Project Title: Integrating Remote Sensing, Field Observations, and Models to Understand Disturbance and Climate Effects on the Carbon Balance of the West Coast U.S.
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GOAL: To develop and apply an approach to quantify and understand the regional carbon balance of the west coast states for the North American Carbon Program.

OBJECTIVE: As an element of NACP research, the proposed investigation is a two pronged approach that derives and evaluates a regional carbon (C) budget for Oregon, Washington, and California. Objectives are (1) Use multiple data sources, including AmeriFlux data, inventories, and multispectral remote sensing data to investigate trends in carbon storage and exchanges of CO_2 and water with variation in climate and disturbance history; (2) Develop and apply regional modeling that relies on these multiple data sources to reduce uncertainty in spatial estimates of carbon storage and NEP, and relative contributions of terrestrial ecosystems and anthropogenic emissions to atmospheric CO_2 in the region; (3) Model terrestrial carbon processes across the region, using the Biome-BGC terrestrial ecosystem model, and an atmospheric inverse modeling approach to estimate variation in rate and timing of terrestrial uptake and feedbacks to the atmosphere in response to climate and disturbance.

APPROACH: In performing the regional analysis, the research plan for the bottom-up approach uses a nested hierarchy of observations that include AmeriFlux data (i.e., net ecosystem exchange (NEE) from eddy covariance and associated biometric data), intermediate intensity inventories from an extended plot array partially developed from the PI's previous research, Forest Service FIA and CVS inventory data, time since disturbance, disturbance type, and cover type from Landsat developed in this study, and productivity estimates from MODIS algorithms. The BIOME-BGC model is used to integrate information from these sources and quantify C balance across the region. The inverse modeling approach assimilates flux data from AmeriFlux sites, high precision CO_2 concentration data from AmeriFlux towers and four new calibrated CO_2 sites, reanalysis meteorology and various remote sensing products to generate statewide estimates of biosphere carbon exchange from the atmospheric point of view.

RESULTS TO DATE:

2010

Forest thinning scenarios for fire hazard reduction and bioenergy (Inventory and remote sensing data analysis over OR, WA, and CA). The prospect of forest derived bio-energy has led to implementation of new forest management strategies with the expectation that this will reduce total CO_2 emissions to the atmosphere. We used a combination of Federal Inventory Analysis data (FIA) and supplementary plot data for the US west coast to quantify forest carbon stocks and fluxes for the period from 2010-2030. Varying biofuels thinning treatments designed to meet multiple objectives emphasizing carbon storage, economic gain, or energy production were applied to determine the net carbon balance and bio-energy potential. Contrary to the management objectives, we found that increased removals over the next 20 years results in substantial decreases in forest carbon stocks and increased emissions. Emissions are expected to increase because preventive thinning removals exceed the CO_2 that would have been emitted due to wildfires, fossil fuel substitution takes decades before it becomes carbon-neutral, and use of woody biomass in short-lived products emits large quantities of CO_2 to the atmosphere. Thinning forests for energy production has the net effect of releasing otherwise sequestered carbon to the atmosphere, which may effectively reduce ongoing carbon uptake by forests and as a result, increase net greenhouse gas emissions, undermining the objective of greenhouse gas reductions over the next several decades (Hudiburg et al. in review).

Atmospheric inverse modeling proof of concept (top-down modeling; Goeckede et al. 2010a). We developed an inverse modeling framework designed to constrain CO_2 budgets at regional scales. The approach captures atmospheric transport processes in high spatiotemporal resolution by coupling a mesoscale model with Lagrangian Stochastic backward trajectory simulations. It is essentially a data assimilation approach, designed to combine information from multiple data sources (see above) to reduce uncertainty in estimates of terrestrial biosphere fluxes. Terrestrial biosphere CO_2 emissions are generated through a simple diagnostic flux model that computes the major components of net carbon exchange (GPP, Ra, Rh). The modeling framework assimilates datasets for advected background CO_2 and anthropogenic fossil fuel emissions as well as highly resolved remote sensing products (MODIS fPAR, Landsat disturbance, age and land cover). We used a Bayesian inversion setup optimizing a posteriori flux base rates for surface types that are defined by the remote sensing products. This strategy significantly reduces the number of parameters to be optimized compared to solving fluxes for each individual grid cell, thus permitting description of the surface in very high resolution. The modeling framework was trained and tested using time series of our high precision CO_2 observations measured at two AmeriFlux tower sites in Oregon. We found the optimum timestep was 4 hours and spatial scale 6km or less. It was effective to classify biomes by ecoregion to characterize their different biogeochemical responses to environmental variables across climatic gradients. Stand age information also improved model performance.

Sensitivity of a Sub-Regional Scale Atmospheric Inverse CO2 Modeling Framework to Boundary Conditions (Goeckede 2010b). This study focuses on the impact of uncertainties in advected background CO2 (CarbonTracker, provided by NOAA CMDL) and fossil fuel emissions (VULCAN data, provided by K. Gurney, Purdue Univ.) on simulated regional scale carbon budgets. We also tested the impact of allowing optimized parameter sets to vary seasonally. We found the simulations to be highly sensitive to systematic changes in advected background CO2, while shifts in fossil fuel emissions played a minor role. Correcting for local-scale biases in the CarbonTracker background concentrations reduced the annual terrestrial CO_2 sink by about 25 percent, and improved the correspondence with the output produced by bottom-up modeling frameworks. Using an optimization strategy with seasonally varying parameters improved the model output, as compared to parameter sets that are constant throughout the year. Analysis of 2

full years of CO2 observations yielded significant interannual variability between 2007 and 2008, and resulted in an averaged statewide CO2 sink of about 45 Tg C per year. In our previous paper, the sink in 2003 and 2004 was 27 and 35 Tg C per year, indicating an almost two-fold range in NEP from year to year.

Integrated Analysis of Regional Land Surface Carbon Flux (Turner et al. In Preparation). (comparison of top-down and bottom-up scaling approaches). We applied and compared bottom-up and top-down scaling approaches to evaluate the spatial and temporal patterns of Net Ecosystem Production (NEP) over a $2.5 * 10^5$ km^2 area in the western United States. Both approaches indicated that the land base was a carbon sink over this heterogeneous region in 2003 and 2004, with carbon uptake primarily in forest areas managed for wood production and in agricultural areas. In 2004, the statewide NEP from the bottom-up approach was 22.9 TgC per year, and 35 TgC per year for the top-down approach. An independent estimate of NEP based on an inventory and remote sensing approach was 15.3 +/- 1.6 Tg C per year. NEP for the study region from the CarbonTracker inversion scheme was considerably lower than all estimates. The seasonality of daily NEP at the ecoregion scale showed similar patterns in the bottom-up and top-down approaches, but with less sensitivity to drought stress in the top-down modeling. In the relatively warm, dry conditions of 2003, the sign of the change in simulated annual NEP was the same (negative) for both scaling approaches but the reduction in NEP was stronger with the bottom-up approach. These results support the need for a multiple constraint approach to evaluation of regional trace gas budgets.

Disturbance mapping - Change Detection (Remote sensing results). The disturbance mapping of the whole study region has been completed in 2010 for all of OR, CA, and WA (western OR, western WA and N CA were completed in 2009). The new trajectory-based change detection maps (TBCD; Kennedy et al., in review; Kennedy et al. 2007) are an improvement over our first disturbance maps that were based on change detection in 5-10 year intervals (disturbance is more difficult to detect with longer periods between images). The Biome-BGC modeling for the whole study region will be completed in summer 2010 using this disturbance mapping as a model input.

Age Mapping. We revisited the use of FIA plot data to model stand age as a continuous variable by ecoregion in Oregon. Relationships were weak but models that capture the distribution of stand age on the landscape are being developed and analyzed. (Duane et al. 2010).

2009

Forest thinning effects on carbon fluxes (Intensive field plot results). The thinning of forests to reduce fire hazard is a wide spread type of forest disturbance not explicitly accounted for in our modeling, yet we recognize the need to do so. Aboveground Net Primary Production is reduced by thinning, as prescribed in the Forest Hill, CA study area of our intensive plots, and often returns to near pre-thinned levels by 16 years, more time than was previously assumed (5 yr). Thinning in this study appears to shift some production from above ground to belowground and from trees to understory. Thinning

reduced soil CO2 efflux only modestly and temporarily (Campbell et al. 2009), contrary to expectations due to reduced live fine root mass for autotrophic respiration.

Assessing FPAR source and parameter optimization scheme in application of a diagnostic carbon flux model (groundwork for the biosphere model used in our top-down scheme). The combination of satellite remote sensing and carbon cycle models provides an opportunity for regional to global scale monitoring of terrestrial gross primary production, ecosystem respiration, and net ecosystem production. FPAR (the fraction of photosynthetically active radiation absorbed by the plant canopy) is a critical input to diagnostic models, however little is known about the relative effectiveness of FPAR products from different satellite sensors nor about the sensitivity of flux estimates to different parameterization approaches. In this study, we used multiyear observations of carbon flux at four eddy covariance flux tower sites within the conifer biome to evaluate these factors. FPAR products from the MODIS and SeaWiFS sensors, and the effects of single site vs. cross-site parameter optimization were tested with the CFLUX model. The SeaWiFs FPAR product showed greater dynamic range across sites and resulted in slightly reduced flux estimation errors relative to the MODIS product when using cross-site optimization. With site-specific parameter optimization, the flux model was effective in capturing seasonal and interannual variation in the carbon fluxes at these sites. The cross-site prediction errors were lower when using parameters from a cross-site optimization compared to parameter sets from optimization at single sites. These results support the practice of multisite optimization within a biome or ecoregion for parameterization of diagnostic carbon flux models.

2008

Regional Carbon Stocks (Inventory data results). The potential to store additional carbon in west coast forests is among the highest in the world because much of the area has forests that are long-lived (e.g. Douglas-fir) and maintain relatively high productivity and biomass for decades to centuries. In Oregon and Northern California (4.4 x 107 ha), total live biomass of forests is estimated at 2.71 +/- 0.28 Pg C (mean of 12 kg C ha-1) in the period 1991-1999. Total dead biomass (does not include fine woody debris or litter stocks) of forests in the region was 0.51 +/- 0.19 Pg C, and total NPP was 0.109 +/- 0.001 Pg C y-1. The majority of live and dead biomass (about 65%) is on public lands (53% of forested land). If forests were managed for maximum carbon sequestration total carbon stocks could theoretically double in the Coast Range, West Cascades, Sierra Nevada, and East Cascades and triple in the Klamath Mountains. Our results indicate that Oregon and California forests are at 54% of theoretical maximum levels (3.2 +/- 0.34 Pg C versus 5.9 +/- 1.34 Pg C) given the absence of stand-replacing disturbance (i.e. catastrophic fire) (Hudiburg et al. 2008).

Age-related findings and modeling implications (Inventory data results). Trends in NPP with age vary among ecoregions, which suggests caution in generalizing that NPP declines in late succession. Contrary to commonly accepted patterns of biomass stabilization or decline, biomass was still increasing in stands over 300 years in the Coast

Range, the Sierra Nevada and the West Cascades, and in stands over 600 years in the Klamath Mountains (Hudiburg et al. 2008).

2007

Pyrogenic carbon emissions (Intensive field plot results). To properly model Net Biome Production across Oregon and Northern California it is necessary to quantify the pyrogenic carbon releases that result from wildfire. Biome-BGC requires prescription of emissions and carbon transformations into dead pools (e.g. litter, coarse woody debris), yet observations were not previously available for our region. Disturbance mapping can quantify area affected by wildfire, but combustion factors relating fire severity to the fraction of biomass combusted are also required. Quantification of combustion factors across many forest C pools showed that combustion factors were highest for litter, humus, and foliage, lowest for live woody pools (Campbell et al. 2007, Turner et al. 2007). Combustion factors increased with burn severity, but were not nearly as high for tree stemwood as previously assumed. We estimate the total pyrogenic carbon emissions from the Biscuit Fire to be between 3.0 and 3.9 Tg C (16 and 19 Mg C ha-1), close to our initial estimate of 3.0 Tg C (Law et al. 2004). We estimate that this flux is approximately 16 times the annual net ecosystem production of this landscape prior to the wildfire. We estimate that wildfires of 2002 may have reduced mean net biome production across the state of Oregon by nearly half (Campbell et al. 2007, Law et al. 2004).

Land Cover (Remote sensing results). We compiled a land cover map for the entire regional study area based primarily on NLCD2001 and amended with information from previous disturbance maps and Gap Analysis Project (GAP) vegetation maps.

Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States (bottom-up modeling results). Bottom-up scaling of net ecosystem production (NEP) and net biome production (NBP) was used to generate a carbon budget for a large heterogeneous region (the state of Oregon, 2.5 * 105 km2) in the western United States. Landsat resolution (30m) remote sensing provided the basis for mapping land cover and disturbance history, thus allowing us to account for all major fire and logging events over the last 30 years. For NEP, a 23-year record (1980-2002) of distributed meteorology (1 km resolution) at the daily time step was used to drive a process-based carbon cycle model (Biome-BGC). For NBP, fire emissions were computed from remote sensing based estimates of area burned and our mapped biomass estimates. Our estimates for logging and crop harvest removals were from the model simulations and were checked against public records of forest and crop harvesting. All of the predominately forested ecoregions within our study region were NEP sinks, with ecoregion averages up to 197 gC m-2 yr-1. Agricultural ecoregions were also NEP sinks, reflecting the imbalance of NPP and decomposition of crop residues. For the period 1996-2000, mean NEP for the study area was 17.1 TgC yr-1, with strong interannual variation (SD of 10.6). The sum of forest harvest removals, crop removals, and direct fire emissions amounted to 63% of NEP, leaving a mean NBP of 6.1 TgC yr-1. Carbon sequestration was predominantly on public forestland, where the harvest rate has fallen dramatically in the recent years. Comparison of simulation results with estimates of

carbon stocks, and changes in carbon stocks, based on forest inventory data showed generally good agreement. The carbon sequestered as NBP, plus accumulation of forest products in slow turnover pools, offset 51% of the annual emissions of fossil fuel CO2 for the state. State-level NBP dropped below zero in 2002 because of the combination of a dry climate year and a large (200,000 ha) fire. These results highlight the strong influence of land management and interannual variation in climate on the terrestrial carbon flux in the temperate zone.

DELIVERABLES:

PUBLICATIONS (pdf files on http://terraweb.forestry.oregonstate.edu)

2010

Cohen, W.B., Z. Yang, and R.E. Kennedy. Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync - Tools for calibration and validation, Remote Sensing of Environment (in review).

Duane, M.V., Cohen, W.B., Campbell, J.L., Hudiburg, T., Weyermann, D., Turner, D.P. Implications of alternative field-sampling designs on Landsat-based mapping of stand age and carbon stocks in Oregon forests. Forest Science (in press).

Goeckede, M., A.M. Michalak, D. Vickers, D.P. Turner, B.E. Law. 2010a. Atmospheric inverse modeling to constrain regional scale CO2 budgets at high spatial and temporal resolution. J. Geophys. Res.-Atmos. (in press).

Goeckede, M., Turner, D.P., Michalak, A.M., Vickers, D. and Law, B.E. 2010b. Sensitivity of a Sub-Regional Scale Atmospheric Inverse CO2 Modeling Framework to Boundary Conditions, JGR. Atmos. (in review).

Hudiburg, T., B.E. Law, C. Wirth, S. Luyssaert. 2010. Eroding forest carbon sinks following thinning for bio-energy production. PNAS (in review).

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Donato, D.C. 2008. Forest Vegetation and Fuel Dynamics Following Stand-Replacing Wildfire, Re-Burn, and Postfire Management in the Siskiyou Mountains, Oregon. Oergon State University PhD Dissertation.

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Campbell, J.C., D.C. Donato, D.A. Azuma, and B.E. Law. 2007. Pyrogenic carbon emission from a large wildfire in Oregon, USA. Journal of Geophysical Research-Atmospheres 112(G4), G04014, doi:10.1029/2007JG000451.

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2006

Turner, D.P., W.D. Ritts, J.M. Styles, Z. Yang, W.B. Cohen, B.E. Law, and P. Thornton. 2006. A diagnostic carbon flux model to monitor the effects of disturbance and interannual variation in climate on regional NEP. Tellus 58B:476-490.

PRESENTATIONS

2009

Baldocchi, D.D., and B.E. Law. Carbon Cycle at Global, Ecosystem and Regional Scales. Interagency Forestry Working Group, California Air Resources Board, Oct 19, 2009, Sacramento, California.

Goeckede, M., 2009. High Resolution Inverse Modeling to Constrain Regional CO2 Budgets. EGU general assembly, Vienna, Austria.

Goeckede, M., 2009. Towards a Fusion of Top-Down and Bottom-Up Modeling Techniques. AGU fall meeting, San Francisco. CA.

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. Progress and results from the West Coast regional project, ORCA. AmeriFlux annual investigators meeting. Sept 21-23, 2009.

Law, B.E., D. Turner, W. Cohen, M. Goeckede, T. Hudiburg, M. Duane, D. Ritts, Z. Yang. The ORCA west coast regional project – diagnosis and attribution. North American Carbon Program. February 16-20, 2009. San Diego, CA.

Turner, D.P., Ritts, W.D., Kennedy, R.E., Yang, Z., Law, B.E. 2009. Accounting for forest harvest and wildfire in a spatially-distributed carbon cycle process model. American Geophysical Union General Meeting. San Francisco, CA. December 14 - 18.
Turner, D.P., Goeckede, M., Law, B.E., Ritts, W.D., Cohen, W.B., Yang, Z., Hudiburg, T., Kennedy, R., Duane, M. 2009. Integrated analysis of land surface carbon flux in the western U.S. 8th International Carbon Dioxide Conference. Jena, Germany. September 13-19.

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Kennedy, R. 2008. A new approach for mapping subtle insect-related mortality and recovery dynamics in mesic and dry conifer forests. International Association of Landscape Ecology US Chapter's Annual Meeting, Madison, WI, April 6-10.

Kennedy, R. 2008 More than land cover maps: New approaches to characterize dynamic forested landscapes with remote sensing. Invited speaker, Dept. of Forest Science Spring Seminar Series, Oregon State Univ., Corvallis, OR, May 7.

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Duane, M., W. Cohen, T. Hudiburg, J. Campbell, D. Turner and B. Law. 2007. The utility of inventory plot data for mapping forest attributes with Landsat imagery. ForestSat2007. November 5-7, Montpellier, France.

Turner, D.P. 2007. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. “Ecology from Afar” Distinguished Lecturer Series. University of Idaho, Moscow ID. February 9.

Education Contribution:

2 post-docs for modeling (Mathias Goeckede, Zhiquan Yang)
1 PhD student for field data collection (Dan Donato)
1 MS student for inventory data analysis (Tara Hudiburg)