

Assessment of Ecosystem Photosynthetic Parameters along Two California Climate Gradients

Sean DuBois¹

University of Wisconsin – Madison, Nelson Institute for Environmental Studies

Abstract: Improving coupled Earth system models of current and future climate requires robust observations that accurately provide parameters and observations for evaluation across spatial scales relevant for the model. Photosynthetic parameters $V_{c_{max}}$ and J_{max} help to characterize the ability of vegetation to assimilate carbon, a required parameter in most land surface modules of climate models. Remote sensing, flux tower data, and field measurements were collected to develop a methodology to estimate the variability in these parameters across diverse landscapes in Southern California and the Sierras, regions experiencing prolonged drought which is expected to become more common in the future. $V_{c_{max}}$ maps were generated with NASA hyperspectral airborne AVIRIS imagery by scaling up leaf level measurements to the canopy and evaluated using flux tower data for nine sites across California. These maps illustrate the expected temporal and spatial changes in the parameter. However, $V_{c_{max}}$ estimated from inverse modeling of flux tower data did not fall in the range found in field measurements. The methods developed in this study expand the applicability of imaging spectroscopy in estimating ecosystem metabolism.

Introduction

Increases in atmospheric carbon dioxide are well documented in the past century (Hofmann et al., 2006) and the resulting change in regional climates are predicted to have impacts on local vegetation, especially for Mediterranean climate systems, through changes in precipitation (Breshears et al., 2005). Vegetation shifts resulting from a changing climate have already been quantified in California (Kelly & Goulden, 2008). Meanwhile, there is a need to provide higher accuracy and increased spatial resolution data to models in order to better estimate ecosystem parameters during times of increased vegetative stress (Vargas et al., 2013). Significant uncertainty exists in our ability to model global photosynthesis and its sensitivity to future climate change.

Recent work by Serbin et al (2012) has indicated strong evidence for the ability to use hyperspectral imaging collected from high altitude airborne missions to detect photosynthetic rates. Spectroscopy was used to predict leaf metabolic properties $V_{c_{max}}$, the maximum rate of carboxylation of the enzyme RuBisCO, and J_{max} , the maximum rate of electron transport necessary to regenerate the RuBP, across ecosystems. A robust relationship between spectra and leaf was developed that is applicable to a wide range of environmental conditions and vegetation types. However, there lacks systematic observations for how leaf level photosynthetic rate constants vary with time and how they scale from leaf to canopy.

Our research in this project assessed the potential to make spatially explicit estimates of $V_{c_{max}}$ and J_{max} from remote sensing that can be scaled to predict seasonal canopy assimilation across large

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areas. These two traits are used to predict photosynthetic capacity using an often employed biochemical model (Farquhar et al., 1980; Farquhar and von Caemmerer, 1982). Field measurements were made to calibrate concurrently collected remote sensing images. Eddy covariance flux tower data – a widely used method to measure ecosystem carbon, water and energy fluxes (Baldocchi and Meyers, 1998) – were used to evaluate the scaling up of leaf level estimates to the canopy. Understanding the spatial variability in these traits will allow for more robust model inputs and thus predictive capacity. The principle objectives of this project were to make maps illustrating the spatial and temporal variations in V_{cmax} across a wide range of vegetation, and to evaluate these models using data collected from flux towers located in these ecosystems. This report summarizes research conducted under partial support of the WSGC Grad fellowship. The fellowship allowed for the study of annual variation in the flux data, including the drought signal, and presentation of these findings to an international audience at the Global Land Project Meeting in Berlin, Germany.

Methods

Site descriptions. The flux tower sites used in this study comprise two climate gradients, one located in southern California (transecting the San Jacinto Mountains) and the other in central California (rising from the San Joaquin Valley into the Sierra Nevada Mountains). The use of sites located along these climate gradients allows for numerous ecosystem types to be studied in relatively close space, ensuring the results from this study to be applicable and replicable in other regions.

The southern California climate gradient covers the vegetation types grassland, coastal sagebrush, and an oak-pine forest on the western slope of the San Jacinto Mountains, and pinyon-juniper woodland, chaparral scrubland and desert scrub located on the eastern slope (Kelly & Goulden, 2008). The Sierra climate gradient is comprised of the three sites oak/pine woodland, ponderosa pine forest, and mixed conifer forest (figure 1).

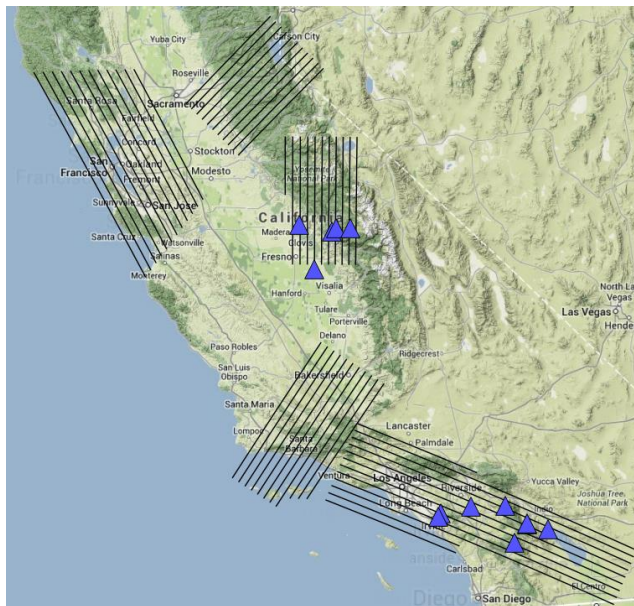


Figure 1: Location of the core study sites found within the five HypsIRI campaign flight boxes. The southern sites comprise the southern California climate gradient, while the northern lie along the Sierra gradient.

Remote sensing collection. The two climate gradients used in the study were flown by the NASA high altitude E-2 aircraft collecting imaging spectroscopy and thermal imagery using the AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) and MASTER (MODIS/ Advanced Spaceborne Thermal Emission and Reflection Radiometer Airborne Simulator) sensors (see figure 1). Flights were conducted at least once a season and timed to capture maximum variation in the ecosystems (figure 2). NASA provided processed

reflectance imagery which were topographically corrected and corrected for bidirectional reflectance distribution function. AVIRIS has a spectral resolution of around 10 nm and covers the electromagnetic range of 414–2447 nm. Using a partial least-squares regression (PLSR) modeling approach similar to Serbin et al. (2014), maps of $V_{c_{max}}$ were generated for the areas around each flux tower (see figure 3).

In conjunction with the airborne measurements, ground-based measurements of canopy LAI and clumping, leaf reflectance, temperature, nutrient status, stomatal conductance, and photosynthetic CO₂-response were conducted at two southern sites and 3 Sierra sites in the spring and summer of both 2013 and 2014. These field measurements were designed to collect data for the calibration of remote sensing products. The field measurements coincided with AVIRIS and MASTER overflights.

Flux Data Collection. Eddy covariance flux tower compute net ecosystem exchange (NEE) of trace gases, energy and momentum based on the turbulent conservation equation for fluids (Baldocchi and Meyers, 1998). NEE can be computed from high-frequency (> 10 Hz) covariation of vertical wind and tracers on towers, collected using the methods and instruments described in Goulden et al. (2012). NEE observations were aggregated into half hourly estimates, as were other meteorological parameters including air temperature and solar flux.

Collection of eddy covariance data on sloped terrain presents issues due to potential vertical movement of air via cold air drainage instead of turbulent flow. Our sites, located along an elevational climate gradient and thus sloped terrain, are impacted by this issue and require specific quality control. Filtering of low friction velocities (u^*) was performed to remove data collected during periods of low turbulence.

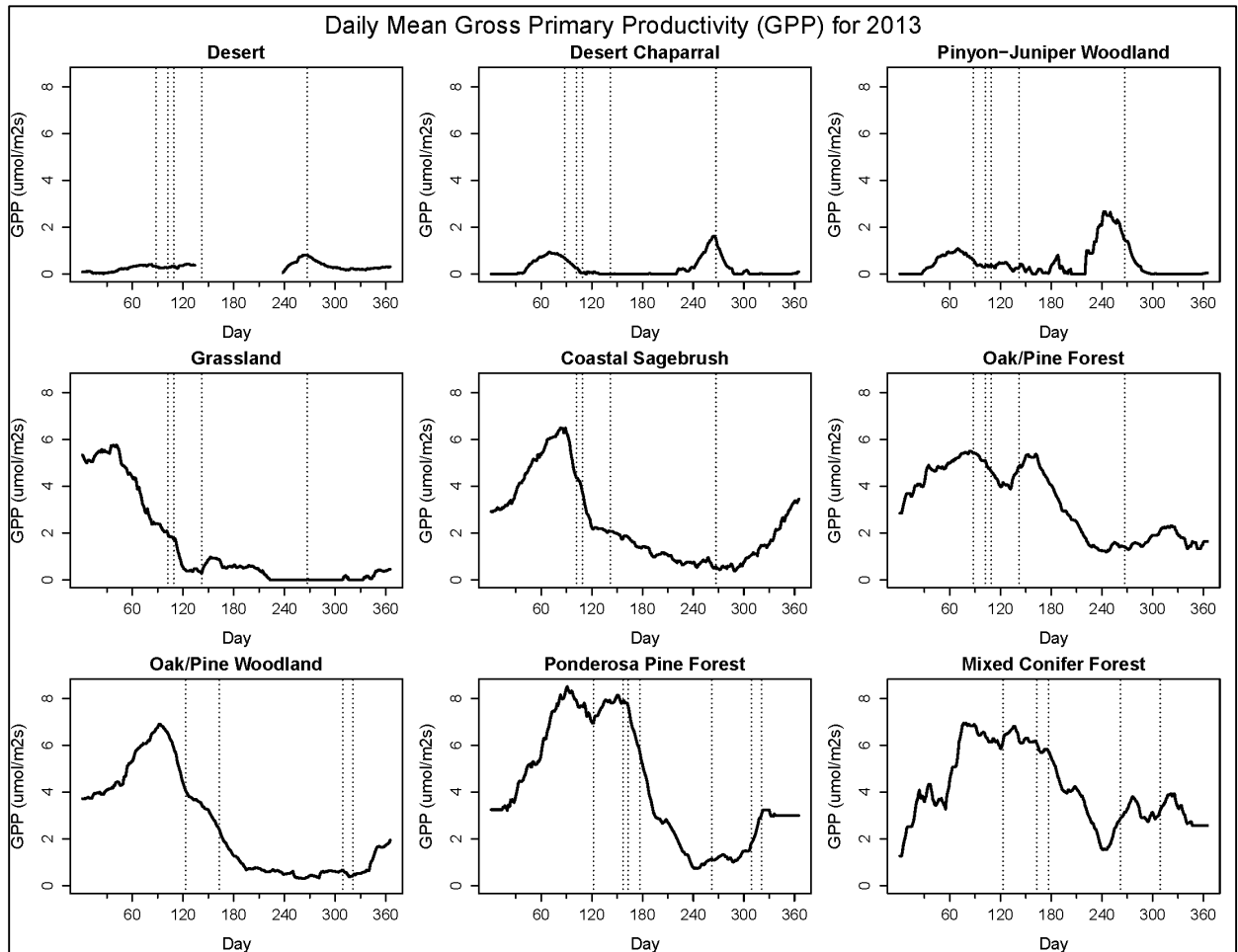
In order to generate a complete time series after removing data during the quality control process, we filled missing data points using the Desai-Cook gap filling model (Cook et al., 2004; Desai et al., 2005). This model was applied to the u^* filtered data, utilizing the 30 minute values for NEE, photosynthetically active radiation (PAR), air temperature and site location. The model uses a variable moving-window mean diurnal variation method to estimate missing meteorological data, with the window size depending on the completeness of the dataset.

The Eyring function (Cook et al., 2004; Eyring, 1935) was applied to the filled data to estimate ecosystem respiration (R_{eco}). Gross Primary Productivity (GPP) was modeled from the difference between the 30 minute modeled R_{eco} and the original NEE data. The computed GPP was fit to a Michaelis-Menton reaction rate equation (Falge et al., 2001; Ruimy et al., 1995) in order to fill gaps. The full time series of R_{eco} and GPP was then used to estimate NEE and fill gaps in the original dataset.

Estimates of $V_{c_{max}}$ from flux tower data were made from inverse modeling a Farquhar-based photosynthesis model following the method described in Wolf et al. (2006). The model was computed using filtered and gapfilled NEE along with meteorological data collected at the flux

tower site. Estimates were made for multiple sites, using data from approximately four or five days depending on site conditions and quality of the extended data.

Analysis. GPP estimated from NEE data was used to categorize ecosystem growing seasons. As our sites covered a variety of climatic zones and precipitation-dependent vegetation types, growing seasons and thus peak productivity do not align across sites. Comparing GPP between sites and AVIRIS collection dates allow for the remote sensing data to be put in the context of each sites' growing season.



Results

California Climate. The Southern California transect can be divided into three climate categories: (i) coastal, which includes coastal sage and grassland, (ii) southern interior, consisting of desert,

Figure 2: GPP for all sites from 2013 with AVIRIS imagery dates indicated by the vertical dashed line. GPP follows the precipitation regime, with maximums often following times of peak precipitation. The AVIRIS imagery captures a range of productivity levels for each site, but misses maximum productivity for the xeric and coastal sites, most likely due to drought causing the growing seasons to retreat into the cooler months.

desert chaparral, and pinyon-juniper woodland, and (iii) southern montane for the oak/pine forest. The coastal sites receive most of their annual precipitation in the cooler winter months before an often dry and warm summer. The southern interior sites are the most xeric, with low precipitation usually in the late winter or spring, and intermittent throughout the rest of the year. The southern montane also receives its most significant rainfall in the winter and early spring, but has moderate temperatures relative to the other southern sites.

The Sierra sites are categorized as central interior (oak/pine woodland) and montane (ponderosa pine and mixed conifer). All sites receive most of the annual precipitation in winter and spring, and at a lesser rate during the rest of the year. The montane sites experience cold winters and moderate summers, while the central interior has moderate winters and warm summers. California is currently enduring severe drought conditions since the 2012 calendar year (US Drought Monitor, 2014). This is evident in our data, as annual precipitation has steadily declined since 2011 (see figure 4). All sites in which we examined previous years' data exhibited a

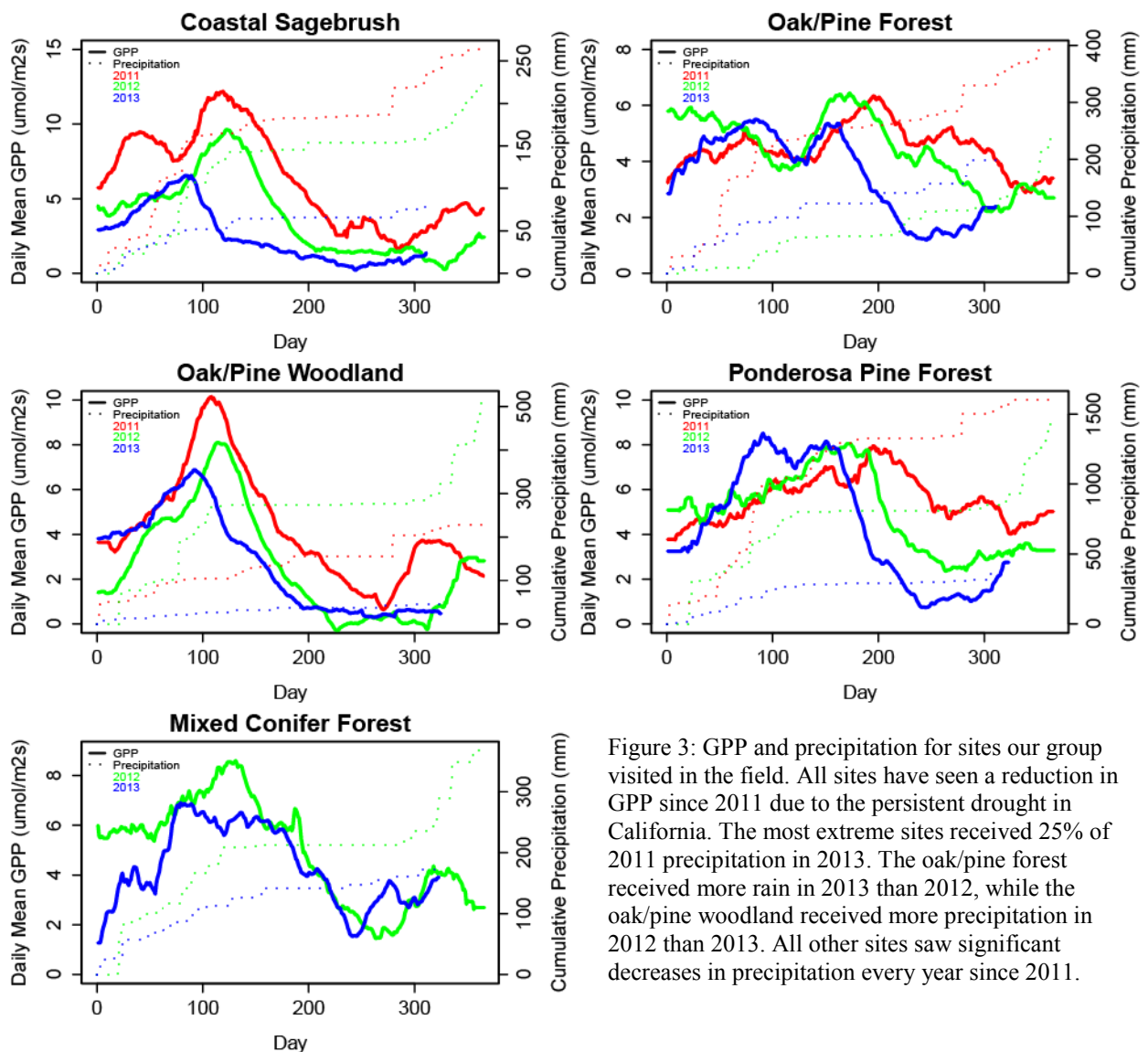


Figure 3: GPP and precipitation for sites our group visited in the field. All sites have seen a reduction in GPP since 2011 due to the persistent drought in California. The most extreme sites received 25% of 2011 precipitation in 2013. The oak/pine forest received more rain in 2013 than 2012, while the oak/pine woodland received more precipitation in 2012 than 2013. All other sites saw significant decreases in precipitation every year since 2011.

decreasing trend in precipitation, with 2013 data often signaling drier conditions than the first year of the drought in 2012. The drought tends to deviate most strongly from previous years' rainfall records in the spring, when the wet season usually delivers a significant portion of the annual precipitation for the southern sites. During drought years, the spring increase in rainfall either did not occur or the magnitude of rainfall was significantly decreased.

Ecosystem carbon fluxes. The most xeric sites (desert, desert chaparral, and pinyon-juniper woodland) have a bimodal growing season (figure 2), caused from two predominant precipitation periods occurring in 2013. These events directly resulted in times of increased production. The mesic sites are categorized as having predominately a single peak in productivity occurring in late winter or spring. The single peak is caused by precipitation events and low water demand in the cooler winter months.

Due to the continuous nature of flux tower measurements compared to the irregular remote sensing campaigns, it is necessary to contextualize the imagery with the eddy covariance measurements. The numerous overflights often were able to categorize annual variability by collecting at periods of both maximum and minimum productivity. However, the sites characterized by maximum GPP occurring in late and early spring (grassland, coastal sagebrush, and oak/pine woodland) reached peak productivity before the first AVIRIS flight of the year. Comparing spectra-derived estimates of photosynthesis must take into account the differences in growing seasons between vegetation types.

V_cmax Inversion. Inverse modeling of the Farquhar photosynthesis model using flux tower data provided V_cmax and LAI estimates for multiple vegetation types in the footprint of each flux tower. The estimates for all sites in 2013 were far below those measured from leaf chamber gas exchange.

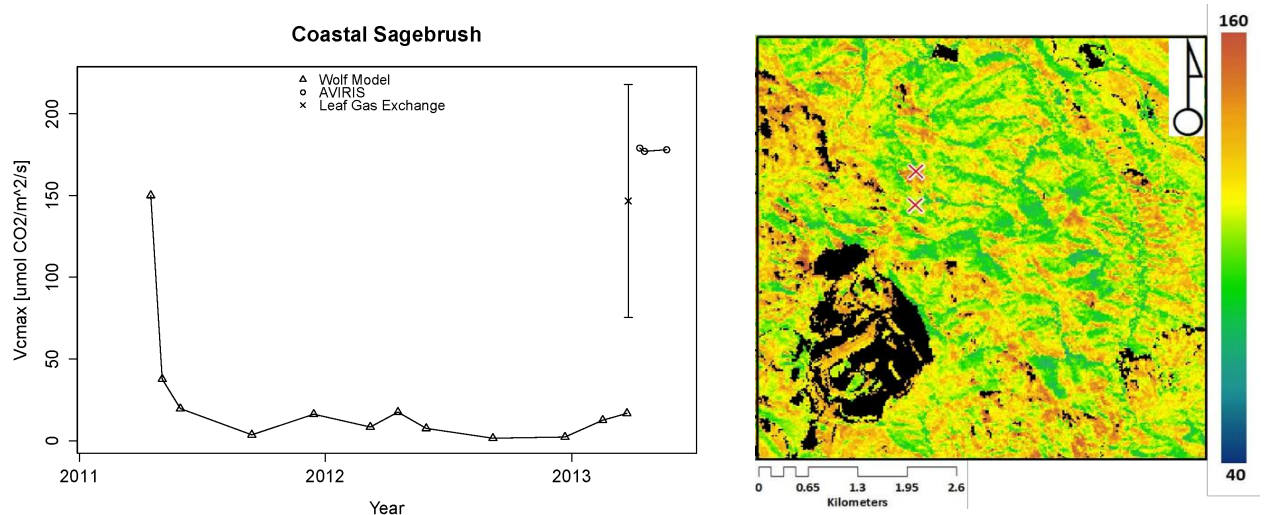


Figure 4: V_cmax values for coastal sagebrush. *Left*: comparison of estimates from the Wolf approach for modeling V_cmax from flux data and AVIRIS image, and measured field values for all dominant species. During drought conditions, the Wolf approach yields much lower estimates compared to pre-drought. However, the estimates from AVIRIS imagery are within the range measured in the field. *Right*: Map of V_cmax from 2013 spring for the coastal sage (north red marker) and grassland (south red marker). Variation in the parameter is high across the landscape.

In order to determine the variability of $V_{c_{max}}$ estimates from the flux tower data, estimates were made going back to 2011. Figure 3 shows a comparison of estimated $V_{c_{max}}$ from the flux tower data, the AVIRIS imagery, and the calculated range of values from leaf chamber gas exchange measurements for the coastal sage site. 2011 estimates of $V_{c_{max}}$ (150 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$) were closer to those collected in the field in 2013 (ranging from 74 to 300 $\mu\text{mol CO}_2/\text{m}^2/\text{s}$ for all dominant species). Preliminary estimates from the AVIRIS imagery are also near the average $V_{c_{max}}$ estimate from field data.

Discussion and Conclusion

This often preceded a significant decrease in summer and fall GPP. The one site that did not follow this trend was the oak/pine woodland, which received higher rainfall in 2012 than in 2011. There is a clear discrepancy between the flux data and the other two methods for estimating $V_{c_{max}}$. Although there are no field measurements in 2011, the Wolf estimated $V_{c_{max}}$ is around the expected value for the coastal sage site during springtime. Even throughout 2012 and 2013, there is variation in the $V_{c_{max}}$ estimate, but it does not reach levels often associated with viable ecosystems. Comparing this to the AVIRIS map of $V_{c_{max}}$, the spatial heterogeneity of $V_{c_{max}}$ does not include such low estimates. Our initial analysis shows that drought reduces the ability of the models used in the inversion to correctly predict ecosystem photosynthetic properties, which is concurrent with previous studies (Vargas et al., 2013). Given the decrease in $V_{c_{max}}$ estimates during the transition between pre-drought to drought conditions, we suggest that the Wolf approach does not accurately estimate $V_{c_{max}}$ during periods of high water stress for our sites. However, $V_{c_{max}}$ estimates are correlated with GPP modeled from flux data ($r=0.70$), and although the estimates do not reach levels measured in the field, the model still captures annual changes in productivity.

The flux tower data provides a long-term view that places the airborne field experiment imagery into context and provides a justification for long-term satellite based sensing of plant photosynthetic rate. The most important observation from tower data is the impact drought currently has on the Californian vegetation. All sites have seen a decrease in annual GPP, with most sites peak GPP reduced as well. Furthermore, peak productivity for the southern sites and some Sierra sites moves to earlier in the year when it is cooler and wetter. A common theme among sites is the drastic reduction in late season GPP. Peak productivity is often affected, but the largest decrease occurs in the summer and fall due to the reduced spring rainfall that historically provided some of the necessary moisture during the times of high water demand in the summer months. Thus, both maximum and minimum GPP are reduced due to the ongoing drought.

Eddy covariance flux measurements were used to inform ground and airborne data collection. Annual variations in vegetation productivity are captured in the flux data. In order to maximize effectiveness of field and airborne campaigns, estimates on timing of vegetation maxima and minima should guide these efforts. During the 2013 campaign, maximum productivity at the grassland and sage sights were missed by AVIRIS flights (figure 2). This appears to be caused in part by the drought, as the GPP maximum has retreated to earlier in the year. Future flights will be

adjusted in order to ensure the capture of the GPP range at each site by making predictions based on previous years' data.

Conclusion. Flux tower measurements were employed to evaluate the ability to scale $V_{c_{max}}$ estimates from the leaf to the canopy level. The inverse modeling technique to derive $V_{c_{max}}$ from the flux tower data was inadequate at predicting reasonable estimates due to the ongoing drought in the western U.S. Flux tower measurements and modeled GPP offer important observations which can inform remote sensing data collection due to the continuous collection, but are limited in spatial coverage. Long-term and high spatial resolution of ecosystem metabolism data is only possible with satellites equipped with imaging spectrometers.

Future work. Flux tower modeled GPP does appear to be a viable alternative to evaluating the spectroscopy scaling issue. It is possible to model GPP from the spectra-derived photosynthetic parameters, so this will be the preferred method for evaluating remote sensing $V_{c_{max}}$ estimates. In addition to the ongoing drought impacting productivity in California, other anthropogenic pollution including ozone is known to have negative impacts on vegetation. Ozone pollution will be compared to annual productivity and is expected to explain certain seasonal and annual variation during times of high pollution.

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