficients for regressions of climate variables on elevation, slope, and aspect.

| Climate variable          | Intercept | Elevation | Slope | sin(Aspect) | cos(Aspect) | Model | Observed Range | N  | Elevation Range | Slope Range | Aspect Range |
|---------------------------|-----------|-----------|-------|-------------|-------------|-------|----------------|----|----------------|-------------|--------------|
| Temperature (°C)          |           |           |       |             |             |       |                |    |                |             |              |
| Mean Annual Temperature   | 12.28     | 2.56      | -0.0036 | 0.0099 | 0.0044 | 0.0185 | 2.43 | 0.1188 | 0.21 | 0.88 | 4.61 | 1.05 | 0.28 | 517 | 509 - 301 | 2.2 - 30.1 |
| Average Summer Temperature| 26.10     | 2.26      | -0.0050 | 0.0079 | 0.0043 | 0.0280 | 2.86 | 0.0907 | 0.43 | 0.94 | 5.94 | 11.14 | 16.01 | 489 | 269 - 301 | 2.2 - 30.1 |
| Growing Degree Days       | 2996.24   | 291.22    | -0.5430 | 0.1509 | 0.3015 | 0.3100 | 3.23 | 0.1212 | 0.37 | 0.91 | 73.64 | 1373.1 | 2047.3 | 481 | 269 - 301 | 2.2 - 30.1 |
| Precipitation (mm)        |           |           |       |             |             |       |                |    |                |             |              |
| Mean Annual Precipitation | -40.94    | 457.20    | 0.3804 | 0.1309 | 0.0324 | 0.0197 | 6.36 | 0.0317 | -75.17 | 54.03 | 1.94 | 0.0181 | 0.19 | 0.10 | 105.9 | 778.8 | 184.0 | 117 | 2420 - 3501 | 0.8 - 15.82 |
| Mean Snow Depth           | -526.76   | 403.37    | 0.3097 | 0.1313 | 0.0324 | 0.0197 | 6.36 | 0.0317 | 108.07 | 41.79 | 6.69 | 0.0297 | 26.62 | 40.11 | 53.3 | 30.00 | 419.2 | 432.7 | 117 | 2420 - 301 | 2.2 - 30.1 |
| Summer Precipitation      | -88.53    | 87.97     | 0.0898 | 0.0285 | 0.0324 | 0.0197 | 4.90-48.1 | 0.0122 | 17.26 | 10.32 | 2.27 | 0.2634 | 28.68 | 11.16 | 6.77 | 0.0938 | 0.12 | 0.08 | 50.0 | 203.7 | 472.0 | 536 | 2420 - 301 | 0.8 - 14.8 |

Note: The table includes coefficients for regressions of climate variables on elevation, slope, and aspect. The coefficients are presented as intercepts, slopes, and elevations with their respective standard errors (s.e.).
Visualizations

Fig. S2. Growing degree days (GDD) decrease with elevation. Partial regression plot of the full model described above.

Fig. S3. GDD decreases with the slope and elevation of the weather station interactively.
**Fig. S4.** Mean annual temperature decreases with elevation of the weather station.

**Fig. S5.** MAT decrease with slope and elevation of the weather stations, interactively.
Fig. S6. Mean summer temperature (MSuT) decreases with elevation of the weather station.

Fig. S7. Mean summer temperature decreases the slope and elevation of the weather station, interactively.
Fig. S8. Mean annual precipitation increases with elevation the weather station.

Fig. S9. Summer precipitation increases with weather station elevation. Stations with a slope > 25 were excluded.
**Fig. S10.** Summer precipitation increased with slope and sin of the aspect (eastern facing slopes) of the weather stations, but decreased with the cosine of aspect (northern facing slopes).

![Fig. S10](image)

**Fig. S11.** Summer precipitation increased with the slope and elevation of the weather stations, interactively.

![Fig. S11](image)
**Fig. S12.** Summer precipitation increased with elevation and southern facing slopes (negative cosine of aspect), interactively.

**Fig. S12.** Snow depth increases with elevation of the weather station and decreases towards eastern facing slope (positive sine of aspect).
Fig. S13. Snow depth at a weather station decreases with elevation and towards eastern facing slopes, interactively.