Supplemental Materials for Soil moisture interacts with temperature to affect plant phenology

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March 30, 2021

Supplemental Methods

Equations for soil moisture and temeprature models: The equations below represent the models we used to understand effects of experimental temperature (eT) and experimental preciptation (eP) treatments treatments on soil moisture and temperature. Since the model structures for our analyses of moisture and temperature were identical, y represents either moisture or temperature.

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

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

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

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

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

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

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

Equations for phenology models: Response variable (y) is day of year of the phenological event (budburst, leafout, flowering, fruiting, or senesence). Predictors are measured air temperature (T) and soil moisture(SM). Random effects are species (sp, random slopes and intercepts); site and year nested within site (random intercepts).

$$y_i = \alpha_{sp[i],site[year[i]]} + \beta_{temp_{sp[i]}} + \beta_{mois_{sp[i]}} + \beta_{temp:mois_{sp[i]}} + \epsilon_i \tag{8}$$

$$\alpha_{sp} \sim N(\mu_{sp}, \sigma_{sp}) \tag{9}$$

$$\mu_{site[year]} \sim N(\mu_{sy}, \sigma_{sy}) \tag{10}$$

$$\mu_{sy} \sim N(\mu_s, \sigma_s) \tag{11}$$

$$\beta_{temp_{sp}} \sim N(\mu_{\beta_{temp}}, \sigma_{\beta_{temp}}) \tag{12}$$

$$\beta_{mois_{sp}} \sim N(\mu_{\beta_{mois}}, \sigma_{\beta_{mois}}) \tag{13}$$

$$\beta_{temp:mois_{sp}} \sim N(\mu_{\beta_{temp:mois}}, \sigma_{\beta_{temp:mois}}) \tag{14}$$

Results

1. **How do climate manipulations affect soil moisture and temperature?**
   (a) 12 sites included: exps 1-5, 7-9,10 and 12-14
   (b) Target temp has a negative effect on soil moisture. (Figure 1)
   (c) Precip treatment has a positive effect on soil moisture.(Figure 1)
   (d) Effects vary by site. (One site, exp07, has positive effect of temperature).
   (e) For supplement: Fit different models for different seasonal temperatures used in Question 2 (phenology models).
2. **How does soil moisture affect phenology?**
   (a) Air temperature (seasonal) has a negative effect on phenology for all phenophases except senescence, which has a positive effect (Figure **??**). Magnitude varies among sites and species.
   (b) Moisture has a negative effect on phenology for all phenophases,. Magnitude varies among phenophases (e.g., LOD is weaker than BBD), sites, and species.
   (c) For supplement: Figures of fruiting and senescence (fewer sites)
3. **Does warming affect soil moisture and phenology similarly in experimental and non-experimental data?** OR **Does soil moisture affect phenology similarly in experimental and non-experimental data?**
4. Soil moisture effect size is bigger in full dataset than in controls only, for BB. Mean and range of SM is similar (though max is a bit higher in full dataset; min is similar).

To do

1. Clean up code
2. Model tables for supplement

3. Figure 2: color code dots by species (by BB day of year, from early to late)

4. Figure showing effects with forecasted shifts in temp and moisture...

References to include

- Later flowering is associated with low precipitation, at least in part (Crimmins et al 2010)
- Ganjurjav et al 2020
- Cabon 2020

Supplemental Tables

Table 1: **Experimental sites and phenophases included in the ExPhen database**. Experimental sites correspond to the map (Figure S1). We give the study ID, location, source, years of data included, ecosystem, number of species, and phenophases included: budburst (bb), leafout (lo), flowering (fl), fruiting (fr), or senesence (sen) day of year. Note that some sites may have multiple sources; however, we list only one here.

study	location	source	data years	ecosystem	species	phenophases
exp01	Waltham, MA, USA	Hoeppner and Dukes 2012	2009-2011	grassland	44	bb,lo,fl
exp02	Montpelier, France	Morin et al. 2010	2004	temperate deciduous forest	5	fl,fr
exp03	Duke Forest, NC, USA	Clark et al. 2014	2009-2014	temperate deciduous forest	37	bb,lo
exp04	Harvard Forest, MA, USA	Clark et al. 2014	2009-2012	temperate deciduous forest	29	bb,lo
exp07	Harvard Forest, MA, USA	Pelini et al. 2011	2010-2015	temperate deciduous forest	8	bb,lo,sen
exp09	Stone Valley Forest, PA, USA	Rollinson and Kaye 2012	2009-2010	temperate deciduous forest	120	lo,fl,fr,sen
exp10	Duke Forest, NC, USA	Marchin et al. 2015	2010-2013	temperate deciduous forest	11	bb,fl
exp12	Kessler Farm Field Laboratory, OK, USA	Sherry et al. 2007	2003	grassland	12	fl,fr

Table 2: **Comparison of coefficients from budburst models fit to data from all plots versus control plots only**.

X	m5.cent	m5cont.cent
(Intercept)	96.44	95.33
temp	-9.31	-9.57
mois	-1.59	0.27
temp:mois	0.77	1.74

Table 3: **Comparison of coefficients from budburst models fit to data from all plots versus control plots only**.

X	Tmod.coef	Tmod.se	SMmod.coef	SMmod.se
int	14.38	1.28	0.18	0.02
temp.treat	1.25	0.09	-0.01	0.00
precip.treat	-0.19	0.15	0.02	0.01
temp.treat*precip.treat	0.04	0.06	-0.00	0.00

Table 4: **Comparison of coefficients from budburst models fit to data from all plots versus control plots only**.

X	m5.cent	m5cont.cent
(Intercept)	96.44	95.33
temp	-9.31	-9.57
mois	-1.59	0.27
temp:mois	0.77	1.74

Supplemental Figures

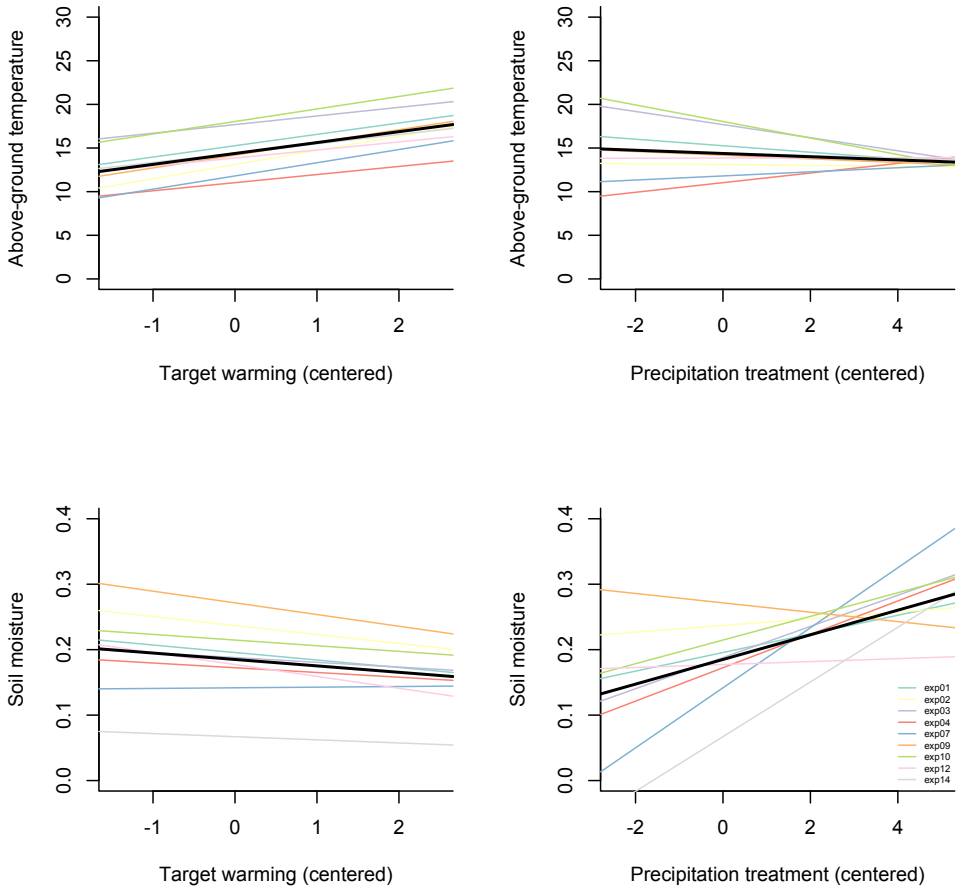

Figure 1: **Effects of target temperature and precipitation treatments on soil moisture.**

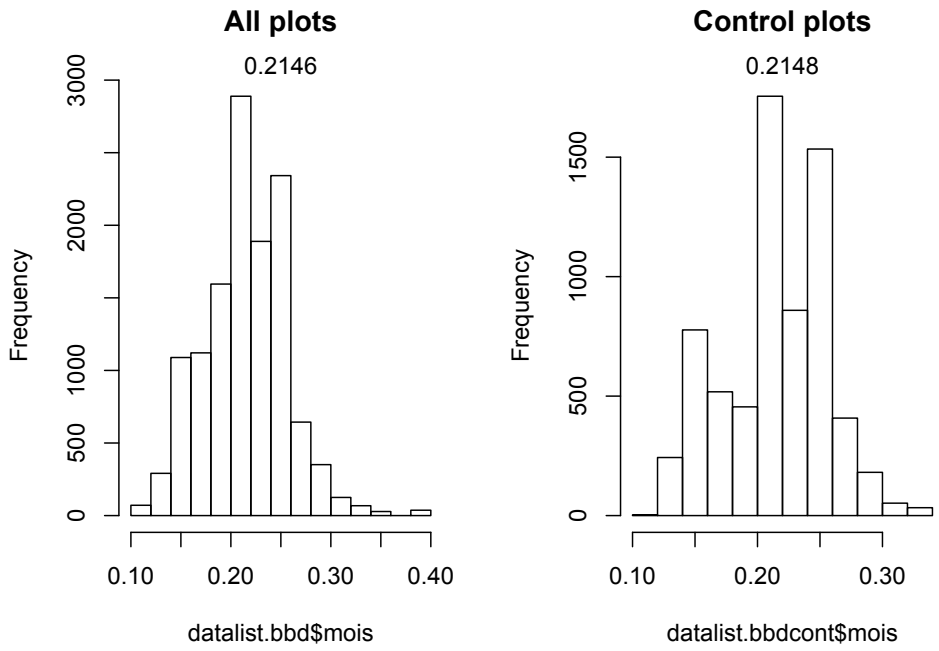

Figure 2: **Observed daily soil moisture in all plots verus control plots.**

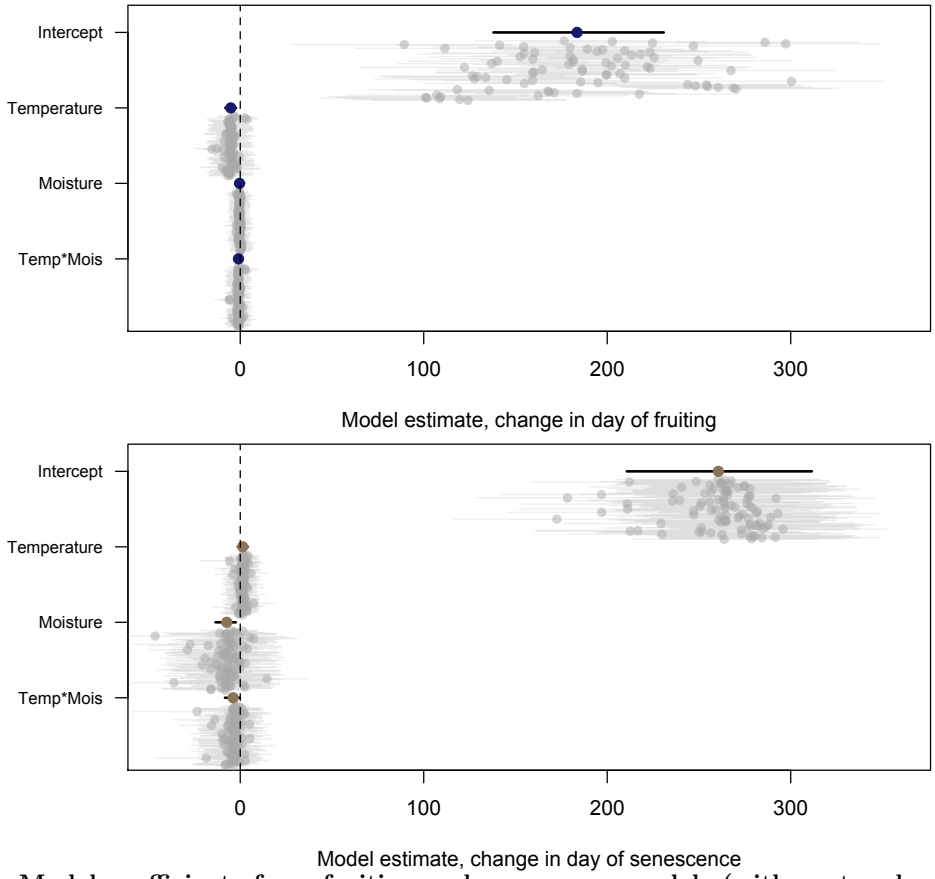

Figure 3: **Model coefficients from fruiting and senescence models (with centered predictors).**