Title: Contributions of anthropogenic warming to drought-induced loss of vegetation health

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Proposed end date: June 28, 2020

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Abstract: Droughts are among the world's costliest natural disasters, damaging both social and ecological systems. Anthropogenic warming exacerbates natural precipitation deficits through heat-induced increases in evaporative demand, which further dries soils and stresses vegetation. Roughly 15-20% of soil moisture loss during the 2012-2015 California drought, for example, was directly attributable to anthropogenic warming. While this drought clearly reduced vegetation health, the proximate climatic drivers (e.g., extreme heat vs. soil moisture loss) and relative contributions of natural variability vs. anthropogenic forcing remain unknown. Here, I propose to quantify anthropogenic contributions to drought-induced loss of vegetation health. I specifically hypothesize that anthropogenic threats to vegetation during the 2012-2015 California drought were even greater than their contributions to loss of soil moisture due to the direct negative effects of higher temperatures and vapor pressure deficits (VPD) on vegetation health. Preliminary results suggest that nearly 50% of reduced vegetation health during the drought was directly attributable to anthropogenic warming, primarily driven by anthropogenic increases in temperature and VPD. This clearly shows that while droughts are generally initiated by natural variability of precipitation, anthropogenic warming exacerbates these conditions, nearly doubling the effect of drought on plant health and productivity. During the PPC Scholar-in-Residence program, I will refine the preliminary workflow, apply the method to additional satellite-based indicators of vegetation health, and write a manuscript on anthropogenic contributions to drought-induced loss of vegetation health for submission to *Nature Climate Change*. Given the importance of vegetated ecosystems for providing economic and environmental services to humanity, this work will be relevant for defining appropriate adaptive management techniques to counter the negative effects of climate change on Earth's ecosystems. I will therefore also write and disseminate a policy-relevant fact sheet (with assistance of PPC staff) and present the research at two conferences and at PPC's fall Lunch and Learn program.

1. PROJECT MOTIVATION AND CONTEXT

Droughts are among the world's costliest natural disasters, causing severe damage to both social and ecological systems. The severe 2012-2015 California drought, for example, directly caused over $3 billion in agricultural losses alone (*1*). While droughts occur naturally, climate change exacerbates precipitation deficits through heat-induced increases in the vapor pressure deficit (VPD) of the atmosphere, enhancing evaporation and transpiration rates and thus increasing soil moisture loss (*2–4*). Through this mechanism, roughly 15-20% of soil drying during the 2012-2015 drought was directly attributable to human-caused warming (*3*). Anthropogenic increases in the frequency and severity of drought have large but still poorly constrained impacts on ecosystem function, including the photosynthesis and growth of plants ("primary production"). Using the severe 2012-2015 California megadrought as a case study, **I will quantify the contributions of anthropogenic warming to drought-induced loss of vegetation health and primary production**. I hypothesize that contributions of anthropogenic warming to loss of vegetation health are even greater than its contributions to soil moisture loss due to the direct negative effects of higher VPD on plant water status and photosynthesis (*5*), which will likely further compound the effects of soil moisture loss. While the California drought will be used as a case study, the empirical "global change ecology" attribution framework developed in this work will be broadly applicable to other impacts of hydroclimatic change and to other regions and ecosystems, including those of the Midwest.

2. PROPOSED WORK

My overarching goal during the PPC Scholar-in-Residence program is to develop and publish a framework for attributing drought-induced loss of vegetation health and productivity to natural vs. anthropogenic causes, including their proximate climatic drivers (e.g., high temperatures vs. reduced soil moisture). The proposed work will rely on two general types of data: 1) satellite-based proxies for vegetation health and primary production (the response variable), and 2) observed and modeled climate data decomposed into natural and anthropogenic components (the predictor variables). The satellite data include monthly estimates of vegetation greenness (the normalized difference vegetation index) from 1982-present, modeled gross primary production from 1982-present, and solar-induced chlorophyll fluorescence (a proxy for photosynthesis) from 2007-present. These satellite-based proxies for vegetation health all have different assumptions, strengths, and weaknesses (*6*), and simultaneous use of all three will allow me to "triangulate" (*7*) an answer to the proposed research question. <u>All data necessary for completion of this project (including both the satellite and climate data) have already been obtained and processed</u>.

I will decompose variability of the monthly satellite-based vegetation indices into components driven by soil moisture (SM), VPD, temperature (TMP), and photosynthetically-active radiation (PAR) using multiple linear regression (*8*):

$$\Delta Veg_t = \alpha^{SM}\Delta SM_t + \alpha^{VPD}\Delta VPD_t + \alpha^{TMP}\Delta TMP_t + \alpha^{PAR}\Delta PAR_t + \varepsilon_t \qquad \text{(Eq. 1)}$$

where ΔVeg represents the satellite-based vegetation anomaly in month *t*, α^{-} represents regression coefficients for a given climate variable, and ε is a residual error term. Since climate variables are intercorrelated, I will also test other modeling frameworks that explicitly (e.g., partial regression or PC regression) or implicitly (e.g., random forests) account for this correlation structure. Initial results based on a PC regression version of Eq. 1 suggest that this modeling framework successfully captures both the seasonality and interannual variability of vegetation health and primary production ($R^2 > 0.9$).

The observed climate data has been decomposed into anthropogenic and natural components, with natural components estimated based on a climate model ensemble driven solely by natural sources of climate variability (volcanic aerosols, solar radiation, etc) and anthropogenic components as the residual between observed and "natural" climate (*3*, *9*). Loss of vegetation health and primary production that is attributable to natural and anthropogenic effects (ΔVeg_{Nat} and ΔVeg_{Anth}, respectively) will be estimated by applying Eqn. 1 to the "natural" and "anthropogenic" decompositions of past climate. The fraction of annual vegetation anomalies that is attributable to natural and anthropogenic factors (f_{Nat} and f_{Anth}) will then be estimated from the integrals of monthly vegetation anomalies attributable to natural factors ($\Delta Veg_{t,Nat}$) and all factors (ΔVeg_t) (Fig. 1):

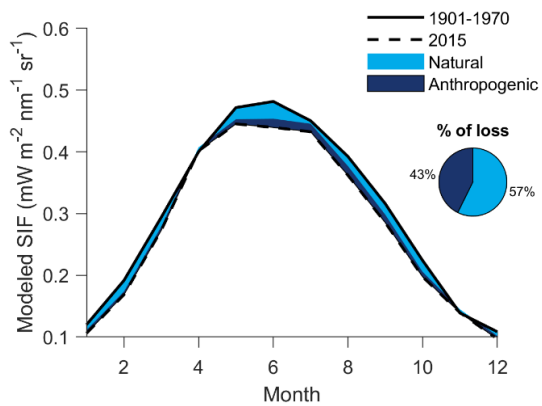

Figure 1. Attribution of monthly solar-induced fluorescence (SIF) anomaly to natural and anthropogenic factors in 2015.

$$f_{Nat} = 1 - f_{Anth} = \frac{\int_{t=1}^{12}(\overline{Veg_t} - \Delta Veg_{t,Nat})}{\int_{t=1}^{12}(\overline{Veg_t} - \Delta Veg_t)} \quad \text{(Eq. 2)}$$

where $\overline{Veg_t}$ is historical mean vegetation index in month *t*.

Variation of vegetation health will be further partitioned into components specifically attributable to natural variability and anthropogenic change *of each individual climate variable* (Fig. 2). The natural and anthropogenic decompositions of each climate variable (e.g., SM_t^{Nat}) will be sequentially passed into Eqs. 1 and 2, while maintaining other variables at their climatological means values. This will attribute drought-induced vegetation loss into seven components: fractions resulting from naturally variability (f_{Nat}^{SM}, f_{Nat}^{VPD}, f_{Nat}^{TMP}, and f_{Nat}^{PAR}) and fractions resulting from anthropogenic warming (f_{Anth}^{SM}, f_{Anth}^{VPD}, and f_{Anth}^{TMP}).

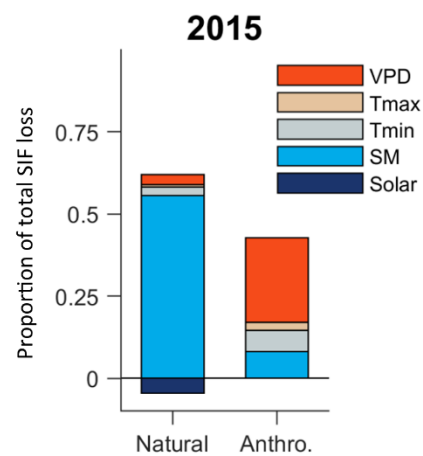

Figure 2. Attribution of total annual drought-induced SIF loss to natural vs. anthropogenic effects on specific climatic factors.

Initial results (Figs. 1 and 2) suggest confirmation of the hypothesis that anthropogenic warming contributed even more to loss of vegetation health than it did to soil moisture loss, with anthropogenic warming contributing to 40-50% of the drought-induced reduction of vegetation health (Fig. 1). Further, while the largest single driver of vegetation health during the drought was natural variability in soil moisture, soil moisture loss from anthropogenic warming explained ~10% of the reduction and anthropogenic increases in temperature and VPD explained an additional ~30% of the loss of vegetation health (Fig. 2). This means that even though droughts are initiated by natural variability in precipitation, anthropogenic climate change nearly doubles the effects of drought on vegetated ecosystems.

3. POLICY RELEVANCE

Mitigating and adapting to climate change is arguably the defining challenge of the 21st century, and managing Earth's vegetated ecosystems—which provide important environmental, economic, and cultural services for humanity—in the face of global change will be an

increasingly important component of environmental policy making. Forests and other ecosystems provide direct economic value through timber, recreational activities, and aesthetic value for residential neighborhoods (*10*). Plants also stabilize soils and inhibit erosion (*11*, *12*), enhance water quality (*13*), reduce stormflow and provide flood control (*12*), and sequester vast amounts of our carbon dioxide emissions (*14*). Understanding and predicting how ecosystem processes are changing, and how they will continue to change in the future, is therefore a key priority for developing effective policy to manage and adapt Earth's ecosystems to climate change. Adaptive management options include thinning, irrigation, assisted migration, treatment of pests and pathogens, and enhancement of genetic or phenotypic diversity, all with the goal of enhancing resilience, maintaining ecosystem services and economic value, and reducing extinction risk (*15–17*). However, understanding ecosystem responses to climate change is a prerequisite for prioritizing appropriate management and adaptation techniques. For example, if warming-induced increases in evaporative demand become more important drivers of vegetation health (*5*), then irrigation (which would alter soil moisture but not heat and VPD) would likely become a less effective solution while planting heat-adapted genotypes (*18*) could provide resilience to stresses experienced in a warmer world. This project will therefore fit within PPC's Environmental Policy research program, especially "Land and Water Management" research.

4. PROJECT OUTCOMES AND TIMELINE

4.1. Project outcomes and deliverables

The primary deliverable from this project will be one publication on attribution of drought-induced losses of vegetation health during the 2012-2015 California drought to natural vs. anthropogenic drivers. The initial results shown above represent, to my knowledge, a first-of-its-kind attribution of drought effects on vegetation to anthropogenic warming, so I intend to submit this manuscript to *Nature Climate Change*, arguably the highest impact journal in climate science (contingency plan: *PNAS* or *Global Change Biology*). The results of this research will also be summarized and disseminated in a brief fact sheet, with a focus on the policy relevance.

In addition to this primary outcome, this project will also have two secondary deliverables. First, it will produce an empirical "global change ecology" attribution framework which will be extensible to other regions and ecosystems beyond the scope of this particular case study. All code to implement the attribution framework will be provided through my GitHub site and archived on Zenodo (which meets the FAIR Data Standard policy). Second, the work will be presented at two conferences (the annual meetings of the Ecological Society of America and the American Geophysical Union) and at one of the PPC's fall Lunch and Learn seminars.

4.2. Project timeline

- Residence period (June 1-28, 2020)
    - *Weeks 1-2*: refine workflow.
    - *Weeks 2-3*: apply the workflow to additional satellite indices.
    - *Weeks 3-4*: write and edit draft manuscript
    - *Week 4*: write and edit policy-relevant fact sheet with assistance of PPC staff
- Post-residence period
    - *July 2020*: finish editing manuscript and submit to *Nature Climate Change*
    - *Aug 2-7*: present at Ecological Society of America Annual Meeting (Salt Lake City)
    - *Fall 2020*: present at PPC Lunch and Learn
    - *Dec 7-11*: present at American Geophysical Union Annual Meeting (San Francisco)

5. REFERENCES

1. B. I. Cook, *Drought: An Interdisciplinary Perspective* (Columbia University Press, New York, NY, 2019).
2. B. I. Cook, J. E. Smerdon, R. Seager, S. Coats, Global warming and 21st century drying. *Clim. Dyn.* **43**, 2607–2627 (2014).
3. A. P. Williams *et al.*, Contribution of anthropogenic warming to California drought during 2012 – 2014. *Geophys. Res. Lett.* **42**, 6819–6828 (2015).
4. N. S. Diffenbaugh, D. L. Swain, D. Touma, Anthropogenic warming has increased drought risk in California. *Proc. Natl. Acad. Sci.* **112**, 3931–3936 (2015).
5. K. A. Novick *et al.*, The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nat. Clim. Chang.* **6**, 1023–1027 (2016).
6. W. K. Smith *et al.*, Remote sensing of dryland ecosystem structure and function: Progress, challenges, and opportunities. *Remote Sens. Environ.* **233**, 111401 (2019).
7. M. R. Munafò, G. D. Smith, Repeating experiments is not enough. *Nature*. **553**, 399–401 (2018).
8. M. Jung *et al.*, Compensatory water effects link yearly global land CO2 sink changes to temperature. *Nature*. **541**, 516–520 (2017).
9. J. T. Abatzoglou, A. P. Williams, Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Natl. Acad. Sci. U. S. A.* **113**, 11770–11775 (2016).
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14. Y. Pan *et al.*, A large and persistent carbon sink in the world's forests. *Science* **333**, 988–993 (2011).
15. R. F. Noss, Beyond Kyoto: Forest Management in a Time of Rapid Climate Change. *Conserv. Biol.* **15**, 578–590 (2001).
16. D. J. Chmura *et al.*, Forest responses to climate change in the northwestern United States: Ecophysiological foundations for adaptive management. *For. Ecol. Manage.* **261**, 1121–1142 (2011).
17. M. I. Williams, R. K. Dumroese, Preparing for Climate Change: Forestry and Assisted Migration. *J. For.* **111**, 287–297 (2013).
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EDUCATION

Ph.D. **University of North Carolina**, Chapel Hill NC, Geography, May 2017
M.A. **University of North Carolina**, Chapel Hill NC, Geography, May 2013
B.A. **Hope College**, Holland MI, English & Philosophy, May 2007

ACADEMIC APPOINTMENTS

2019 –	**University of Iowa**, Iowa City, IA Assistant Professor, Dept. of Geographical and Sustainability Sciences
2017 – 2018	**University of Arizona**, Tucson, AZ Postdoctoral Research Associate, Sch. of Natural Resources and the Environment

SELECTED HONORS AND AWARDS (2018-present)

2020	John Russell Mather Paper of the Year Award, Climate Specialty Group, American Association of Geographers
2019	John I. Davidson President's Award for Practical Papers (2nd Place), American Society for Photogrammetry and Remote Sensing
2018	Best Paper Award for Early Career Scholars in Remote Sensing, Remote Sensing Specialty Group, American Association of Geographers
2018	Ellen Mosley-Thompson Best Publication Award (with Erika K. Wise), Paleoenvironmental Change Specialty Group, American Association of Geographers

SELECTED PUBLICATIONS (*N* = 21, *h*-index = 9)

Selected publications most closely related to the proposed project

Dannenberg, M. P., C. Song, E. K. Wise, N. Pederson, and D. A. Bishop (2020), Delineating environmental stresses to primary production of U.S. forests from tree rings: Effects of climate seasonality, soil, and topography, *Journal of Geophysical Research: Biogeosciences*, 125, e2019JG005499.

Smith, W. K.*, **M. P. Dannenberg***, et al. (2019), Remote sensing of dryland ecosystem structure and function: Progress, challenges, and opportunities (*invited*), *Remote Sensing of Environment* 233, 111401. [**Smith and Dannenberg contributed equally*.]

Dannenberg, M. P., E. K. Wise, and W. K. Smith (2019), Reduced tree growth in the semiarid United States due to asymmetric responses to intensifying precipitation extremes, *Science Advances* 5(10), eaaw0667.

Dannenberg, M. P. and E. K. Wise (2017), Shifting Pacific storm tracks as stressors to ecosystems of western North America, *Global Change Biology* 23(11), 4896-4906.

Wise, E. K. and **M. P. Dannenberg** (2017), Reconstructed storm tracks reveal three centuries of changing moisture delivery to North America, *Science Advances* 3, e1602263.

Dannenberg, M. P., C. Song, T. Hwang, and E. K. Wise (2015), Empirical evidence of El Niño—Southern Oscillation influence on land surface phenology and productivity in the western United States, *Remote Sensing of Environment* 159, 167-180.

Selected other significant publications

Dannenberg, M. P., X. Wang, D. Yan, and W. K. Smith (2020), Phenological characteristics of global ecosystems based on optical, fluorescence, and microwave remote sensing (*invited*), *Remote Sensing*, 12(4), 671.

Wise, E. K. and **M. P. Dannenberg** (2019), Climate factors leading to asymmetric extreme capture in the tree-ring record, *Geophysical Research Letters* 46, 3408-3416.

Dannenberg, M. P., C. Song, and C. R. Hakkenberg (2018), A long-term, consistent land cover history of the southeastern United States, *Photogrammetric Engineering and Remote Sensing* 84(9), 559-568.

Dannenberg, M. P., E. K. Wise, M. Janko, T. Hwang, and W. K. Smith (2018), Atmospheric teleconnection influence on North American land surface phenology, *Environmental Research Letters* 13(3), 034029.

Dannenberg, M. P. and E. K. Wise (2016), Seasonal climate signals from multiple tree-ring metrics: a case study of *Pinus ponderosa* in the upper Columbia River basin, *Journal of Geophysical Research: Biogeosciences* 121, 1178-1189.

Wise, E. K. and **M. P. Dannenberg** (2014), Persistence of pressure patterns over North America and the North Pacific since AD 1500, *Nature Communications* 5, 4912.

GRANTS AND FELLOWSHIPS (2018-present)

2020 – 23 *Collaborative Research: P2C2 - Multi-century perspectives on current and future flow in the Lower Missouri River Basin*, Paleo Perspectives on Climate Change (P2C2), National Science Foundation, PI: Matthew P. Dannenberg, $177,382.

2019 – 21 *Once and future forests: Exploring divergent responses of Douglas-fir and limber pine to recent climate change in the central Rocky Mountains*, Center for Global and Regional Environmental Research, University of Iowa, PI: Matthew P. Dannenberg, $30,000.

SELECTED SCHOLARLY PRESENTATIONS (2018-present)

2020 "Once and future forests: Responses of terrestrial ecosystems to changes in hydroclimatic variability," Department of Biology, University of Iowa, Iowa City, IA (28 February 2020).

2019 "Large-scale reductions in terrestrial carbon uptake due to central Pacific El Niño revealed by remote sensing and land surface models," *American Geophysical Union Fall Meeting*, San Francisco, CA.

2019 "Reduced tree growth in the United States due to asymmetric responses to intensifying precipitation extremes," *Annual Meeting of the Ecological Society of America*, Louisville, KY.

2019 "A long-term, consistent land cover history of the southeastern United States based on automatic adaptive signature generalization and multi-temporal Landsat imagery," *Annual Meeting of the American Association of Geographers*, Washington, DC.

2018 "Ocean-atmosphere influence on North American ecosystems: patterns and predictability," School of Geography and Development, University of Arizona, Tucson, AZ (30 March 2018).

2018 "Responses of North American vegetation to coupled ocean-atmosphere circulation patterns," Department of Geography, Indiana University, Bloomington, IN (22 January 2018).

2018 "Linking ecosystem processes to oceanic and atmospheric circulation: patterns and predictability," Department of Geographical and Sustainability Sciences, University of Iowa, Iowa City, IA (18 January 2018).

2018 "Atmospheric teleconnection influence on North American land surface phenology," *American Geophysical Union Fall Meeting*, Washington, DC.

TEACHING (2018-present)

GEOG:1020: The Global Environment (Spring 2020)
GEOG:2310: Introduction to Climatology (Fall 2019)
GEOG:4470: Ecological Climatology (Spring 2020)
GEOG:6300: Seminar in Environment, Conservation and Land Use (Spring 2019)
GEOG:7000: Geography Colloquium (Fall 2019, Spring 2020)

SELECTED SERVICE AND PROFESSIONAL ACTIVITIES (2018-present)

Service to discipline

Panelist, NSF Geography and Spatial Sciences, 2020.

Organizer and Chair, "Automating land cover change analyses of multi-temporal satellite imagery," Annual Meeting of the American Association of Geographers, 3-7 April 2019, Washington, DC.

Convener, Chair and OSPA Liaison, "B43A: Integrated Understanding of Climate, Carbon, Nutrient Cycles, Human Activities, and their Interactions in Terrestrial Ecosystems," American Geophysical Union Fall Meeting, 10-14 December 2018, Washington, DC.

Ad hoc manuscript reviews: *Climate Research, Ecology Letters, The Holocene, Hydrological Processes, Journal of Geophysical Research: Biogeosciences, International Journal of Remote Sensing* (2), *Journal of Applied Remote Sensing, Progress in Physical Geography, Remote Sensing of Environment* (2), *Science of the Total Environment*

Service to department and University of Iowa

Seed Grant reviewer, Center for Global and Regional Environmental Research, 2019-2020
Faculty Assembly, College of Liberal Arts and Sciences, 2019-2020
Executive Committee, Dept. of Geographical and Sustainability Sciences, 2019-2022
VAP Search Committee, Dept. of Geographical and Sustainability Sciences, 2019
Graduate Committee, Dept. of Geographical and Sustainability Sciences, 2019-present
Kohn Colloquium Coordinator, Dept. of Geographical and Sustainability Sciences, 2019-2020