Diagnosing drought-induced conifer stress in mountains using solar-induced chlorophyll fluorescence from satellites

Across the globe, the terrestrial biosphere is responding to growing climate extremes, including more frequent heatwaves, droughts, and high-impact weather events[1]. For North American forests, this means increasing physiological stress on one of the continent's most important carbon sinks, along with the vast quantity of biodiversity that these ecosystems support. A fundamental way to understand and potentially mitigate the ecological impacts of extreme heat and drought events is by tracking carbon uptake through photosynthesis (i.e., gross primary productivity, GPP), across seasons at the forest-scale[2]. However, large-scale monitoring of GPP is challenging when considering the highly dynamic and remote nature of mountain biomes, which make up a substantial portion of North American biomass[3]. Montane landscapes exhibit vast gaps in spatial coverage of surface-level GPP measurements, along with complex topography that makes land surface models and atmospheric tracer approaches prone to significant uncertainty[4]. Thus, remotely-sensed data from space present a promising tool to fill in these spatial gaps to better understand forests' response to stress and the implications for the terrestrial carbon cycle.

Traditionally, forest-level GPP has been derived from satellites using reflectance-based indices that quantify the "greenness" of a land surface. However, the temperate and boreal forests that comprise many North American mountain biomes consist mainly of evergreen conifer trees which retain their needles, and therefore, greenness, even in photosynthetically dormant seasons (e.g., drought or winter). Thus, studies that use reflectance-based indices as metrics of conifer GPP face significant challenges in capturing seasonal to decadal changes of photosynthetic activity[5,6]. In contrast, solar-induced chlorophyll fluorescence (SIF), which is emitted by chlorophyll pigments as a byproduct of the photosynthetic process and can be measured via satellite instruments, has been shown to closely follow the seasonal cycle of photosynthetic production in evergreen forests[7]. The combination of newly available remotely-sensed high-resolution SIF data, in conjunction with measures of complex terrain characteristics (e.g., slope angle, aspect and elevation), represents a unique opportunity for understanding GPP over mountain biomes. In my proposed work, I will analyze GPP derived over the Sierra Nevada mountain range in California using ground-based flux tower data, biogeochemical models, and remotely-sensed SIF and reflectance-based data in order to test the hypotheses described below and in **Figure 1**.

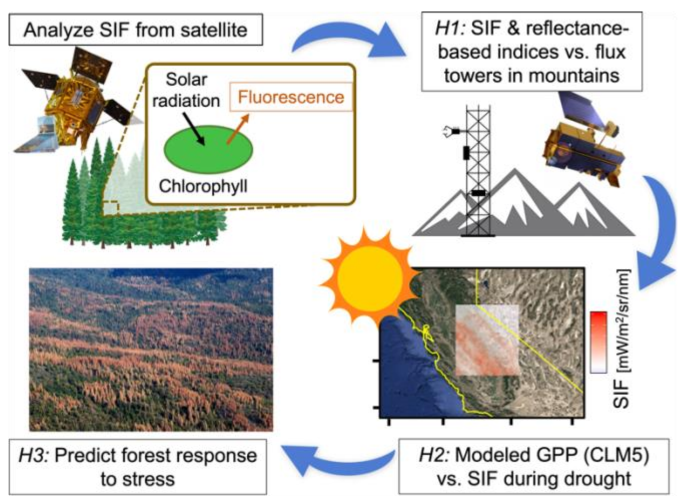

Fig. 1: Satellite-based SIF will be analyzed against reflectance-based indices and modeled GPP in mountains to assess drought-induced stress.

<u>*Hypothesis 1 (H1) - SIF is an improved way to measure GPP over montane conifer ecosystems compared to traditional reflectance-based remote sensing indices.*</u> High-resolution SIF from satellites provides extensive spatial data coverage, but satellite-based SIF has yet to be analyzed for fine-scale spatial and elevation gradients in complex terrain. To test *H1*, I will analyze SIF data from the TROPOMI and OCO-2/3 satellite instruments over the Sierra Nevada range, comparing to GPP measured at eddy-covariance flux towers from the NSF-funded National Ecological Observatory Network (NEON) and Southern Sierra Critical Zone Observatory sites in the Sierra Nevada range. I will then compare SIF and traditional reflectance-based indices (NDVI, EVI, CCI) to quantify differences in their ability to predict seasonal and interannual GPP as a function of elevation and terrain characteristics.

<u>*Hypothesis 2 (H2) - Characterization of mountain conifer forests response to drought can be improved with the aid of remotely-sensed SIF.*</u> The Sierra Nevada range has consistently experienced extreme drought conditions over the past decade; these forests' productivity in response to drought can be estimated using

biogeochemical models, but does the spatial resolution of a model limit its ability to resolve such dynamic processes over complex terrain? Based on insights from *H1* and using SIF as a means of constraining modeled GPP, I will test *H2* by comparing remotely-sensed SIF to GPP modeled using the Community Land Model version 5 (CLM5) over the Sierra Nevada region for timeframes with available high-resolution SIF data, detecting mismatch between satellite- and model-derived GPP over seasonal and interannual cycles during observed drought periods.

<u>*Hypothesis 3 (H3) - SIF can provide information towards early warning capabilities for forest health in response to drought conditions.*</u> Assuming a direct linkage between forest productivity and physiological stress, remotely-sensed measures of GPP could act as highly localized indicators of forest health in drought-stricken regions. Using information gleaned from *H1* and *H2*, I will analyze high-resolution SIF data with recent records of forest drought disturbances to quantify trends in SIF as they are correlated with drought events. Through this analysis I will uncover statistical relationships between SIF and drought stress in the context of variables such as elevation, aspect, and snow cover to determine the extent to which SIF can act as an early warning system for forest health over land-use management scales.

Collaborations and Computing Resources: To complete this work, I will build on an existing NSF-funded collaboration between the University of Utah and researchers at California Institute of Technology (led by Prof. Christian Frankenberg) to access high-resolution, pre-processed topography-corrected SIF data products over the Sierra Nevada range. I will also work with the University of California–Irvine Innovation Center for Advancing Ecosystem Climate Solutions to engage regional Sierra Nevada stakeholders in scientific discussion. To accommodate the computational needs associated with my work, I will utilize dedicated group-access nodes (purchased by advisor Prof. John Lin) on two supercomputers maintained by the University of Utah's Center for High-Performance Computing.

<u>**Intellectual Merit**</u> – ***Global Carbon Budget:*** Remotely-sensed SIF has the potential to track forest productivity over global scales and is a promising tool for rectifying uncertainties in the carbon budget of mountains. My work will be among the first to examine high resolution SIF over complex terrain in order to address uncertainties in forest drought response. As heat and drought stress grow increasingly prevalent due to climate change, understanding the highly dynamic response of montane carbon stocks will be critical for improving terrestrial biosphere models that inform global climate policy. ***Forest Management:*** High resolution SIF can help diagnose features of forest wellbeing and tree mortality at scales meaningful to land use management. Through assessment of *H3*, I will examine how SIF can be used to provide early warning capabilities for near-term forest disturbances and allow land managers to adapt to rapid changes in forest health from critical stress events. These capabilities ultimately aid in emergency preparedness capabilities to mitigate damage from wildfires and bark beetle die-off.

<u>**Broader Impacts**</u> – ***Stakeholder Engagement:*** The U.S.D.A. Forest Service Region 5 and Sierra Nevada Conservancy have a vested interest in central California's forest health and wildfire management, motivated by public protection, forest resource care, and conservation advocacy. In addition, the California Air Resources Board is seeking accurate methods to estimate forest carbon stocks for implementation of carbon accounting policies. Through collaboration with UC–Irvine (see above), I will engage stakeholder representatives from these institutions through ongoing virtual correspondence and regularly held stakeholder meetings to disseminate my findings on forest drought response and early warning capabilities. ***Code Sharing:*** As I have already done in my previous publications, I plan to provide open access to R and python scripts to the entire research community produced through my personal Github webpage (*github.com/lkunik*).

References: **[1]** IPCC 6th Assessment Report, (2021) **[2]** E. Tomppo, et al. (2021) *Remote Sens.* 13, 597. **[3]** D. Schimel, et al. (2002) *Eos Trans. AGU.* 83(40), 445–449. **[4]** M. Rotach, et al. (2014) *Bull. Amer. Meteor.* 95(7), 1021-1028. **[5]** K. Springer, et al. (2017) *Remote Sens.* 9, 1–18. **[6]** D. Sims, et al. (2006) *J. Geophys. Res.* 111, G04015. **[7]** T. Magney, et al. (2019) *Proc. Natl. Acad. Sci.* 116(24), 11640-11645.