Measuring the Effects of Disturbance & Climate on the CO_2 & Energy Exchange of Ponderosa Pine Forests in the Pacific Northwest: Integration of Eddy Flux, Plant and Soil Measurements

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

OBJECTIVE: Combine tower and ground-based observations to quantify the effects of disturbance on processes controlling carbon storage and CO_2 and energy exchange in varying climatic conditions. Specific objectives are:

1. Investigate the effects of logging and fire on carbon storage and carbon dioxide and energy exchange in chronosequences of ponderosa pine, using consistent methodology.
2. Determine key environmental factors controlling carbon storage and carbon dioxide and energy exchange in these forests through a combination of measurements and process modeling.
3. Assess spatial variation of the concentrations and transport in complex terrain.

APPROACH: The eddy covariance method is used for measurements of CO_2, water vapor, and energy exchanges in a chronosequence of ponderosa pine forests (burned in 2002 wildfire, 10 year-old stand, 90 year-old mature stand). The mature stand has been an AmeriFlux site since 2000 (following previous flux sites in young and old stands initiated in 1996). In addition to the eddy covariance measurements, a large suite of biological processes and ecosystem properties are determined for the purpose of developing independent forest carbon budgets and NEP estimates; these include photosynthesis, stand respiration, soil CO_2 fluxes, annual litterfall, foliar chemistry, and bole increment, and soil organic matter among other parameters. The measurements are being integrated and evaluated with two ecosystem models (BIOME-BGC and SPA). Such analyses are needed to assess regional terrestrial ecosystem carbon budgets. The results will contribute scientific understanding of carbon processes, and will provide comprehensive data sets for forest managers and those preparing national carbon inventories to use in assessments of carbon sequestration in relation to interannual climate variation and disturbance. Frameworks and methodologies developed by the PI will contribute to AmeriFlux Network facility functions for data acquisition, exchange and modeling of results in a broad spectrum of carbon cycle research.

RESULTS TO DATE:

Objective 1: Investigate the effects of logging and fire on carbon storage and carbon dioxide and energy exchange in chronosequences of ponderosa pine, using consistent methodology.

Heterotrophic respiration two years after wildfire was not significantly different from that of unburned forests, and there was a consistent relationship between annual soil respiration and aboveground NPP across burned and unburned forests. Based on continuous seasonal measurements of soil respiration in a severely burnt plot, in areas kept free of ground vegetation, soil heterotrophic respiration accounted for 56% of total soil CO_2 efflux, comparable to the values previously reported for two of the unburnt forest plots. Estimates of total ecosystem heterotrophic respiration (R_h) were not significantly different between plot types two years after fire. The ratio R_h/NPP averaged 1.85, 1.16 and 0.85 in the severely burnt, moderately burnt and unburnt plots respectively. Annual soil CO_2 efflux was linearly related to above ground net primary productivity (ANPP) with an increase in soil CO_2 efflux of 1.48gC y^{-1} for every 1g increase in ANPP (p<0.01, r^2=0.76). There was no significant difference in this relationship between the recently burnt and unburnt plots.

Severely burnt forests were a significant source of CO_2 to the atmosphere two years after wildfire, and carbon pools were significantly lower than unburned plots (Irvine et al. in review): We measured carbon pools and fluxes in moderate and severely burnt forest stands two years after a fire in semi-arid ponderosa pine forests near the burnt flux site to determine the controls on net ecosystem productivity (NEP) and make comparisons with unburned stands in the same region. Soil carbon to 1 m depth was the largest, most stable pool, with no significant differences between plot categories. Carbon stored in the bole of living trees accounted for 37%, 31% and 2% of total ecosystem carbon in the unburned, moderately burnt and severely burnt plots respectively. Total ecosystem carbon in soil and live and dead pools in the burnt stands was on average 63% that of unburned stands (9.3 and 14.7 kgC m^{-2} respectively, p<0.01). NEP was significantly lower in burnt compared to unburned stands (p<0.01) with an increasing trend from -143 ±44 gC m^{-2} y^{-1} (±1 SD) in severely burnt plots (stand replacing fire), to -44 ±96 and +141±111 gC m^{-2} y^{-1}in moderately burnt and unburned plots respectively. Net primary production NPP (gC m^{-2} y^{-1}, ±1 SD) of severely burnt plots was 47% of unburned plots (167 ± 76, 346± 148, respectively p<0.05), with forb and grass above ground NPP accounting for 74% and 4% of total above ground NPP respectively. Contrary to expectations that the magnitude of NEP two years post fire would be principally driven by the sudden increase in detrital pools and increased rates of R_h, the data suggests NPP was more important in determining post-fire NEP (Irvine et al. in review). Based on biometry data, the burnt flux site was a net carbon loss of 136gC y^{-1} two years after the fire (Irvine et al. in review, plot 601). The rates of decomposition of below-ground detritus and standing charred trees, in conjunction with the time-course of vegetation succession, will play a vital role in the timing of transition of the burnt flux site from carbon source to sink.

Objective 2: Determine key environmental factors controlling carbon storage and carbon dioxide and energy exchange in these forests through a combination of measurements and process modeling.

Inter-annual variability in NEP and GPP with climate (Schwarz et al. 2004): Improving our understanding of the mechanisms underlying inter-annual variability in carbon exchange is vital to carbon cycle modeling. We investigated the relative importance of climatic versus biotic controls on gross primary production (GPP) and water vapor fluxes in seasonally drought-affected ponderosa pine forests using flux and sapflow measurements, and a process model, SPA. The study was conducted in young (YS), mature (MS) and old stands (OS) over four years at the AmeriFlux Metolius sites. Model simulations showed that interannual variation of GPP did not follow the same trends as precipitation, and effects of climatic variation were smallest at the OS (< 10%), largest at the MS (> 50%), and intermediate at the YS (< 20%). In the young, developing stand, interannual variation in leaf area has larger effects on fluxes than climate, although leaf area is a function of climate in that climate can interact with age-related shifts in carbon allocation and affect whole-tree hydraulic conductance. Older forests, with well-established root systems, appear to be better buffered from effects of seasonal drought and interannual climatic variation. Interannual variation of net ecosystem exchange (NEE) was also lowest at the OS, where NEE is controlled more by interannual variation of ecosystem respiration, 70% of which is from soil, than by the variation of GPP, whereas variation in GPP is the primary reason for inter-annual changes in NEE at the YS and MS. Across spatially heterogeneous landscapes with high frequency of younger stands resulting from natural and anthropogenic disturbances, interannual climatic variation and change in leaf area are likely to result in large interannual variation in GPP and NEE.

Inter-annual variation in soil CO_2 efflux and thus ecosystem respiration can be large and play a critical role in interannual variation in NEP (Irvine et al. 2004). Based on automated soil chamber data, we found that over four years, soil CO_2 efflux varied by 217 g C m^{-2} y^{-1} at the mature pine site, which amounts to 40 % of the mean annual soil efflux (CV=18 %). Much of this inter-annual variability appears driven by climate, in particular the timing and intensity of rain events. It is important to stress the value of long-term automated soil efflux measurements as periodic manual measurements haven't shown clear patterns.

Trends in NEP following disturbance from harvest (Law et al. 2003): Earlier simulations of NEP using the process model Biome-BGC showed a shift from net carbon source to net sink (on an annual basis) 10 to 20 years after stand replacing disturbance from logging or wildfire. Our biometric estimates of NEP at 12 plots along a harvest chronosequence that includes the three aged flux sites showed that the ponderosa pine forests growing in the East Cascades first attain positive NEP about 30 years following disturbance (Campbell et al. 2004, Law et al. 2003). Comparing successional trends after logging along a precipitation gradient from the coast to the East Cascades, we found that the most pronounced successional trends in NPP occur at the East Cascade site where

wood, coarse root, and foliage all contribute to a doubling of NPP between the initiation and mature age classes. At this site, a decline in woody debris respiration over time is somewhat compensated by an increase in soil and forest floor respiration leaving total heterotrophic respiration remarkably consistent across the entire chronosequence such that the trend in NPP is the primary driver of the trend in NEP. (subsequent research showed that interannual variation in NEP in older forests, however, is controlled by soil respiration; see Schwarz et al. above).

Objective 3. Assess spatial variation of the concentrations and transport in complex terrain.

Standard methods for calculating nocturnal CO2 fluxes with moderate and strong stability are inadequate and lead to large random flux errors for individual records, due partly to inadvertent inclusion of mesoscale motions that strongly contaminant the estimation of fluxes by weak turbulence (Vickers and Mahrt, 2006a). Such large errors are serious for process studies requiring CO2 fluxes for individual records, but are substantially reduced when averaging fluxes over longer periods as in calculation of annual NEE budgets. We have employed a superior method for estimating fluxes in stable conditions with a variable averaging width.

Existing techniques for estimating advection of CO2 are unreliable, partly due to the inability to estimate the mean vertical velocity with 3-d sonic anemometers and tilt correction methods. The eddy flux, storage and vertical advection terms in the budget equation for net ecosystem exchange (NEE) of carbon were evaluated at the young pine site (Vickers and Mahrt, 2006b). Mean vertical motion was computed from 3-d sonic anemometer measurements using three different tilt correction methods. The mean vertical motion was sensitive to the choice of tilt correction method, and for a given tilt correction approach, the mean vertical motion was sensitive to the time-scale chosen for averaging the wind components.

The mean vertical motion was also computed from mass continuity using the horizontal divergence estimated from a nine-tower network of 2-d sonic anemometers. The estimates based on mass continuity were in agreement with the subsidence expected from the decrease of roughness in the downwind direction at the site. Because all of the tilt correction methods assume that the long-term mean vertical motion is zero, albeit in different forms, they fail to reproduce the vertical motion based on the persistent horizontal divergence. The mean vertical motion from the mass continuity equation had much less scatter compared to that based on the 3-d sonic anemometer, however, the magnitude of the divergence can be dependent on the spatial scale over which the horizontal gradients are calculated.

Estimates of vertical advection of CO2 based on mass continuity and the vertical CO2 gradient indicate that it is the largest term in the NEE equation on weak mixing nights where strong vertical gradients of CO2 coupled with weak systematic sinking motion transport lower CO2 into the control volume. On strong mixing nights, the vertical advection is negligible due to weak vertical gradients despite stronger systematic sinking

motion. We estimate that at the young pine site, the nocturnal vertical (measured) and horizontal (inferred) advection terms are of opposite sign and that they tend to cancel each other. In contrast to the mass continuity method, use of a tilt correction method to obtain mean vertical motion yields estimates of advection that are not plausible.

At the writing of this report, we are finishing up a manuscript that re-examines the utility of the commonly used u* filter for eliminating records where the NEE is thought to be inadequately estimated due to incomplete mixing (Vickers and Mahrt, 2006c). At the tall mature pine site (LAI = 3), the u*-filter approach fails because the turbulence is apparently never strong enough to fully couple the CO2 flux measurements made above the canopy with the respiration at night. The flux measurements are decoupled from the surface in part due to strong temperature inversions associated with the sparse canopy and radiational cooling of the surface (Lee and Mahrt, 2005). Measurements of the flux and storage imply that advection of lower CO2 is significant even when u* above the canopy is substantial.

We examined a variety of potential filter variables: u* above the canopy, heat flux above the canopy, Richardson number and a subcanopy Richardson number. u* above the canopy was found to be slightly preferable to the heat flux and the Richardson numbers based on objective critera, although theoretically, u* is an incomplete indicator of the degree of mixing since it is influenced by pressure fluctuations that do not directly lead to mixing of scalars such as carbon dioxide. Use of the heat flux in concert with u* may provide a better filter.

At the young pine site which has a much shorter canopy and is in fairly flat terrain, the net influence of advection of CO2 appears to be small, however, application of the standard u*-filter approach is complicated due to an apparent u*-dependence of the flux footprint coupled with well-defined spatial variability of the vegetation and presumably the respiration rate. The flux footprint was estimated from a 3-d forward Lagrangian stochastic trajectory model, however, we note that the assumptions required by the footprint model are not always met in stable conditions, and the footprint results must be considered approximate. The complex terrain burned site displays the dual signatures of advection of lower CO2 in well organized nocturnal drainage flows and a u*-dependent flux footprint.

Most of the land surfaces in the world are heterogeneous, whether in flat or complex terrain. We conclude that application of the u*-filter approach to such situations is uncertain. Footprint analysis could potentially improve assessments of the carbon budget except for strongly stable conditions where the assumptions behind footprint theory are unlikely to be met. The young pine site does not imply substantial advection of lower CO2 at night. This type of site is under-represented by existing tower networks or else the method of inferring advection is incorrect.

AWARDS (Impact of Research)

Law et al. (2003) was one of the top three most cited articles in Global Change Biology (impact factor 4.333 in 2004, rated 1/134 in Environmental Sciences; http://www.blackwellpublishing.com/journal.asp?ref=1354-1013).

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

Five Most Important Publications

Irvine, J., B.E. Law, M. Kurpius, P.M. Anthoni, D. Moore, P. Schwarz. 2004. Age related changes in ecosystem structure and function and the effects on carbon and water exchange in ponderosa pine. Tree Physiology 24:753-763.

Law, B.E., D. Turner, J. Campbell, O.J. Sun, S. Van Tuyl, W.D. Ritts, W.B. Cohen. 2004. Disturbance and climate effects on carbon stocks and fluxes across western Oregon USA. Global Change Biology 10:1429-1444.

Law, B.E., O. Sun, J. Campbell, S. Van Tuyl, P. Thornton. 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. Global Change Biology 9:510-524.

Campbell, J.L., O. Sun, B.E. Law. 2004. Disturbance and net ecosystem production across three climatically-distinct forest landscapes. Global Biogeochemical Cycles 18:GB4017, doi:10.1029/2004GB002236, 11pp.

Schwarz, P.A., B. E. Law, M. Williams, J. Irvine, M. Kurpius, D. Moore. 2004. Climatic versus biotic constraints on carbon and water fluxes in seasonally drought-affected ponderosa pine ecosystems. Global Biogeochemical Cycles 18:GB4007, doi:10.1029/2004GB002234.

Other Refereed Publications

Lee, Y.-H, and L. Mahrt, 2005: Effect of stability on mixing in open canopies. Agric. Forest Meteorol., 135, 169-179.

Williams, M., P. Schwarz, B.E. Law, J. Irvine, M. Kurpius. 2005. An improved analysis of forest carbon dynamics using data assimilation. Global Change Biology 11:89-105.

Coops, N.C., R.H. Waring, B.E. Law. 2005. Assessing the Past and Future Distribution and Productivity of Ponderosa Pine in the Pacific Northwest using a Process Model, 3-PG. Ecological Modelling 183:107-124.

Aranibar, J.N., J.A. Berry, W.J. Riley, D.E. Pataki, B.E. Law, J.R. Ehleringer. 2006. Combining meteorology, eddy fluxes, isotope measurements, and modeling to understand environmental controls of carbon isotope discrimination at the canopy scale. Global Change Biology 12:710-730.

Van Tuyl, S., B.E. Law, D. Turner, A. Gitelman. 2005. Variability in net primary production and carbon storage in biomass across Oregon forests – An assessment integrating data from forest inventories, intensive sites, and remote sensing. Forest Ecology and Management 209:273-291.

Campbell, J.L., and B.E. Law. 2005. Forest soil respiration across three climatically-distinct chronoseqeunces. Biogeochemistry 73:109-125.

Ryan, M.G., and B.E. Law. 2005. Interpreting, measuring and modeling soil respiration. Biogeochemistry 73:3-27.

Irvine, J., B.E. Law, M. Kurpius. 2005. Coupling of canopy gas exchange with root and rhizosphere respiration in ponderosa pine: correlations or controls? Biogeochemistry 73:271-282.

Hibbard, K.A., B.E. Law. M. Reichstien, J. Sulzman, et al. 2005. An analysis of soil respiration across northern hemisphere temperate ecosystems. Biogeochemistry 73:29-70.

Heinsch, F.A., M. Zhao, S.W. Running, J.S. Kimball, R.R. Nemani, K.J. Davis, P.V. Bolstad, B.D. Cook, A.R. Desai, D.M. Ricciuto, B.E. Law, W.C. Oechel, H. Kwon, H. Luo, S.C. Wofsy, A.L. Dunn, J.W. Munger, D.D. Baldocchi, L. Xu, D.Y. Hollinger, A.D. Richardson, P.S. Stoy, M.B.S. Siqueira, R.K. Monson, S.P. Burns, L.B. Flanagan. 2005. Evaluation of Remote Sensing Based Terrestrial Production from MODIS Using AmeriFlux Eddy Tower Flux Network Observations. IEEE Transactions on Geoscience and Remote Sensing. In press.

Turner, D.P., W.D. Ritts, W.B. Cohen, T.K. Maeirsperger, S.T. Gower, A.A. Kirschbaum, S.W. Running, M. Zhao, S.C. Wofsy, A. Dunn, B.E. Law, J.L. Campbell, W.C. Oechel, H.J. Kwon, T.P. Meyers, E.E. Small, S.P. Kurc, J.A. Gamon. 2005. Site-level evaluation of satellite-based global terrestrial gross primary production and net primary production monitoring. Global Change Biology 11:1-19.

Campbell, J.L., O. Sun, B.E. Law. 2004. Supply side controls on soil respiration among Oregon forests. Global Change Biology 10:1857-1869.

Sun, O.J., J. Campbell, B.E. Law, V. Wolf. 2004. Dynamics of carbon storage in soils and detritus across chronosequences of different forest types in the Pacific Northwest, USA. Global Change Biology 10:1470-1481.

Treuhaft, R.N., B.E. Law, G.P. Asner. 2004. Forest attributes from radar interferometric structure and its fusion with optical remote sensing. BioScience 54:561-572.

Treuhaft, R.N., B.E. Law, G.P. Asner. 2004. Forest attributes from radar interferometric structure and its fusion with optical remote sensing. BioScience 54:561-572.

Hibbard, K.A., B.E. Law, M.G. Ryan, E.S. Takle. 2004. Issues and recent advances in soil respiration. EOS Transactions 85:220.

Kelliher, F.M., Ross, D.J., Law, B.E., Baldocchi, D.D., N.J. Rodda. 2004. Carbon and nitrogen mineralization in litter and mineral soil of young and old ponderosa pine forests during summer drought and after wetting. Forest Ecology and Management 191:201-213.

McDowell, N.G., D.R. Bowling, A. Schauer, J. Irvine, B.J. Bond, B.E. Law, J.R. Ehleringer. 2004. Associations between carbon isotope ratios of ecosystem respiration, water availability and canopy conductance. Global Change Biology 10:1767-1784.

McDowell, N.G., D.R. Bowling, B.J. Bond, J. Irvine, B.E. Law, P. Anthoni, J.R. Ehleringer. 2004. Response of the carbon isotopic content of ecosystem, leaf, and soil respiration to meteorological and physiological driving factors in a Pinus ponderosa ecosystem. Global Biogeochemical Cycles 18, GB1013, doi:10.1029/2003GB002049.

Pendall, E., S. Bridgham, P.J. Hanson, B. Hungate, D.W. Kicklighter, D.W. Johnson, B.E. Law, Y. Luo, J.P. Megonigal, M. Olsrud, M.G. Ryan, P. Thornton, S. Wan. 2004. Belowground Process Responses to Elevated CO_2 and Temperature: A Discussion of Observations, Measurement Methods, and Models. New Phytologist 162:311-322.

Kelliher, F.M., Ross, D.J., Law, B.E., Baldocchi, D.D., N.J. Rodda. 2004. Carbon and nitrogen mineralization in litter and mineral soil of young and old ponderosa pine forests during summer drought and after wetting. Forest Ecology and Management 191:201-213.

Reichstein, M., A. Rey, A. Freibauer, J. Tenhunen, R. Valentini, J. Banza, P. Casals, Y. Cheng, J. Grunzweig, J. Irvine, R. Joffre, B.E. Law, D. Loustau, F. Miglietta, W. Oechel, J-M. Ourcival, J. Pereira, A. Peressotti, F. Ponti, Y. Qi, S. Rambal, M. Rayment, J. Romanya, F. Rossi, V. Tedeschi, G. Tirone, M. Xu, D. Yakir. 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature, and vegetation productivity indices. Global Biogeochemical Cycles 17(4):1104, doi:10.1029/2003GB002035, pp. 15-1 to 15-15.

Bowling, D.R., N.G. McDowell, J.M. Welker, B.J. Bond, B.E. Law, J.R. Ehleringer. 2003. Oxygen isotope content of CO_2 in nocturnal ecosystem respiration 1. Observations in forests along a precipitation transect in Oregon, USA. Global Biogeochemical Cycles 17(4), 1120, doi:10.1029/2003GB002081, pp. 31-1 to 31-14.

Bowling, D.R., N.G. McDowell, J.M. Welker, B.J. Bond, B.E. Law, J.R. Ehleringer. 2003. Oxygen isotope content of CO_2 in nocturnal ecosystem respiration 2. Short-term dynamics of foliar and soil component fluxes in an old-growth ponderosa pine forest. Global Biogeochemical Cycles 17(4), 1124, doi:10.1029/2003GB002082, pp. 34-1 to 34-12.

Treuhaft, R.N., G.P. Asner, B.E. Law. 2003. Structure-based biomass from fusion of radar and hyperspectral observations. Geophysical Research Letters 107(D21), 4568:1-13.

Publications in Press/Review

Irvine, J., B.E. Law, K.A. Hibbard. 2006. Post-fire carbon dynamics and recovery in a semi-arid ponderosa pine forest in central Oregon. Global Change Biology (in review).

Vickers, D., and L. Mahrt, 2006a: A solution for flux contamination by mesoscale motions with very weak turbulence. Boundary-Layer Meteor., DOI:10.1007/s10546-005-9003-y, in press.

Vickers, D., and L. Mahrt, 2006b: Contrasting mean vertical motion from tilt correction methods and mass continuity. Agric. Forest Meteorol., in press.

Vickers, D., and L. Mahrt, 2006c: Problems estimating nocturnal net ecosystem exchange of carbon. Manuscript in draft form, to be submitted.

Student Training

3 post-docs, 2 PhD students benefited from the project. 1 post-doc was funded by the project (Irvine), and two post-docs and 4 PhD students used our Metolius flux site data in their research:

James Irvine, post-doctoral research associate, conducted research on the coupling of carbon dioxide and water vapor exchange and how this varied with forest age.

Paul Schwarz, post-doctoral research associate, used eddy flux and meteorological data to parameterize and test a process model, SPA, which he used to test hypotheses about sensitivity of GPP and respiration to interannual variation in climatic variables.

John Campbell, PhD student, conducted research on variation in NEP with forest age using biometric and soil CO_2 flux data.

Nate McDowell, PhD student, used our flux site data in his PhD dissertation research.

Dave Bowling, post-doctoral research associate, used our flux data in his research on stable isotopes.

Gretchen Miller, PhD student, conducted an analysis of soil moisture dynamics using multi-year data from four AmeriFlux sites, including Metolius young and mature sites. It required soil moisture profiles, sapflow, and water vapor exchange data over several years to parmeterize and test a quasi-steady state soil moisture dynamics model.

Juliette Aranibar, PhD student, conducted a study using Metolius flux site data, where she combined meteorology, eddy fluxes, sapflow, and isotope measurements, and the ISOLSM model to understand environmental controls of carbon isotope discrimination at the canopy scale.