

Final Technical Report

Title: The Effects of Disturbance & Climate on Carbon Storage & the Exchanges of CO₂ Water Vapor & Energy Exchange of Evergreen Coniferous Forests in the Pacific Northwest: Integration of Eddy Flux, Plant and Soil Measurements at a Cluster of Supersites

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KEYWORDS: carbon dioxide exchange, NEE, water vapor exchange, terrestrial carbon processes, disturbance, climate, AmeriFlux

GOAL: Quantify and understand the influence of climate and disturbance on ecosystem processes and thus net carbon uptake by forests.

OBJECTIVE: (1) To quantify and understand the effects of wildfire on carbon storage and the exchanges of energy, CO₂, and water vapor in a chronosequence of ponderosa pine (disturbance gradient); (2) To investigate the effects of seasonal and interannual variation in climate on carbon storage and the exchanges of energy, CO₂, and water vapor in mature conifer forests in two climate zones: mesic 40-yr old Douglas-fir and semi-arid 60-yr old ponderosa pine (climate gradient); (3) to reduce uncertainty in estimates of CO₂ feedbacks to the atmosphere by providing an improved model formulation for existing biosphere-atmosphere models; and (4) To provide high quality data for AmeriFlux and the NACP on micrometeorology, meteorology, and biology of these systems.

APPROACH: (1) Produce micrometeorological estimates of the exchanges of CO₂, water and energy at three AmeriFlux sites – a young ponderosa pine forest (18 yrs), mature ponderosa pine forest (60 yrs), and mature Douglas-fir forest – to quantify seasonal and interannual variation in fluxes with major forest type, climate, and disturbance history; (2) Improve estimates of NEE through enhanced micrometeorological measurements with a roving network (two subcanopy flux systems) and spatially distributed profiles of temperature and wind measurements to explain variability in subcanopy fluxes; develop and evaluate a new formulation for subcanopy mixing that includes subcanopy stability; (3) Produce biological estimates of annual net ecosystem production (NEP) with emphasis on belowground processes (turnover rates, microbial and root responses) at the MP, YP and replicated burn plots that include the former BP site (disturbance chronosequence), and at the MF site and in several Douglas-fir stands at different developmental stages in the vicinity of the MF site to quantify landscape variability in NEP; (4) Conduct measurements of component fluxes (transpiration, respiration), carbon pools in soil and vegetation, and biological properties for model parameters (assimilation rates of Douglas-fir, changes in respiration rates with phenology), and turnover rates and sources of soil respired CO₂ at the two pine flux sites and the Douglas-fir site; (5) Combine data with the Biome-BGC process model to establish how the ecosystem carbon balance depends on climate, disturbance, vegetation type, and related changes in processes (phenology, physiology, soil processes); (6) Generalize the model to include the strong influence of diurnal variation of the within-canopy stability on exchange in sparse semi-arid canopies and assess its influence on NEE uncertainties.

RESULTS TO DATE:

Science objective (1): Quantify and understand the effects of wildfire on carbon storage and the exchanges of energy, CO₂, and water vapor in a chronosequence of ponderosa pine (disturbance gradient).

2011

Simulating fire effects on carbon dynamics across a heterogeneous forested landscape. Fire influences carbon dynamics from local to global scales, but fire effects are highly variable across space and time. This study integrated satellite remote sensing, AmeriFlux data, and field surveys in a simulation modeling framework to estimate the effects of high-, moderate-, and low-severity fire on carbon pools and fluxes. The simulation area was a 244,600 hectare landscape encompassing the Metolius Watershed in central Oregon, USA. Landsat-based fire maps and the Biome-BGC process model were used to quantify pyrogenic carbon emissions, tree mortality, and net carbon exchange associated with four large wildfires that burned ~50,000 hectares in 2002-2003. Simulated total pyrogenic emissions were 0.732 Tg C, which is equivalent to 2.4% of Oregon statewide anthropogenic carbon emissions over the same two-year period. Although the simulated total carbon transfer due to tree mortality was four times higher than pyrogenic carbon emissions, dead trees will take decades to release their carbon to the atmosphere. Immediately post-fire, the model indicated that burned areas were a carbon source (net C exchange: $-0.076 \text{ Tg C y}^{-1}$; mean \pm SD: $-142 \pm 121 \text{ g C m}^{-2} \text{ y}^{-1}$). As expected, high-severity, stand-replacement fire had disproportionate carbon impacts. The per-unit area effects of moderate-severity fire were substantial, however, and the extent of low-severity fire merits its inclusion in landscape-scale analyses. These results demonstrate the potential to reduce uncertainties in landscape to regional carbon budgets by accounting for both stand-replacement and partial disturbance effects on carbon pools and fluxes. This study was conducted by a MS student as part of the Metolius AmeriFlux research project (Meigs et al. 2011).

2009

Moderate in addition to high severity fire emissions and NEP are important for estimates of changes in carbon stocks and fluxes. The study focused on four large fires that collectively burned about 100,000 acres in 2002-2003 within the Metolius River Watershed. We used satellite imagery and plot measurements to sample the full gradient of fire severities 4-5 years after the fires in two forest types. We found that 1) In the four fires in the western United States, low- and moderate-severity fire released 58 and 82 percent as much carbon emissions, respectively, as high-severity fire; 2) Most emissions were from the combustion of the forest floor and understory vegetation, and only about 1% of live tree mass was combusted on average; 3) Total combustion was lower than previous estimates. Total pyrogenic emission from the 100,000 acre area over the two years was 0.76 Tg C, represent only about 2.5% of statewide anthropogenic emissions from fossil fuel combustion and industrial processes for the same period (Meigs et al., 2009).

Science objective (2): To investigate the effects of seasonal and interannual variation in climate on carbon storage and the exchanges of energy, CO₂, and water vapor in mature conifer forests

in two climate zones: mesic 40-yr old Douglas-fir and semi-arid 60-yr old ponderosa pine (climate gradient).

2011

Net carbon uptake is over three times greater at a mature pine forest compared with young pine. Five years of coincident eddy-covariance flux measurements were used to contrast estimates of the carbon fluxes for a mature (94-year-old) ponderosa pine forest and a nearby young (19-year-old) ponderosa pine plantation to study the dependence on successional stage or time since disturbance, and the responses of the ecosystems to water-stress (Vickers et al., 2011). The mature forest with larger leaf area and wetter and cooler soils has a net uptake of carbon 3.3 times that of the young plantation. In the spring, photosynthesis is larger at the mature site as expected based on the difference in leaf area, however, another important factor is the reduction in springtime respiration at the mature site due to lower soil temperatures associated more shade from the canopy. Patterns of photosynthesis, inherent water-use efficiency and tree transpiration indicate that the young plantation responds to the seasonal drought sooner and to a more severe degree. Lower sensitivity to seasonal drought at the mature site is likely due to higher soil moisture reserves year round and a deeper root system that can access more water. Outside the seasonal drought period, the inherent water-use efficiency is the same at both sites, suggesting a species-specific value. Larger relative interannual variability at the plantation is associated with water-year drought and aggrading (increasing productivity as the young forests grows towards maturity).

2009

The site hydrology is the main driver of seasonal and interannual variability in carbon and water exchange of a semi-arid forest with the atmosphere. Identifying drivers of observed variability in seasonally water-limited ecosystems may help predict future response of carbon and water dynamics to climate change in biomes likely to experience similar conditions. Seven years of data (2002-2008) at the semi-arid mature ponderosa pine site (MP) showed interannual and seasonal variability of net carbon exchange was primarily related to variability in growing season length, which was a linear function of plant-available soil moisture in spring and early summer (Thomas et al. 2009). Soil moisture was closely related to snow cover depth and duration, and spring precipitation. Seasonal variability was explained best by a novel concept that delineates functional seasons within a hydro-ecological year based on ecologically meaningful events in the site hydrology. A multi-year drought (2001-2003) led to a significant reduction of net ecosystem exchange (-44% compared to the 7-year average of $-465 \pm 116 \text{ gC m}^{-2} \text{ yr}^{-1}$) due to carry-over effects in soil moisture and carbohydrate reserves in plant-tissue. Reduction in carbon gain by photosynthesis balanced carbon loss by ecosystem respiration in a single year drought (2005) resulting in a nullified response in net ecosystem exchange. *Carry-over effects are not captured well in process models and they are driven with meteorology on a calendar year basis, and may miss ecosystem response to interannual variation in water availability.*

In a semi-arid ponderosa pine forest, the interannual variability in the rate carbon is lost from the soil and forest floor is considerable and related to the variability in tree growth as much as it is to variability in soil climatic conditions (Irvine et al. 2008). Over a six year period the interannual variability in soil respiration, a pathway which returns about 60% of photosynthetically fixed carbon back to the atmosphere, was considerable (range 6.1 to 10.4

Mg-C/ha) and strongly correlated with the rate the trees were growing ($r^2=0.7$). Moreover, the rate at which the trees were transpiring water and assimilating carbon were highly linearly correlated with the rate roots were respiring carbon ($r^2=0.90$ and $r^2=0.83$, respectively). Root respiration increased by $0.43\text{gC m}^{-2} \text{d}^{-1}$ for every $1\text{gC m}^{-2} \text{d}^{-1}$ increase in photosynthesis. Such information demonstrates that improvements in our efforts to model short term variability in soil respiration will require greater consideration of carbon recently fixed by the canopy than perhaps previously considered in the development of empirical models.

Science objective (3): Reduce uncertainty in estimates of CO_2 feedbacks to the atmosphere by providing an improved model formulation for existing biosphere-atmosphere models

2011

Flux data from a tall ponderosa pine site support a physical basis for filtering nighttime data with friction velocity above the canopy. Two distinct nocturnal subcanopy flow regimes are observed beneath the tall (16 m) mature ponderosa pine forest. The first was characterized by weaker mixing above the canopy, stronger stability, westerly downslope flow and much smaller than expected ecosystem respiration from the eddy flux plus storage measurements compared to chamber estimates. The second regime was characterized by stronger mixing above the canopy, weaker stability, southerly flow coupled to the flow above the canopy and good agreement between the eddy flux plus storage estimate and the chamber-based estimate of ecosystem respiration. The observations support the inference that in weak mixing conditions cold air drainage flow systematically advects air with lower carbon dioxide concentration to the site. The inferred advection is negligible for the second regime where stronger downward mixing of momentum eliminates the drainage flow. The friction velocity, standard deviation of vertical velocity, bulk Richardson number, Monin-Obukhov length scale and the subcanopy 3-m wind direction are all good indicators of subcanopy drainage flow and missing carbon dioxide at this site. Because the subcanopy flow regime is largely determined by the turbulence above the canopy, these data support a physical basis for the commonly used filtering approach for nighttime fluxes based on friction velocity above the canopy (Vickers et al. 2011).

The non-linear structure and behavior of spatial temperature gradients and the flow field require enhanced sensor networks to estimate advective fluxes in the subcanopy of forest to close the surface energy balance in forests. Fundamental differences were found for the space-time variability between the wind and temperature fields in the subcanopy at the mature Douglas-fir site (Thomas 2011). Motions dominating the flow and the transport of sensible heat occupy similar spatial, but different temporal scales. This mismatch aggravates the computation of meaningful estimates of horizontal advection and may explain the ambiguity and unresolved problems of the contribution of horizontal advective fluxes to the canopy energy and mass balances reported in the literature. Data were collected from a subcanopy sensor network of ten stations sampling horizontal wind speed and direction, and air temperature over several months. Furthermore, both spatial temperature gradients and advective fluxes were demonstrated to be sensitive to network geometry and method of analysis. The assumption of linear spatial gradients was found to be incorrect and leads to increased space-time variability in both variables, at least at the studied site. A novel method is suggested to estimate the size of the control volume most promising to yield more consistent estimates of horizontal advection

for studies focusing on the experimental evaluation of the concept of energy and mass conservation in tall forests.

We examined the relative magnitude and contribution of parameter and driver uncertainty to the confidence intervals on model estimates of net carbon fluxes. We used data from the young ponderosa pine flux site and a simple daily model of coupled carbon and water fluxes (DALEC). Geostatistical simulations generated an ensemble of meteorological driving variables for the site, consistent with the spatio-temporal autocorrelations inherent in the observational data from 13 local weather stations. Simulated meteorological data were propagated through the model to derive the uncertainty on the CO₂ flux resulting from driver uncertainty typical of spatially extensive modeling studies. With at least one meteorological station within 25 km of the study site, driver uncertainty was relatively small (~10% of the total net flux), while parameterization uncertainty was larger at 50 % of NEE. The largest source of driver uncertainty was due to temperature (8% of NEE). Precipitation was a larger source of bias in NEE estimates than temperature estimates, although the biases partly compensated for each other. The time-scales on which precipitation errors occurred in the simulations were shorter than the temporal scales over which drought developed in the model, so drought events were reasonably simulated. The approach provides a means to assess the uncertainty and bias introduced by meteorological drivers in regional-scale ecological forecasting (Spadavecchia et al. 2011).

2010

Lasslop et al. (2010) commented on our 2009 paper concerning self-correlation between assimilation and respiration resulting from flux partitioning of eddy-covariance CO₂ fluxes. In our reply (Vickers et al., 2010a), we ultimately reached the same conclusion we presented in the original 2009 paper: While we do not argue against a true strong correlation between GEP and ER based on eco-physiological considerations, we do argue that one cannot quantify the true correlation using eddy-covariance flux measurements and standard flux partitioning methods without accounting for the self-correlation that arises from the shared variable problem. At a forest site, we found that one-half of the observed variance of GEP explained by ER was due to the shared variable problem.

Reliable estimates for flux uncertainties are needed to improve model validation and data assimilation in process-based carbon models, inverse modeling studies and model-data synthesis, where the uncertainties may be as important as the fluxes themselves. A new observational approach was presented to approximate the uncertainty (scatter or error variance) in 1-hour averaged turbulence fluxes from eddy-covariance measurements (Vickers et al., 2010b). The daytime relative flux uncertainty was half as large (20%) at a simple maize site compared to two more complex forest sites (40%) for all scalars possibly due to the more homogeneous vegetation, flat terrain and especially the lower measurement height. A theoretical prediction for the pure random sampling error based on the flux integral timescale was smaller by a factor of two compared to the observed variability.

2009

The timescale dependence of the random and systematic flux sampling errors in the mid-day convective boundary layer at our three flux tower sites (mature pine, young pine and

mature fir) were examined using an orthogonal decomposition technique. Results show that the additional flux obtained by increasing the perturbation timescale beyond about 10 minutes is dominated by random sampling error, and therefore little confidence can be placed in its value. The standard practice at most sites is to use 30 minute perturbation and averaging time scale. Such random errors are important in canopy models and coupled climate-carbon models (e.g. SPA), where sub-daily temporal resolution flux estimates are required for model validation or data assimilation. The random errors are less important for biogeochemistry modeling that operates at monthly or longer timescales (e.g. Biome-BGC and 3PG) because the random errors tend to cancel due to the large number of samples. The systematic flux error (under-estimation of the flux) at our sites was found to be small compared to other sites where such errors have been reported. The standard practice of using 30 minutes for the perturbation timescale for long-term carbon exchange is justified at our three sites because increasing the timescale beyond 30 minutes to one, two or even four hours has only a negligible effect on the long-term average CO₂ flux (Vickers et al. 2009).

Spurious correlation between assimilation (GEP) and ecosystem respiration (Re) results from partitioning flux measurements. Artificial correlation between GEP and Re is a consequence of flux partitioning of eddy covariance flux data when GEP is computed as the difference between NEE and computed daytime Re (e.g. using nighttime Re extrapolated into daytime using soil or air temperatures). That is because both GEP and Re share a common variable, Re. At our MP site, the artificial correlation is found to be nearly as large as the observed correlation for the 6-year dataset for 2002-2007. Therefore, *no statistical significance can be attached to relationships between assimilation and respiration developed from eddy-covariance measurements, even though a causal relationship is expected based on tree physiology* (Vickers et al. 2009).

Tower-data must be adequately spatially averaged before comparison to gridded model output as the time variability of both is inherently different. Spatially distributed observations of the wind field in the subcanopy of our MF tower site were used to analyze the space-time structure of mesoscale motions in the stable boundary layer. The relevance of these motions to scalar exchange is that they enhance horizontal dispersion and vertical diffusion not currently captured in biosphere-atmosphere turbulence models. The time variability of the subcanopy flow decreased systematically with increasing spatial averaging which implies that a comparison to model winds (with implied spatial averaging over the grid cell) requires spatial averaging of the observations (Mahrt et al. 2009).

2008

Alternative approach to estimate daytime ecosystem respiration from atmospheric NEE measurements. The eddy-covariance data collected at the mature ponderosa pine site were used to develop and evaluate a new method to extract the signal of ecosystem respiration directly from daytime NEE. The method is based on the coherency of scalar exchange between CO₂ and water vapor and uses anomalies in their vertical exchange to sense respiration signals. Daytime subcanopy R_e estimates derived from the new method agreed with those derived from (i) the intercept of light-response curves, and (ii) soil CO₂ efflux chambers for three of the five sites. Limitations to the method were found at a dense, multi-layered deciduous canopy site, and intense vertical turbulent mixing at another coniferous site. In addition, refixation of respired CO₂ by the understory (CO₂ recycling) may cause an underestimation of daytime R_e . An

indicator relating the canopy shear length scale L_s to the adjustment length scale L_d was proposed to evaluate the skill of the new method, and found to be useful in four of the five sites. Analysis of vertical coupling in the plant canopy using exchange regimes could explain the failure of the new method for the remaining site (Thomas et al. 2008).

Science objective (4): To provide high quality data for AmeriFlux and the NACP on micrometeorology, meteorology, and biology of these systems.

2011

We submitted our flux and biological and ancillary data to the AmeriFlux web site and to Fluxnet, through the 2010 calendar year. This includes soil fluxes, NPP, carbon stocks, LAI, and disturbance history. Fluxnet is updating the original La Tuile files and will include the more recent years of data. They will be using a new approach to compute GPP, following discussions within the network about the need to improve GPP methodology.

2008

Flux and biological data from Metolius MP site were used in data assimilation in DALEC (spatial version of SPA model) reduced model uncertainty in NEP. An Ensemble Kalman Filter (EnKF) was used to assimilate canopy reflectance data into an ecosystem model. We demonstrate the use of an augmented state vector approach to enable a canopy reflectance model to be used as a non-linear observation operator. A key feature of data assimilation (DA) schemes, such as the EnKF, is that they incorporate information on uncertainty in both the model and the observations to provide a best estimate of the true state of a system. In addition, estimates of uncertainty in the model outputs (given the observed data) are calculated, which is crucial in assessing the utility of model predictions. Results were compared with eddy-covariance observations of CO₂ fluxes over three years at the young pine forest site. The assimilation of 500 m spatial resolution MODIS reflectance data significantly improved estimates of Gross Primary Production (GPP) and Net Ecosystem Production (NEP) from the model, with clear reduction in the resulting uncertainty of estimated fluxes (Quaife et al. 2008).

2007

Dr. Law developed the biological and ancillary data and meta data (BADM) template and data submission protocols for AmeriFlux. Her research team submitted 6 years of flux and met data to CDIAC for the MP site and one complete year of data for the MF site as of Dec 2008, as well as the BADM templates for these sites and the previous sites that are no longer operational. The data are being used in the NACP model-data site level interim synthesis, and appear in several synthesis papers, including two papers published in Nature (Luyssaert et al. 2008. Magnani et al. 2007).

AWARDS (Impact of Research)

Dan Donato – Ecological Society of America (2008) Outstanding Student Research in Ecology Award for Most Outstanding Graduate Student Research (2008); Oregon State University Mason Award at OSU for Integrity and Moral Courage (2008); FS Dept student of the year (2006); Best

Overall Presentation at the International Association of Wildland Fires.

Garrett Meigs: International Fire Conference (2008) Outstanding Graduate Student Presentation Award at the 'Yellowstone and Beyond' fire conference in Jackson, WY.

Beverly Law: Impact of research: Author/co-author of 150 refereed journal articles, 2 books and 4 book chapters, with Web of Science citations: 6,040 total, H index 41.

Lipi Gupta: (2008, 2009, 2010) Lipi is a high school student who worked on our project on growth of forests after wildfire in the landscape around the Metolius flux site. She presented her results at several state and national competitions and was offered a 4-year scholarship to Oregon State University. She is now attending Cornell University.

DELIVERABLES:

Publications (pdf files can be found on www.fsl.orst.edu/terra)

2011

Meigs, G.W., Turner, D.P., Ritts, W.D., Yang, Z., Law, B.E. 2011. Landscape-scale simulation of heterogeneous fire effects on pyrogenic carbon emissions, tree mortality, and net ecosystem production. *Ecosystems* 14: 758-775 DOI: 10.1007/s10021-011-9444-8.

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2010

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Vickers, D., C.H. Thomas, B.E. Law. 2009. Random and systematic CO₂ flux sampling errors for tower measurements over forests in the convective boundary layer. *Agric. For. Meteorol.* 149:73-83, doi:10.1016/j.agrformet.2008.07.005.

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2008:

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2007:

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Student Training

4 post-doc research associates (James Irvine, Christoph Thomas, Jonathan Martin, Cory Pettijohn)
1 PhD student (Dan Donato)
1 MS student (Garrett Meigs)

Presentations

Law, B.E. Integration of observations and modeling to quantify forest carbon stocks and fluxes. IPCC Expert Meeting on Uncertainty and Validation of Emission Inventories. March 23-25, 2010. Utrecht, The Netherlands.

Law, B.E. The Role of Forests and Forestry in the Terrestrial Carbon Cycle: Considerations for a Changing Climate. Forests and the Environment. Apr 18-20, 2011. Bologna, Italy.

Law, B.E. Carbon Consequences of Disturbance in the West Coast U.S. States. American Geophysical Union. Dec 14-18, 2009. San Francisco, CA.

Law, B.E. Drought effects on Forest Carbon Processes. Coordination Action Carbon Observation System workshop on parameters related to ecosystem condition. 7th Framework Programme on Climate Change. October 19-20, 2009. Amsterdam, The Netherlands.

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Cameron, D., M. van Ojen, M. Williams, B.E. Law. Calibration of ecosystem models: the problem of using datasets that are imbalanced and not at the believable scale of the model. Uncertainty in Computer Models (UCM) 2010 Conference. July 12-14. Sheffield, UK.

Meigs GW, Kennedy RE, Law BE. April 2010. Fire and insects on the Deschutes National Forest: Implications for carbon dynamics and multiple disturbance interactions. Central Oregon Fire Science Symposium, Bend, OR.

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Changes in Project Management

The Co-PI in atmospheric sciences, responsible for the atmospheric part of the proposed work was Larry Mahrt, who retired in 2008. He was replaced with Assistant Professor, Christoph Thomas in 2008 (College of Oceanic and Atmospheric Sciences at OSU).