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Constraining regional CO_2 flux with multiple top-down and bottom-up approaches

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Introduction

- Quantifying and predicting regional (100s-100,000s km^2) CO_2 net ecosystem exchange (NEE) continues to post a major challenge for carbon cycle science
- Top-down atmospheric-based downscaling and bottom-up ecosystem-based upscaling approaches can be used
- Here we compare estimates of monthly and annual regional NEE in the upper Midwest from several approaches
- We take advantage of the plethora of ecological, eddy covariance and atmospheric tracer observations in this region taken by investigators in the Chequamegon Ecosystem-Atmosphere Study (ChEAS, *http://cheas.psu.edu*) cooperative network (Fig. 1)

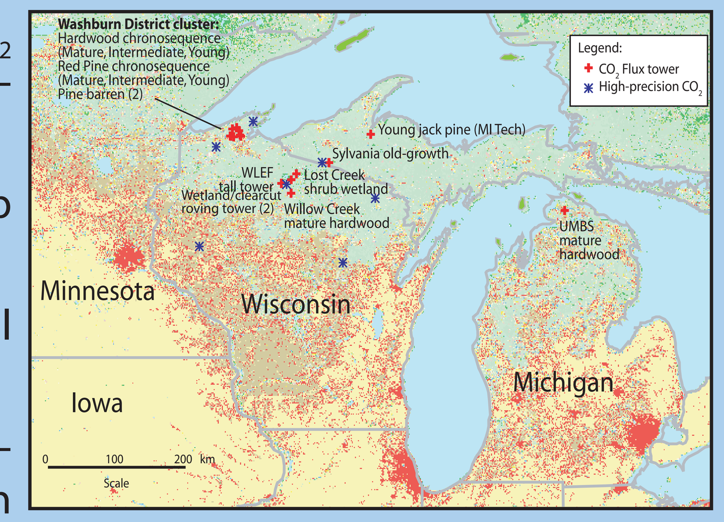

Fig 1. MODIS land cover map of region showing locations of eddy covariance towers (red cross) and summer 2004-2005 CO_2 tracer deployment (blue stars).

Top-Down: LEF Tall Tower

- The 447m tall WLEF tower has measured eddy covariance NEE from 3 levels (30m, 122m, and 396m) since mid 1996
- The observed NEE is an estimate of regional flux because of the relatively large fetch (~1-10 km), which samples a regionally representative mosaic of uplands and wetlands
- Annual NEE since 1997 has continually been a net source of CO_2 to the atm. (Fig 2.), with significant interannual variability

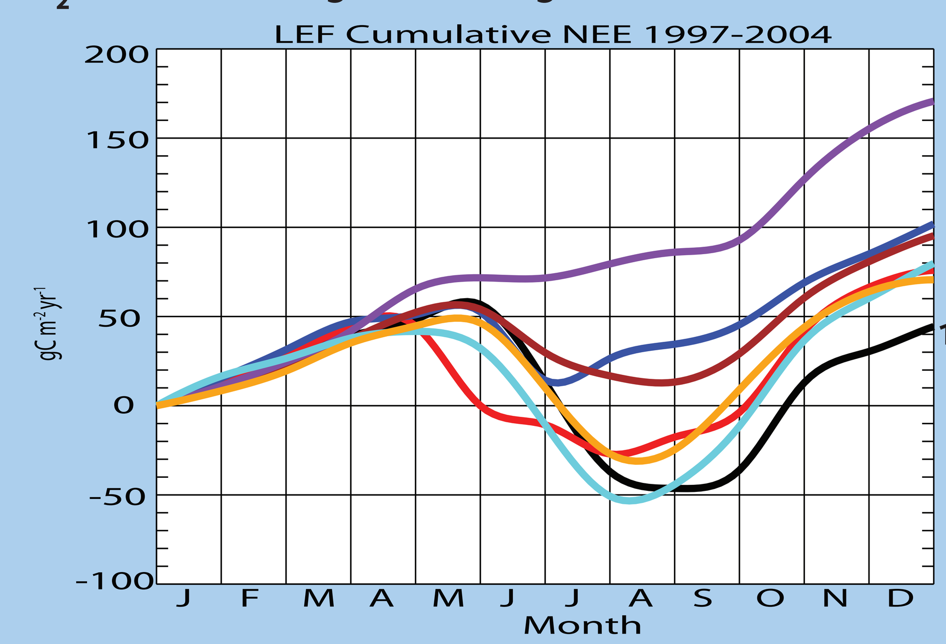

Fig 2. Cumulative NEE from the WLEF tall tower for 1997-2004. Data from 2002 is missing due to instrument failure. The 2001 NEE anomaly is due to a forest tent caterpillar defoliation episode in spring of that year

References:

Davis, K.J., P.S. Bakwin, C. Yi, B.W. Berger, C. Zhao, R.M. Teclaw, and J.G. Isebrands, 2003. The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower, *Global Change Biology*, 9 (9), 1278-1293.

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Bottom-up: Multisite Aggregation

- Fixed and roving stand-scale (10-40 m) eddy covariance flux towers observe NEE at a wide range of ecosystems in the region (Fig. 1)
- In summer 2002 and 2003, 13 towers were running and observed a wide variation in growing season NEE as a function of stand type and age (Fig. 3)
- Land cover data (Fig. 4) and simple aggregation and assimilation schema were used to upscale tower observations

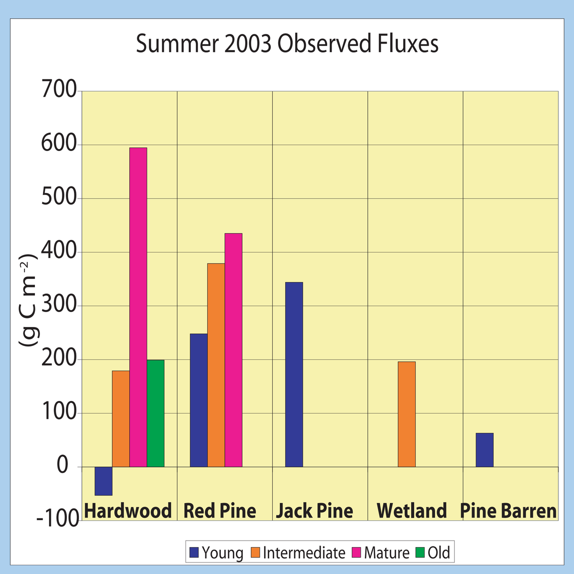


Fig 3. Growing season net ecosystem production (NEP = (-1) * NEE) for June-August 2003 for the set of eddy covariance flux towers in operation in the region and used in the upscaling

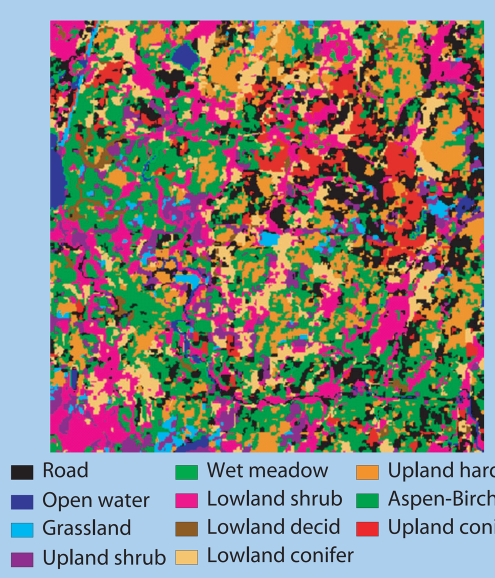


Fig 4. IKONOS 4m land cover in 10x10 km section around the LEF tall tower. For aggregation to a 40-km radius region, 30m LANDSAT and USFS Forest Inventory Analysis (FIA) data were used

References:

Desai, A.R., A.N. Noormets, P.V. Bolstad, J. Chen, B.D. Cook, K.J. Davis, E.S. Euskirchen, C.M. Gough, J.G. Martin, D.M. Ricciuto, H.P. Schmid, J.W. Tang, and W. Wang, in press. Influence of vegetation and surface forcing on carbon dioxide fluxes across the Upper Midwest, USA: Implications for regional scaling, *Agricultural and Forest Meteorology*.

Comparison of Regional NEE

- Top-down NEE from tall tower eddy covariance (**LEF**) and boundary layer budgets (**ABL-Helliker** and **ABL-Bakwin**) are compared to bottom-up NEE from the multi-tower aggregation (**Multisite**) and an ecosystem model (**ED Model**). Focus is on regional NEE centered around LEF tall tower in Park Falls, WI. Footprints may vary significantly by method
- All methods capture seasonal cycle well but have some differences in timing of spring onset, strength of spring respiration and summer peak NEE (Fig. 8)
- LEF and ABL-Bakwin are net annual sources of CO_2 to the atmosphere, while the other methods all show CO_2 sinks (Fig. 9a). The ED model and Multisite, both calibrated on stand or plot level data, have the largest sinks. Over the summer (Jun-Aug), all methods are usually CO_2 sinks, but the magnitude varies widely (Fig. 9b)
- Three methods have data for 1997-2001. To test if these methods have similar interannual variability (IAV), despite different source/sink strengths, mean NEE from 1997-2001 for each method was subtracted and annual deviation NEE found (Fig. 10a). The ED model generally tracks IAV of LEF, which is not the case for ABL-Helliker. The analysis is less clear when instead looking at interannual dNEE/dt (e.g., 1998 - 1997, 1999 - 1998, etc...) (Fig. 10b)

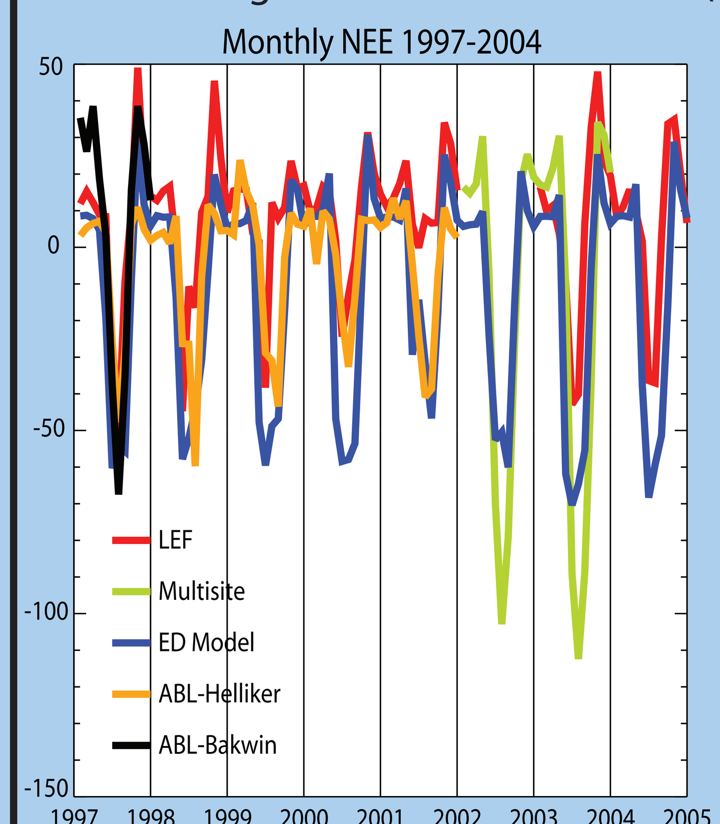
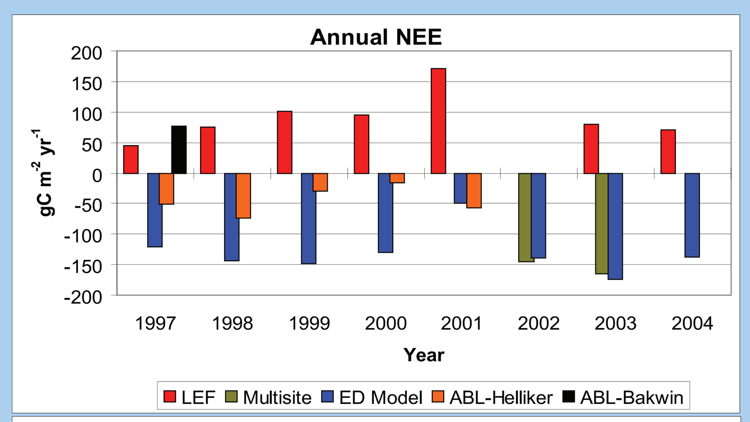


Fig 8. Monthly NEE from 1997-2004 for the top-down and bottom-up methods



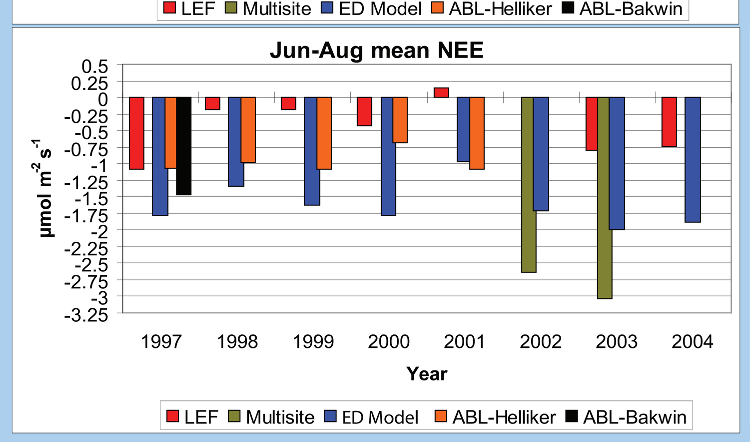
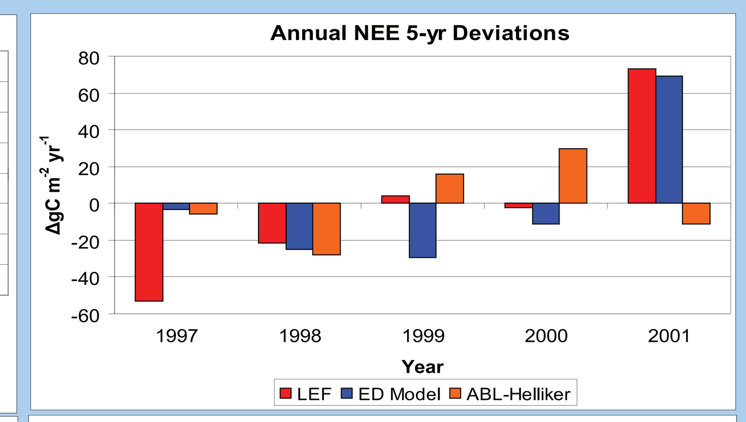


Fig 9. a) Annual NEE from 1997-2004 from the various top-down and bottom-up methods b) Same but for Jun-Aug



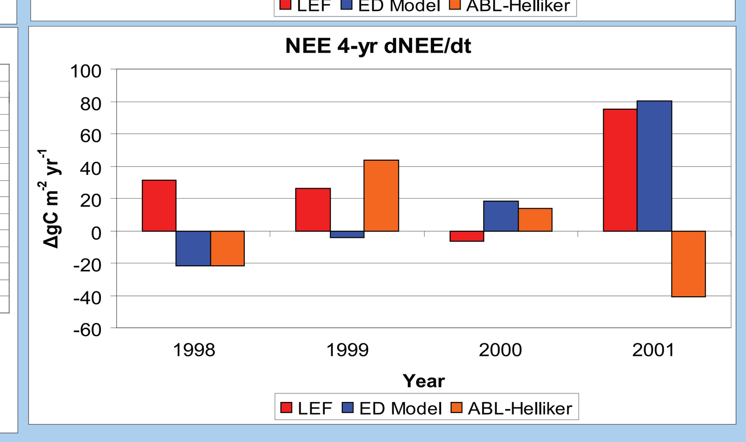


Fig 10. a) Deviations from mean 1997-2001 NEE for the three methods (LEF, ED Model, ABL-Helliker) with data over the entire time period. b) Annual dNEE/dt for 1998-2001

References:

Desai, A.R., B. Helliker, K.J. Davis, P.V. Bolstad, P.R. Moorcroft, in prep. Constraining regional CO_2 flux with combined top-down and bottom-up approaches, *Journal of Geophysical Research - Biogeosciences*.

Conclusions

- Results are promising but continue to show major differences, especially in summer peak NEE. Bottom-up methods are more consistent with LEF interannual variability than top-down, but top-down NEE magnitude is closer to LEF than bottom-up.
- This analysis is only one of a few top-down / bottom-up comparisons of regional NEE, yet such analyses are essential for advancing science in regional carbon programs such as NACP and for making predictions of the response of vegetation to climate change and CO_2 fertilization.
- Extension of ABL budget to a 3D regional inversion (Uliasz/Denning) with the network of CO_2 tracer data, enhancement of stand-scale tower scaling with the addition of roving eddy covariance towers in clearcuts and wetlands (see N. Saliendra poster), continued plot-level land cover characterization, and development of a model-data assimilation experiment will all refine quantifications of regional NEE and hopefully further mechanistic understanding of vegetation CO_2 exchange at regional scales.

Top-Down: ABL Budgets

- Atmospheric boundary layer (ABL) budgets infer regional NEE from profiles of CO_2 concentration in ABL and free troposphere (FT). ABL-Helliker method is described. ABL-Bakwin is similar but uses different methods to infer entrainment and storage
- A regional NEE equation is derived by assuming horizontal advection is negligible, ABL storage of CO_2 averages to 0 over long time scales (weeks) and rates of free air entrainment for water vapor and CO_2 are the same (Eq. 1). Results can be sensitive to choices for FT CO_2 and FT entrainment rate (Fig. 5)

$$\rho h \frac{\delta C_m}{\delta t} = F_{NEE} - \rho W (C_t - C_m)$$

$$F_{NEE} = \rho W (C_t - C_m) \quad F_q = \rho W (q_t - q_m) \quad \rho W_{FD} = F_q/(q_t - q_m) \qquad \text{Eq. (1)}$$

$$F_{NEE} = F_q (C_t - C_m)/(q_t - q_m)$$

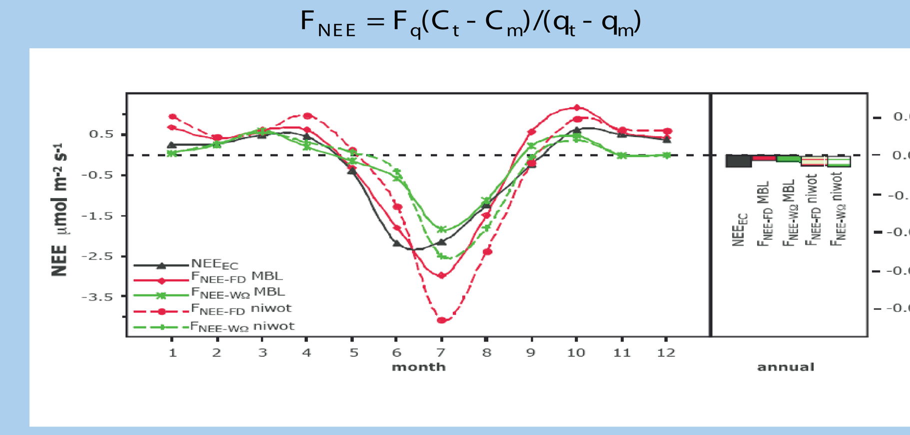


Fig 5. Comparison of regional ABL NEE as a function of choice of tropospheric CO_2 (MBL/Niwot) and use of water vapor similarity method (FD) or reanalysis vertical velocity (WΩ) Figure courtesy of B. Helliker

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Helliker, B.R., J.A. Berry, A.K. Betts, P.S. Bakwin, K.J. Davis, A.S. Denning, J.R. Ehleringer, J.B. Miller, M.P. Butler, and D.M. Ricciuto, 2004. Estimates of net CO_2 flux by application of equilibrium boundary layer concepts to CO_2 and water vapor meas. from a tall tower, *Journal of Geophysical Research-D*, 109(D20), 1-13.

Bakwin, P.S., K.J. Davis, C. Yi, S.C. Wofsy, J.W. Munger, L. Haszpra, and Z. Barcza, 2004. Regional carbon dioxide fluxes from mixing ratio data, *Tellus, Series B: Chemical and Physical Meteorology*, 56B, 301-311.

Bottom-up: ED Model

- The Ecosystem Demography (ED) model is a height-and-age structured statistical dynamic ecosystem gap model that simulates the ensemble-average influence of subgrid dynamics on forest structure and fluxes
- Plot-level ecological data, forest inventory analysis and historical climate forcing were used to run the model from 1800-2005 for upland, hardwood and conifer sub-regions
- Model NEE compared well to most stand-scale eddy covariance tower NEE (Fig. 6) and revealed the strong impact of stand age on regional NEE (Fig. 7)

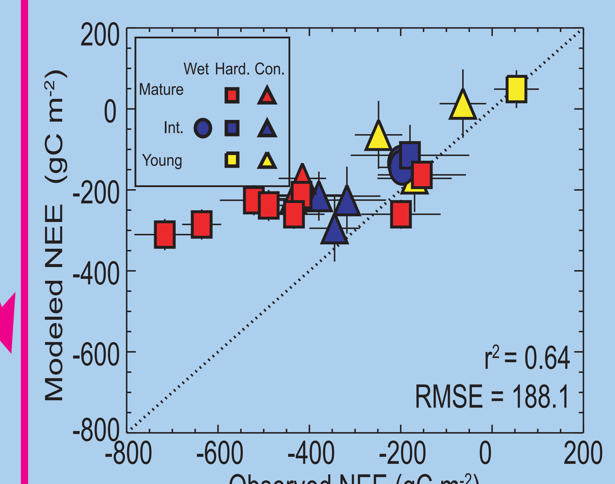

Fig 6. Comparison of model to observed growing season (Jun-Aug) NEE in 2002 and 2003 across the range of eddy covariance flux towers used in the multi-site aggregation. ED underpredicts flux observed at several mature hardwood sites

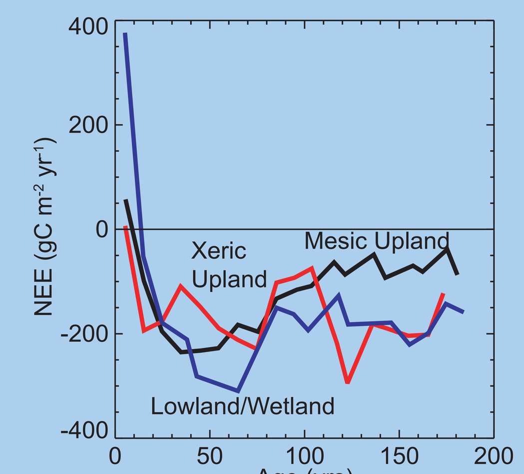

Fig 7. Annual NEE (averaged from 1995-2005) as a function of stand age for the three subregions run in ED. Young sites are net sources, mature sites large sinks and old sites near neutral

References:

Desai, A.R., P.R. Moorcroft, P.V. Bolstad, and K.J. Davis, accepted. Regional carbon fluxes from a biometrically-constrained dynamic ecosystem model: Impact of disturbance, CO_2 fertilization and heterogeneous land cover. *Journal of Geophysical Research - Biogeosciences*.

Acknowledgments

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