**Observed biogeochemical impacts of severe drought in a topographically-diverse wet tropical forest**

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**Abstract**

As the planet’s dominant land use, agriculture often competes with the preservation of natural systems that provide globally and regionally important ecosystem services,.

**Keywords**

Conservation | Amazonia | Land use | Ecosystem services

**Introduction**

**Methods Summary**

***Field location information***.

The research will be conducted in the Luquillo Experimental Forest (LEF), Puerto Rico, USA (Lat. 18°18’ N; Long. 65° 50’ W). The forest is congruent with El Yunque National Forest managed by the US Forest Service. The LEF contains approximately 11,500 ha of contiguous forest area, spanning an elevation gradient from approximately 350 to 1075 m above sea level.

We will make use of a range of environmental conditions present in the LEF to compare and contrast bedrock types (volcanoclastic and dioritic), topographic zones (ridge, slope, upland valley, riparian valley) and precipitation regimes (windward to leeward, lower and upper elevation). These sites have all been well characterized as part of the on-going LTER and the LCZO projects based on the LEF (Scatena 1989, Silver et al. 1999, Liptzin et al. 2011, Hall et al. 2012, Wood and Silver 2012). Soils in the LEF are derived from volcanoclastic sediments with quartz diorite intrusions (Beinroth 1982). Soils are predominantly classified as Ultisols and Oxisols (Scatena 1989, USDA NRCS 2002). Mean monthly temperatures range from 23.5ºC in January to 27ºC in September at low elevation, and from 17 to 20ºC in the upper elevations. Precipitation ranges from less than 3000 mm y-1 in the low elevations and leeward sites to approximately 5000 mm y-1 near the uppermost elevation and windward locations. The forest can be classified into four life zones based on the Holdridge Life Zone System: subtropical wet and subtropical rain forests are found at low and mid elevations, lower montane rain and lower montane wet forests at high elevations (Brown et al. 1983). These life zones correspond to four dominant vegetation communities that decrease in species richness (Barone et al. 2008), stature, NPP, and aboveground biomass with elevation (Weaver and Murphy 1990).

***Experimental design***.

***Moisture, oxygen and rainfall measurements***.

Soil O2 sensors (Apogee Instruments model SO-210) will be installed in gas-permeable soil equilibration chambers (295 mL, 5 cm diameter, 15 cm height) (*sensu* Liptzin et al. 2011).

We will also determine the importance of rainfall as a predictor of soil O2 concentrations using data from experiments 1 and 2 coupled with rainfall data collected from nearby gauges as part of the long-term on-going climate monitoring program in the LEF. This program includes 24 rainfall collectors distributed across the LEF; gauges are maintained by the USGS, US Forest Service, University of Puerto Rico, and U.C. Berkeley. Rain gauge data are currently being coordinate by the LCZO which has generously offered to share it with this project (see attached letter of support). Temporal and spatial patterns in rainfall will be compared with soil O2, temperature, and soil moisture data (see below).

***Gas flux measurements***.

To determine patterns in trace gas fluxes across the soil atmosphere interface we will use automated surface flux chambers imbedded in the sensor network plots. Automated chambers will be connected to a GC (GC14A, Schimadzu Scientific Inc) and powered by a generator. The generator and GC will be housed off the plots in a shed. The dynamic chamber design and plumbing is slightly modified from Pape et al. (2009). Chambers will be approximately 17 cm high. The purge system will use ambient air with an intake above the top of the closed chamber. When chambers are open, lids will be stored in the vertical position approximately 10 cm away from the chamber based (on a louvered-arm system) to minimize impact on the sampling area. We will have a total of 12 automated chambers which will be divided evenly across treatments: three per topographic zone in experiment 1, six per soil type in experiment 2, and six per rainfall regime in experiment 3. Trace gases will be analyzed automatically on a GC outfitted as above. Samples collection will occur hourly.

***Soil variable sampling and processing***.

We will explore the effects of topography on soil O2 concentrations in the Bisley Research Watersheds located at 350 m elevation on the volcanoclastic soils. The site receives approximately 3500 mm annual rainfall and has a mean daily temperature of 25 oC (Scatena 1989). We will install 5 randomly located sensor pair plots along a 10 m transect parallel to the contour in each of four topographic positions (experiment 1). Topographic zones include ridges, slopes, upland valleys, and riparian valleys (n = 40 sensors). Slope length (top to bottom) and steepness (rise over run) will be measured for each sensor plot. Three of the sensor plots per transect will also have a combined soil moisture and temperature sensor (Campbell Scientific) installed at both depths to record soil microclimate conditions (n = 24). Data will be collected hourly for 6 months using data loggers (Campbell Scientific CR1000) and multiplexers (Campbell Scientific AM16/32). Soils will be sampled at both depths at the end of the experiment from within and immediately adjacent to the soil equilibration chambers. Soil texture will be measured using the hydrometer method (Gee and Bauder 1986). Soil C and N content will be analyzed on an elemental analyzer (CE Elantec, Lakewood, NJ). Bulk density will be measured using separate quantitative cores from each depth interval that will be oven dried at 105 oC to determine the dry mass per unit volume.

Soils will be sampled as described above at the end of each experiment and analyzed for soil P, pH, Fe(II), and poorly crystalline Fe concentrations. Separate subsamples will be extracted in a NaHCO3 solution as an index of labile P and in NaOH as an index of more recalcitrant Fe- and Al-bound P (Tiessen and Moir 1993). Soil pH will be measured in a 1:1 solution in water and in KCl. Iron(II) concentrations will be measured using an HCl extract (Lovley and Phillips 1987) as modified by Liptzin and Silver (2009). We will use a citrate ascorbate extraction to estimate poorly crystalline Fe (Reyes and Torrent 1997).

We will also measure mineral N pools following extraction in 2 M KCl (Hart et al. 1994).

***Statistical analyses***.

We will use wavelet analyses to determine the temporal variability of the O2 time series’ and their relationship with climate drivers and soil temperature and moisture (Liptzin et al. 2011). This spectral technique, analogous to Fourier analysis, breaks up the process variance into pieces, each of which represents the contribution on a particular scale (Cazelles et al. 2008). The wavelet transformation of a discrete signal *Xn* (or hits *n*-order stationary increment) of length *N* recorded at δt interval, is defined as the convolution integral (Lau and Weng 1995; Torrence and Compo 1998) in equation 1:

where is the complex conjugate of the scaled and translated mother wavelet, and *s* is the wavelet scale at which the transformation is applied. The continuous wavelet transformation is calculated by continuously shifting the scale and time in equation (1). The wavelet power spectrum (WPS), is then computed as WPS*n*(*s*) = *Wn*(*s*)*W*(*s*). Analogously, the wavelet co-spectrum (WCS) between two time series *xn* and *yn* is defined as WCS. The global wavelet power spectra, the analog of Fourier spectra, are the time average of WPS (or WCS) in equations 2 and 3:



These quantities can be combined to form the wavelet magnitude square coherence, or simply wavelet coherence WC:

where the angular brackets indicate ensemble averages if multiple realizations of *x* or *y* are available. WC can be thought of as the spectral correlation between two time series and, equivalent to the *R*2, can vary between 0 and 1. Importantly, WC finds regions in the frequency space where two time series co-vary, but do not necessarily have high common power (Cazelles et al. 2008; Grinsted et al. 2004; Yates et al. 2007). The use of a complex wavelet in this analysis also allows for exploration of the phase difference between the time series evaluated as tan-1 (Liptzin et al. 2011). The results provide an indication of the strength of the relationship between time series. We will also use analysis of variance (ANOVA) to explore spatial patterns in mean soil O2, temperature, moisture, and soil physical and chemical characteristics across topographic zones, soil textures, and rainfall regimes.

We will explore temporal patterns in soil O2, trace gas concentrations and fluxes using the wavelet analysis described above and an additive mixed modeling framework implemented in the mgcv package in R (Wood 2006). Additive models fit smooth trends to data using flexible spline functions with a degree of curvature determined during the model fitting process. This method allows modeling of non-linear temporal trends that are not easily described by a single function, and provides a Bayesian method of confidence interval estimation. Models will also include random effects to account for spatial correlation and repeated sampling. We will select the optimal random effect structure for each model by first saturating models with fixed effects and then comparing different random effect structures using Akaike’s information criterion (AIC) and residual plots. We will use multivariate ANOVA to explore the effects of topography, texture, and rainfall regime on mean trace gas fluxes as well as relationships to soil chemical and physical properties. We will compare patterns in these soil chemical properties with both the mean and the coefficient of variation in soil O2 concentrations using ANOVA and regression analyses.

We will analyze data from the sensor network and automated chamber system described above to see if we can differentiate background patterns from pulsed and high flux or concentration data. We will use a bootstrapping procedure to identify potential thresholds or breakpoints in the datasets (sensu Wu et al. 2012). We will then run the additive mixed modeling framework described above with increasingly stringent thresholds applied to the flux and concentration data to determine if this improves the relationships with soil O2 concentrations and/or climate. We will use the hot spots and hot moments identified by the above procedure to explore potential mechanisms responsible by determining relationships with the soil chemical and physical data measured at each chamber site.

***Study Plan For*:** **Belowground responses to an observed drought across a topographic gradient in a wet tropical forest**

September 16, 2015

*Sections included here:*

* Introduction
* Hypotheses/justification
* Study plan brief approach
* Methods details
* Significance and desired outcomes

*What else is Christine supposed to deliver? a.k.a. forthcoming things:*

* This is a rough, rough, rough draft of this study plan… nearly everything needs to be altered/amended

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**Belowground responses to an observed drought across a topographic gradient in a wet tropical forest**

*Keywords: global change, oxygen availability, soil moisture, nutrient cycling, ecosystem thresholds*

**Introduction:**

Humans are altering climatic trends on a global scale. However, considerable uncertainty surrounds the effects of future precipitation changes on tropical forests1. Climate models generally agree that global warming is likely to decrease rainfall and increase drought events across the tropics2. In wet tropical forests, where plant species3 and soil microbial communities

4 are less likely to have adapted to combat drought stress, such droughts have the potential to drastically shift belowground nutrient cycling.

Drought mediates changes to the tropical terrestrial carbon (C), nitrogen (N) and phosphorus (P) and other nutrient cycles in several ways. First, droughts reduce soil moisture and increase soil oxygen, thus altering reduction-oxidation (redox) chemical conditions. These effects may change the rates at which soil microbes decompose organic C5,6 and produce CO2, methane (CH4) and nitrous oxide (N2O), three important greenhouse gases7,8. Changes to decomposition and so-called trace gas production may lead to a net change in soil C7, though both the direction and magnitude of this effect are not well quantified1. Changes to decomposition and to the redox dynamics of soil can also affect the availability of N, P and key exchangeable cations (calcium (Ca2+), magnesium (Mg2+), sodium (Na+) and potassium (K+)), though the direction of these patterns remains poorly understood and the driving mechanisms for post-drought changes in nutrient cycling likely vary widely by site. Shifting redox conditions9 can change the amount of available P and altered microbial activity10 can change the amount of available N, with implications for plant productivity and vegetative C storage1,11. In combination, droughts have the potential to substantially alter belowground nutrient dynamics in wet tropical forests.

In this study, we take advantage of high-resolution, temporal datasets that document the changing belowground context before, during, and after an observed drought in Luquillo Experimental Forest (LEF), Puerto Rico. The effect of drought on soil oxygen, moisture, and nutrient cycling like varies with small-scale topographic and edaphic variation. *Here, we document the changes to soil abiotic conditions and nutrient availability across a topographic gradient and observe non-linear, threshold responses to initial drought impacts and, potentially, recovery*.

**Study plan approach/hypotheses:**

I will conduct this research under the mentorship of Professor Whendee Silver (UC Berkeley), who has decades of experience researching the dynamics of wet tropical forests at the LEF and in Puerto Rico. LEF has heavy year-round precipitation (mean annual rainfall of 3500 mm/year10) but rainfall will likely decline in the future2.

The proposed study takes advantage of an established array of soil moisture and oxygen sensors across a ridge-to-valley slope in LEF and complements that high-resolution dataset with targeted soil sampling to measure changes to nutrient cycling.

We address two core questions:

Question 1: How do soil oxygen and moisture patterns change after drought across a topographic gradient?

*Hypothesis:*

(1.1) The observed drought will lead to threshold effects (e.g., non-linearities in soil moisture and O2 responses) from ridge to valley, with valley and low-slope soils having lower soil O2 availability than mid-slope and ridge soils.

Question 2: How do post-drought soil oxygen and moisture patterns alter soil nutrient pools across a topographic gradient?

*Hypotheses:*

(2.1) C will be affected like AAA.

(2.2) N will be affected like AAA.

(2.3) P will be affected like AAA.

(2.4) Fe? pH? What else?

To address these questions, we will record soil moisture and O2 at 35 locations in LEF (Figure 1). The sampling array has five transects associated with topographic locations: ridge, upper slope, mid slope, low slope, and valley transects. Each transect has 7 sensor locations (5 transects \* 7 locations/transect = 35 observations). Each sensor location is, more precisely, the location of two sensors, one to record soil moisture and a second to record soil O2. Data is recorded hourly.

Additionally, we will conduct soil sampling along the ridge, mid-slope and valley transects periodically. The following things will be measured on those collected soils: A, B, C, D, and E. We collected soils before the drought (?), after the drought began (began in mid-April, 2015), longer after the drought was continuing, and after drought recovery.

This is the sketchy first-pass. Fill in much more methodological detail as you improve this document. Create a “methods” section.

This approach allows us to track the abiotic implications of drought at a high temporal frequency from beginning of drought through to the end, a rare opportunity to observe the immediate, medium-term and longer-term impacts of drought on soil moisture and O2, addressing Question 1, above. The periodic soil sampling will allow us to track changes to several nutrients of interest over the study period and draw correlative relationships between drought stage, topographic position and nutrient dynamics, addressing Question 2, above.

**Methods:**

Christine still needs to write this.

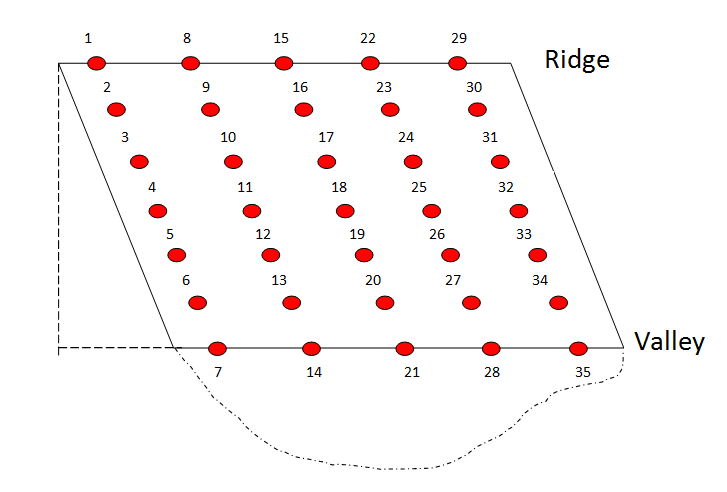
**Significance and desired outcomes:**

*Significance*: One of the major uncertainties in predicting future climate is how terrestrial nutrient cycles will be modified by climate changes12-14. Tropical forests in particular contain globally important C stocks12-14, including large vegetative biomass15 and soil organic carbon pools16. Decreases to either could lead to increases in atmospheric carbon dioxide (CO2) concentrations and associated climate impacts13 while alterations to N and P availability could have wide-reaching effects on terrestrial productivity. This study documents the below-ground effects of an observed drought on the abiotic consequences of drought in a wet tropical forest and how nutrient availability responds to those changes.

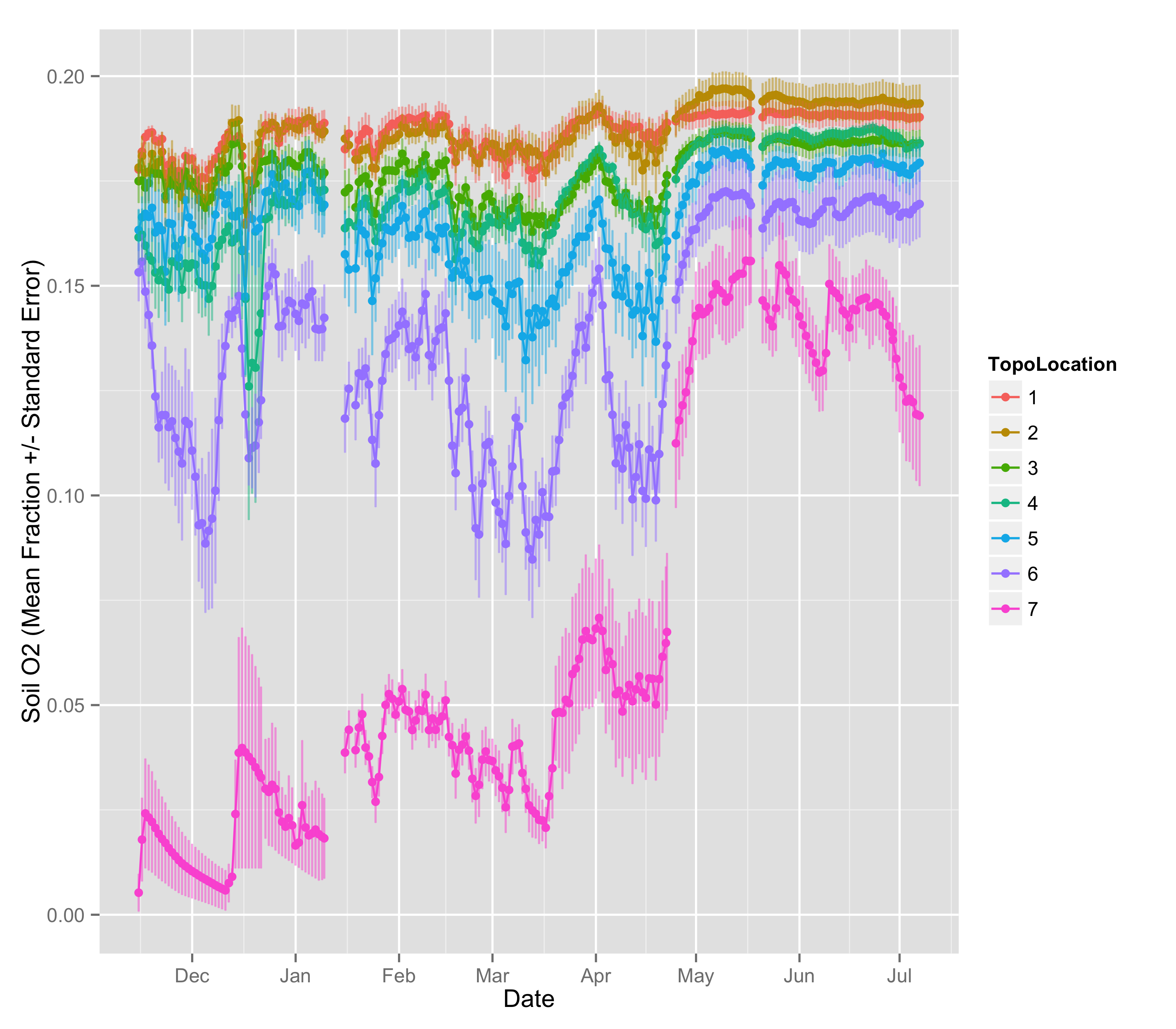
*Desired outcomes*: I see two key outcomes coming from this project. First, I will aim to efficiently and rapidly “get a handle on” the field context in PR during my initial months at Cal. Second, I expect that a manuscript will be written based on this project, which I initially anticipate could be aimed at a mid-tier soils or global change journal.

*Broader impacts*: I would like to write up a lesson plan for an 8th grade classroom on the “ecology of drought” that compares the California drought to a drought in a tropical forest. I will work with a friend (Tom McFadden) who teaches at San Mateo’s Nueva School to target the lesson appropriately and come visit his classroom when it works for his class schedule.

**Figures**



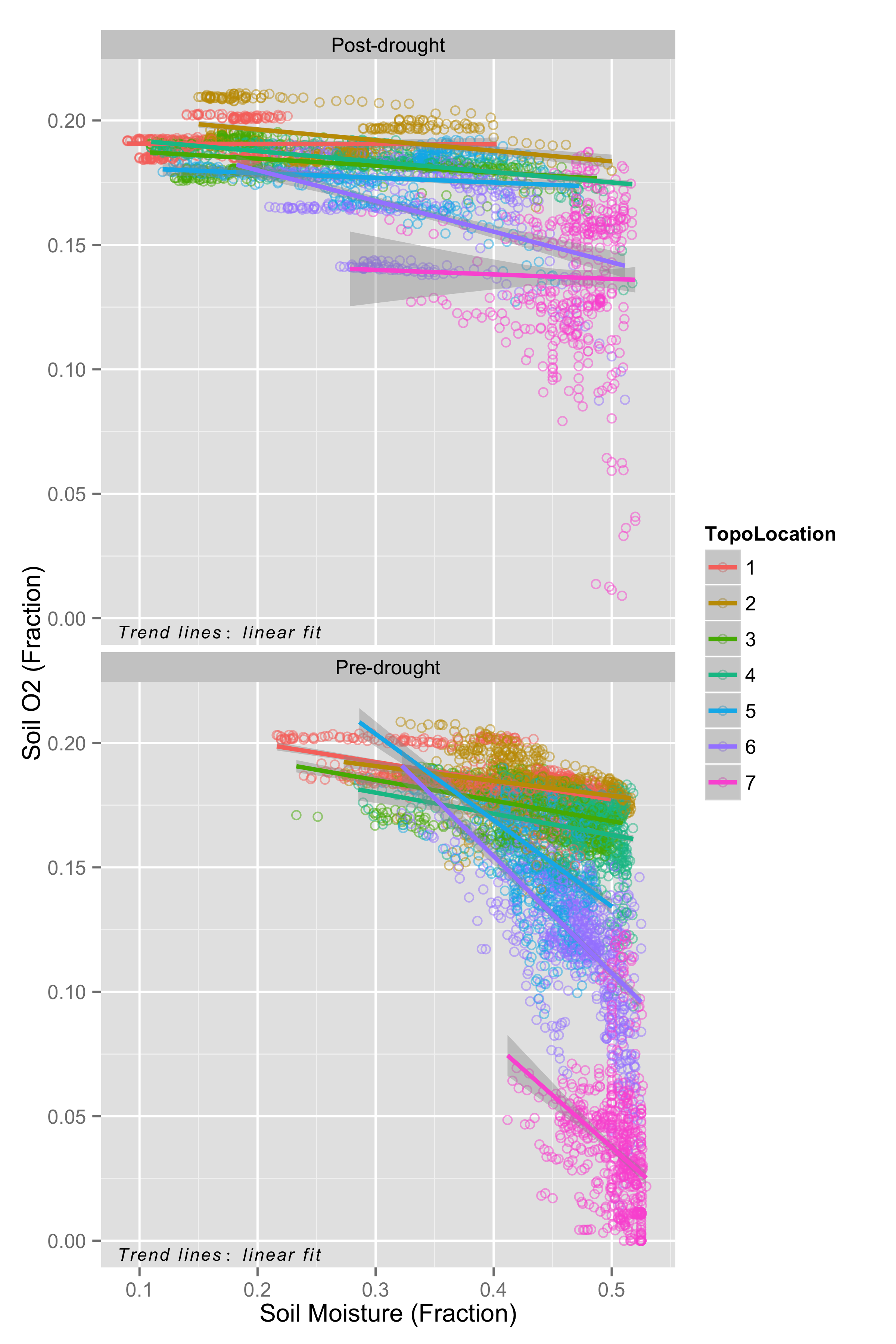
**Figure 1**. Soil moisture and O2 sensor locations across a topographic gradient in LEF. The sampling array has five transects associated with topographic locations: ridge, upper slope, mid slope, low slope, and valley transects (transects go left to right in the schematic here). Each transect has 7 site locations (5 transects \* 7 locations/transect = 35 observations). Each site location is, more precisely, the location of two sensors, one to record soil moisture and a second to record soil O2. Data is recorded hourly.



**Figure 2**. Initial data collection tracking soil O2 from pre-drought through the onset of drought (mid-April). Clear topographic patterns have emerged in how rapidly oxygen availability increases in some sites over others after drought conditions begin. Variability also differs across topography, with the valley sensors seeing larger standard error values.



**Figure 3**. Initial data collection tracking soil moisture from pre-drought through the onset of drought (mid-April). Valley sites lose moisture less so than slope or ridge sites.



**Figure 4**. Write a better caption. This is just for Christine to check out how the O2-moisture relationship changes across the topo grandient and pre- and post-drought. Weird that the valley’s relationship between soil O2 and moisture flattens post-drought. ???

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