

# Using a Regional Cluster of AmeriFlux Sites in Central California to Advance Our Knowledge on Decadal-Scale Ecosystem-Atmosphere Carbon Dioxide Exchange

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## Abstract

Continuous eddy covariance measurements of carbon dioxide, water vapor and heat were measured continuously between an oak savanna and an annual grassland in California over a 4 year period. These systems serve as representative sites for biomes in Mediterranean climates and experience much seasonal and interannual variability in temperature and precipitation. These sites hence serve as natural laboratories for how whole ecosystems will respond to warmer and drier conditions.

The savanna proved to be a moderate sink of carbon, taking up about  $150 \text{ gC m}^{-2}\text{y}^{-1}$  compared to the annual grassland, which tended to be carbon neutral and often a source during drier years. But this carbon sink by the savanna came at a cost. This ecosystem used about 100 mm more water per year than the grassland. And because the savanna was darker and rougher its air temperature was about 0.5 C warmer.

In addition to our flux measurements, we collected vast amounts of ancillary data to interpret the site and fluxes, making this site a key site for model validation and parameterization. Datasets consist of terrestrial and airborne lidar for determining canopy structure, ground penetrating radar data on root distribution, phenology cameras monitoring leaf area index and its seasonality, predawn water potential, soil moisture, stem diameter and physiological capacity of photosynthesis

## Final Report

### 1. Eddy covariance flux measurements of carbon, water and energy.

Eddy covariance measurements of net carbon dioxide, water vapor and sensible heat exchange were conducted at an oak savanna and annual grassland in northern California during the extent of this project, extending the dataset from 2000 through 2013. Table 1 gives the annual sums of these fluxes. In general the savanna was a moderate sink of carbon ( $-157 \pm 60 \text{ gC m}^{-2} \text{ y}^{-1}$ ), while the annual grassland was a small source and essentially carbon neutral ( $15 \pm 117 \text{ gC m}^{-2} \text{ y}^{-1}$ ).

The investment of deep roots and the establishment of a sparse canopy enabled the savanna to endure dry years better than the grassland, yielding a smaller year to year variability in net carbon exchange. Yet this greater carbon sink for the savanna came at a cost. This darker and rougher oak savanna ecosystem system tended to evaporate nearly 100 mm more water per year and the air was about 0.5 C

warmer than that of the annual grassland. Consequently, this study enabled us to reflect on the cost and benefits of these comparable and neighboring ecosystems.

Table 1. Annual sums of gross and net carbon fluxes from the savanna and annual grassland sites

	NEE Tonzi (gC m <sup>-2</sup> yr <sup>-1</sup> )	NEE Vaira (gC m <sup>-2</sup> yr <sup>-1</sup> )	GPP tonzi Tonzi (gC m <sup>-2</sup> yr <sup>-1</sup> )	GPP Vaira (gC m <sup>-2</sup> yr <sup>-1</sup> )	Reco Tonzi (gC m <sup>-2</sup> yr <sup>-1</sup> )	Reco Vaira (gC m <sup>-2</sup> yr <sup>-1</sup> )
2000		-42.4967		546.4256		503.9289
2001	-162.346	-159.705	760.1924	720.8268	597.8462	561.1215
2002	-192.419	-15.26	1050.889	642.1212	858.4698	626.8612
2003	-175.297	-73.4651	1171.076	811.809	995.7785	738.3438
2004	-138.183	51.5528	914.9402	507.2285	776.7571	558.7813
2005	-186.816	-49.5657	1431.274	1020.215	1244.458	970.6488
2006	-109.046	148.7724	1098.484	617.3077	989.4371	766.0801
2007	-135.485	-36.1552	1048.353	689.6462	912.8682	653.4909
2008	-123.221	150.215	868.0589	351.8181	744.8378	502.0331
2009	-175.612	11.8071	1094.503	698.3787	918.8909	710.1858
2010	-312.679	-9.905	1182.411	815.7873	869.7325	805.8823
2011	-144.877	278.9525	1136.96	617.9994	992.0833	896.9519
2012	-157.261	0.5001	1030.546	704.373	873.285	704.8731
2013	-27.7404	121.3027	992.313	572.7559	964.5726	694.0586
2014	-159	-145	858	641	713	481
average	-157.142	15.43664	1045.571	663.8461	889.4298	678.2828
std dev	60.89433	117.8008	167.5815	153.0551	155.9871	145.0406

## Climate and Energy Balance

Long term energy flux measurements afforded us the opportunity to investigate the effect of land use on differences in air and surface temperature and interpret these differences through examination of the surface energy balance.. Using an extensive decade-long dataset of meteorological conditions, we show that changes in land cover have a marked impact on the air temperature of a landscape. Specifically, we observed that the potential air temperature over an oak savanna was 0.5 °C warmer than the air above an annual grassland, 2 km away.

Using a combination of energy flux measurements and model computations with a coupled energy balance/planetary boundary layer model, our data support the overarching hypothesis that the air above the oak woodland is warmer than that above the grassland in part because the oak woodland is darker, so it absorbs more radiation. Furthermore, the oak woodland is aerodynamically rougher.

Consequently, is able to inject more sensible heat into the atmosphere than the grassland. But, this extra sensible heat did not convert into warming in a linear fashion. The magnitude of the temperature differences above the savanna and grassland were conditional on time of year, phenology, biophysical conditions of the surface and the depth of the planetary boundary layer.

The greatest differences in potential air temperature occurred during the winter when net radiation fluxes overlapped one another, more sensible heat exchange was lost by the savanna, and more latent heat was lost by the grass. These differences in how energy was partitioned occurred because the grass maintained a lower surface resistance, while the woodland established a smaller aerodynamic resistance, thereby enabling the woodland to inject more sensible heat into the atmosphere and warm the air more. During the winter, the planetary boundary layer did not grow deep, so differences in sensible heat could translate into relatively large differences in air temperature.

We observed the smallest differences in potential air temperature during the spring/summer transition despite the fact that the savanna gained much more net radiation and lost much more sensible heat, and, despite the fact that the surface temperature of the grassland was warmer than that of the savanna. Greater latent heat exchange by the savanna and more long-wave energy lost by the grassland diminished the potential air temperature differences between the two sites. Yet, a complete explanation for these temperature differences depended upon computations of the growth of the planetary boundary layer. During the summer, the planetary boundary layer could grow up to 2500 m and buffer the daily range of air temperature.

In closing, land managers are faced with a number of interesting and conflicting ecological services regarding the presence or absence of forests, as a factor for mitigating climate change. These ecosystems are effective carbon sinks and provide a wide range of favorable ecosystem services outside climate regulation like habitat, soil preservation and water storage. But, forests are also darker, so they can absorb more energy. Plus, forests may transpire more than grass, causing their surface temperatures to be cooler through latent heat exchange. And forests are aerodynamically rougher than grasslands, so they are able to exchange sensible heat more effectively across a smaller temperature gradient, than grasslands. Consequently, forests may recharge less groundwater than other vegetation classes and to provide less run-off for stream flow compared to grasslands.

#### Site MetaData

The interpretation of the long term flux data depends upon site meta data information on structure and function. Much effort was made to study the canopy structure, its seasonal dynamics and the physiological potential of this vegetation. We conducted studies examining structure using terrestrial and airborne lidar, with upward and downward looking cameras, with hand held measurements of gap fraction and with a traversing tram that measures light transmission. We have high resolution data on where trees are, what is their height and crown size and estimates of the leaf area within those crowns and their clumping. These data have been pivotal for testing and applying 3 dimensional radiative transfer models, which then are used to compute the energy balance of the surface and canopy photosynthesis.

With regards to below ground resources, we conducted exhaustive surveys of roots, root distribution and soil carbon. We also monitor dynamics in soil moisture and assess soil evaporation and soil respiration with the aid of an understory eddy covariance flux system and with a network of soil CO<sub>2</sub> probes that interpret soil respiration with Fick's Law of Diffusion.

### Soil Carbon and Roots

We continued expanded the scope of our efforts below ground too. We tested the ability of ground penetrating radar to sample the vertical and horizontal distribution of coarse roots and conducted exhaustive sampling surveys to sample the fine root and soil carbon distribution of the savanna and its surrounding grassland.

We sampled five trees and two tree clusters from an oak/grass savanna to determine how fine root biomass and soil carbon vary across the landscape, and to understand how fine roots sustain ecosystem metabolism through a summer of limited moisture and high heat. To account for spatial heterogeneity, we sampled trees of different size/age class via a stratified sampling scheme that accounted for variance with lateral distance from the tree bole, or cluster center, and soil depth. We were able to infer total fine root biomass per tree by using patterns of soil carbon accumulation, and to upscale these estimates using site-specific information from a lidar survey.

We found that fine root biomass and soil carbon increased dramatically as trees age. Both fine root density and the soil volume occupied by roots increase over time. The pattern of soil carbon accumulation reflects both the gradient in root biomass and the duration of tree influence over soil properties.

*Q. douglasii* possesses a dimorphic fine root architecture to harvest all available water during the short window of spring growth. This tree also exhibits high plasticity among trees of different size/age and tree clusters, indicating the potential for adaptability to anticipated climatic change.

An outreach activity, associated with our Randomized Root sampling paper, published in Plant and Soil, was a video demonstrating the method. <http://www.youtube.com/watch?v=Xi1EW2LMkUM>

### Tree Physiology

We applied our skills as biometeorologists who are expert in data logging environmental variables and heat transfer in improving how sap flow transpiration of trees is measured. The heat pulse method is widely used to measure water flux through plants; it works by using the speed at which a heat pulse is propagated through the system to infer the velocity of water through a porous medium. No systematic, non-destructive calibration procedure exists to determine the site-specific parameters necessary for calculating sap velocity, e.g., wood thermal diffusivity and probe spacing. Such parameter calibration is

crucial to obtain the correct transpiration flux density from the sap flow measurements at the plant scale and subsequently to up-scale tree-level water fluxes to canopy and landscape scales.

The purpose of our study was to present a statistical framework for sampling and simultaneously estimating the tree's thermal diffusivity and probe spacing from in-situ heat response curves collected by the implanted probes of a heat ratio measurement device. Conditioned on the time traces of wood temperature following a heat pulse, the parameters are inferred using a Bayesian inversion technique, based on the Markov chain Monte Carlo sampling method. The primary advantage of the proposed methodology is that it does not require knowledge of probe spacing or any further intrusive sampling of sapwood. The Bayesian framework also enables direct quantification of uncertainty in estimated sap flow velocity.

Experiments using synthetic data show that repeated tests using the same apparatus are essential for obtaining reliable and accurate solutions. When applied to field conditions, these tests can be obtained in different seasons and can be automated using the existing data logging system. Empirical factors are introduced to account for the influence of non-ideal probe geometry on the estimation of heat-pulse velocity, and are estimated in this study as well. The proposed methodology may be tested for its applicability to realistic field conditions, with an ultimate goal of calibrating heat ratio sap flow systems in practical applications.

We also were able to report on the physiological conditions of the oak trees. The California Mediterranean savanna has harsh summer conditions with very low water availability, high temperature, high incoming solar radiation, and little or no precipitation. Despite these conditions, deciduous blue oaks only have foliation during the spring and summer. The objective of this work is to fully characterize the seasonal trends of photosynthesis in the blue oaks as well as the trend in the mechanistic relationships between leaf structure and function. We estimate radiative load of the leaves via the FLiES model and perform *in situ* measurements of leaf water potential, nitrogen and chlorophyll content, photosynthetic capacity, and electron transport, among other measurements. Our study included measurements from multiple trees and spanned 3 years providing data from a range of drought conditions. Our study included one individual that demonstrated strong drought stress as indicated by changes in chlorophyll content, leaf nitrogen, and all measures of leaf functioning. In the year following severe environmental stress, the individual altered foliation patterns on the crown but did not die. In all other individuals, we found that photosynthesis and  $V_{cmax}$  decreased during the summer drought. Chlorophyll content, electron transport rate, and quantum yield of photosystem II did not show the strong decrease during the summer, however. Aside from one individual, measurements of photosystem II and chlorophyll content did not indicate any leaf damage throughout the season in most individuals. Photosynthesis was very tightly coupled to stomatal conductance. Electron transport rate, however, was not tightly coupled to photosynthesis indicating the strong potential for the contribution of alternative electron sinks as a mechanism for surviving the summer drought. Our work demonstrates that the blue oaks avoid damage by maintaining the capacity to process light during the hot summer drought and are effective at fixing carbon by maximizing rates during the mild spring conditions

## Modeling

Water availability is the dominant control of global terrestrial primary productivity with concurrent effects on evapotranspiration and ecosystem respiration, especially in arid and semi-arid ecosystems. Process-oriented ecosystem models are critical tools for understanding land-atmosphere exchanges and for up-scaling this information to regional and global scales. Thus, it is important to understand how ecosystem models simulate ecosystem fluxes under changing weather conditions including drought. Here, we applied both time-series analysis and meta-analysis techniques to study how five ecosystem process-oriented models simulated gross primary production (GPP), ecosystem respiration (Reco), and evapotranspiration (ET). Ecosystem fluxes were simulated for three years at a daily time step from four evergreen and three deciduous Mediterranean oak woodlands (21 site-year measurements; 105 site-year-simulations), which are typically subject to drought conditions. There were data-model disagreements at multiple temporal scales for GPP, Reco, and ET at both plant functional types. Systematic underestimation of the temporal variation of Reco was found at both plant functional types at temporal scales between weeks and months, and an overestimation at the yearly scale. Modeled Reco was systematically overestimated during drought for all sites, but daily GPP was systematically underestimated only for deciduous sites during drought. In contrast, daily estimates of ET showed good data-model agreement even during drought conditions. Our results bring attention to the importance of drought conditions for modeling purposes in representing forest dynamics in water limited ecosystems.

## Data Contributions to other Projects and Peer-Reviewed Papers.

We participated in several multi-site synthesis projects and papers this past year. One by Peichl et al was published in *Ecological Letters* on the Convergence of potential net ecosystem production among contrasting C3 grasslands. Metabolic theory and body size constraints on biomass production and decomposition suggest that differences in the intrinsic potential net ecosystem production (NEPPOT) should be small among contrasting C3 grasslands and therefore unable to explain the wide range in the annual apparent net ecosystem production (NEPAPP) reported by previous studies. We estimated NEPPOT for nine C3 grasslands under contrasting climate and management regimes using multiyear eddy covariance data. NEPPOT converged within a narrow range, suggesting little difference in the net carbon dioxide uptake capacity among C3 grasslands. Our results indicate a unique feature of C3 grasslands compared with other terrestrial ecosystems and suggest a state of stability in NEPPOT due to tightly coupled production and respiration processes. Consequently, the annual NEPAPP of C3 grasslands is primarily a function of seasonal and short-term environmental and management constraints, and therefore especially susceptible to changes in future climate patterns and associated adaptation of management practices.

Another was a paper by Schwalm et al on Loss of carbon uptake during the turn of the century drought in western North America, published in *Nature Geoscience*. We estimated the carbon consequences of

the turn of the century drought in western North America through comparison to a non-drought baseline condition. Using data from reanalysis, remote sensing, and global monitoring networks we show that the 2000 to 2004 drought resulted in an anomalous carbon source, emitting 30 to 298 Tg C yr<sup>-1</sup>. We further document a pronounced drydown of the terrestrial biosphere, decreased river discharge, and a loss in cropland productivity. Reconstructions of drought severity confirm that the last drought event similar to the turn of the century drought occurred over 800 years ago. Based on forecasted changes in precipitation and drought severity the mid-latitude sink of 177 to 623 Tg C yr<sup>-1</sup> in western North America may be permanently disabled by 2100. Furthermore the dry conditions in 2000 to 2004 are expected to become the wet end of a new climatology consistent with the beginning of a modern mega-drought.

We continue to collaborate with James Shuttleworth's team at the University of Arizona and the COBRA project, including Trenton Franz. They have installed a cosmic ray sensor at the site to detect changes in areal averaged soil moisture.

Dr. Richard Cuenca is monitoring soil moisture fields at the Tonzi Ranch as part of his project NASA AirMOSS project. We are also collaborating with a team lead by Mahta Moghaddam at USC and Dara Entekhabi at MIT that was funded by NSPIRES. The project is called "Land information system for SMAP Tier-1 and AirMOSS EV-1 decadal survey missions...". This project will rely on soil moisture measurements taken at Tonzi and Vaira. This includes our own data and a network of sensors installed by the team.

The distinct attributes of our field sites, representing annual grasslands and savanna and growing in a Mediterranean climate with distinct wet and dry seasons has yielded much use by our colleagues. We performed a google scholar search for papers using data from the Tonzi Ranch and Vaira Ranch. We found over 140 citations to papers and reports that used data from the Tonzi Ranch and the Vaira Ranch.

### **Book Chapters and Refereed Papers,**

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