How does soil moisture interact with temperature to affect phenology?

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Statement of authorship All authors conceived of this manuscript, which began at a Radcliffe Exploratory Seminar in 2016, and all authors contributed to manuscript revisions. AKE and EMW conceived of the idea for the literature review, database compilation, and related Radcliffe Exploratory Seminar. AKE compiled the datasets; AKE analyzed the data and created the figures; AKE wrote the manuscript.

Data Accessibility The MC3E and ExPhen databases are available at KNB (Ettinger & Wolkovich, 2018),

along with all R code from the analyses included in this paper. (Currently, metadata are published there; the full databases and R code are available to reviewers on github.)

Running title Key words global warming, warming experiment, microclimate, soil moisture, phenology, budburst, direct and indirect effects, active-warming, target temperature

Outline

1. How do climate manipulations affect soil moisture and temperature?

2. Approach: Use MC3E database. Fit multilevel models of soil moisture as a function of temperature and precipitation treatments. For this we need two equations where we evaluate the effects of experimenal temperature (eT) and experimental preciptation (eP) treatments on soil moisture and temperature. We're hoping to nest year within site on the intercept and slopes:

$$y_i = \alpha_{site[year[doy[i]]]} + \beta_{1site[i]} eT_i + \beta_{2site[i]} eP_i + \beta_{3site[i]} eT_i eP_i + \epsilon_i \tag{1}$$

$$\alpha_{site[year[doy]]} \sim N(\mu_{site[year]}, \sigma_{site[year]}) \tag{2}$$

$$\mu_{site[year]} \sim N(\mu_{sy}, \sigma_{sy}) \tag{3}$$

$$\mu_{sy} \sim N(\mu_s, \sigma_s) \tag{4}$$

$$\beta_{1site} \sim N(\mu_{\beta 1}, \sigma_{\beta 1}) \tag{5}$$

$$\beta_{2site} \sim N(\mu_{\beta 2}, \sigma_{\beta 2}) \tag{6}$$

$$\beta_{3site} \sim N(\mu_{\beta 3}, \sigma_{\beta 3}) \tag{7}$$

$$\beta_{1sp} \sim N(\mu_{\beta 1}, \sigma_{\beta 1}) \tag{8}$$

$$\beta_{2sp} \sim N(\mu_{\beta 2}, \sigma_{\beta 2}) \tag{9}$$

$$\beta_{3sp} \sim N(\mu_{\beta 3}, \sigma_{\beta 3}) \tag{10}$$

3. Does warming affect soil moisture similarly to warming in experimental and non-experimental data?

   Compile data from Duke Forest (maybe just soil moisture?) and from Harvard Forest (soil moisture and O'Keefe phenology data). Think on best model and how to model temperature as y variable ... here's one idea where y could be daily moisture data across multiple years and T would be MAT and P would be percent different than mean for that year:

$$y_i = \alpha_{doy[i]} + \beta_{1site[i]} T_i + \beta_{2site[i]} P_i + \beta_{3site[i]} T_i P_i + \epsilon_i \tag{11}$$

$$\alpha_{doy} \sim N(\mu_{doy}, \sigma_{doy}) \tag{12}$$

   First we need to use seasonal or annual temperature (T) and soil moisture (S) data to predict phenology (so here textity is DOY):

$$y_i = \alpha_{site[year[i]]} + \alpha_{sp[i]} + \beta_{1sp[i]} T_i + \beta_{2sp[i]} S_i + \beta_{3sp[i]} T_i S_i + \epsilon_i \tag{13}$$

$$\alpha_{site[year]} \sim N(\mu_{sy}, \sigma_{sy}) \tag{14}$$

$$\mu_{sy} \sim N(\mu_s, \sigma_s) \tag{15}$$

$$\alpha_{sp} \sim N(\mu_{sp}, \sigma_{sp}) \tag{16}$$

4. How does soil moisture affect phenology? How does soil moisture affect GDDcrit?

   (a) Compile phenology data that goes with climate data in MC3E database. (Name the phenology database!)

(b) Fit models with soil moisture, temperature, and interaction to phenology data (budburst, leafout, flowering, fruiting, senesence? (See what phenophases have enough data.)

Does the effect of soil moisture on phenology differ between experiments and observational data? We can then combine equations from Question 1 (which predict MAT and soil moisture on an annual scale, we hope) with equations from Questions 3 (at the annual scale) to answer: how much does 1 degree change in target temperature (eT) affect phenology, if this were the only effect of the experiment? Similarly, how much does 50% change in precipitation (eP) affect phenology, if this were the only effect of the experiment? And how big a change does each make acknowledging that they both change moisture and temperature together? We can do this by plugging in different values of eT (e.g., all 1 C, then try with all 2 C) and eP to calculate different outcomes of moisture and temperature which we can evaluate in the equations in Question 3 to assess changes in phenology.

References

Ettinger, A. & Wolkovich, E. (2018). Microclimate from climate change experiments (MC3E). doi:10.5063/F1QV3JQR.

Figures

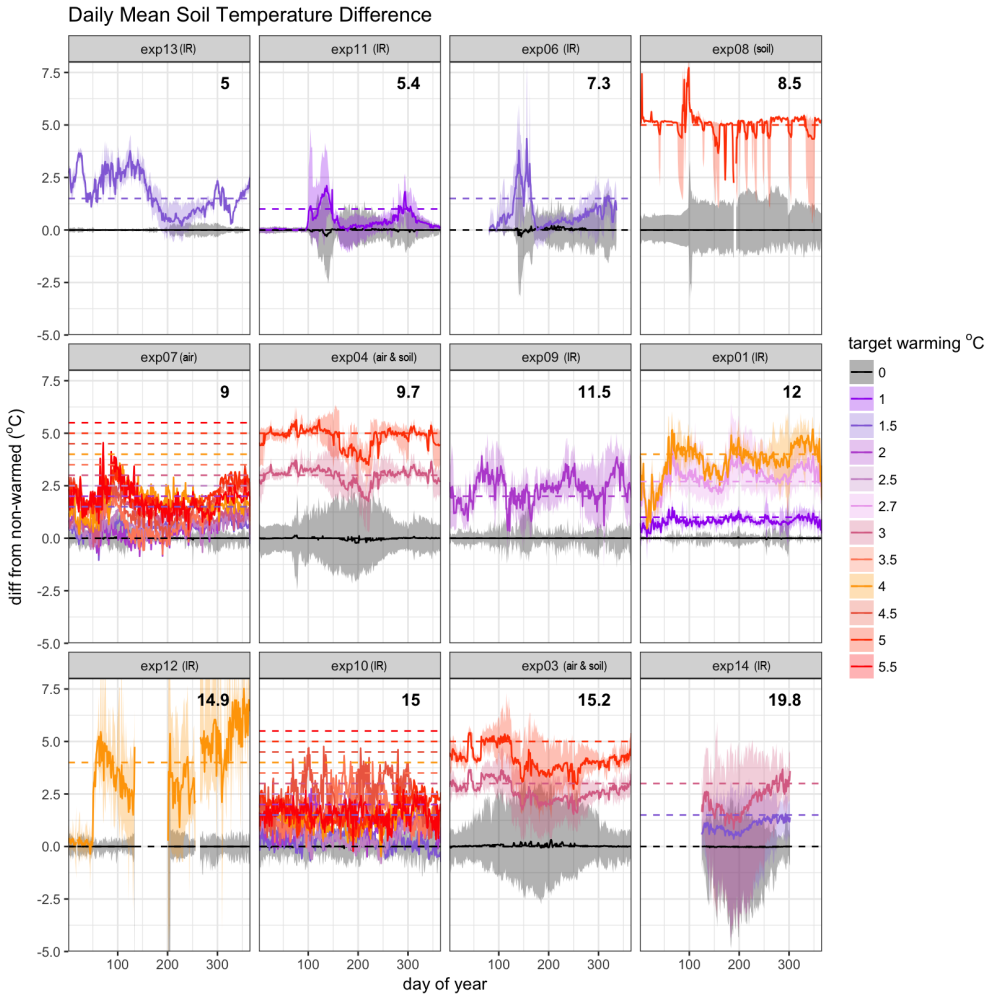

Figure 1: **Deviations in daily observed warming from mean control soil temperature for 12 study sites,** excluding data from plots that manipulated precipitation. We show soil, rather than above-ground, temperature, as this was the most frequently recorded temperature variable in the MC3E database. Solid lines show observed difference between warming treatment (colors) and control (black) plots, averaged across replicates and years; shading shows 95% confidence intervals. Dashed lines represent target warming levels. (Note that the following studies had no explicit target temperature: exp06, exp11, exp12; for these studies, we used their reported level of warming.) Two sites not shown here did not monitor soil temperature. Experimental sites are ordered by low to high mean annual soil temperature (shown in the upper right corner of each panel). The heating type is listed in parentheses next to the site number (IR= infrared, soil= soil cables, air= forced air).