

## **Mid-Continent NACP Intensive Campaign in 2005**

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### ***A. Scientific goals.***

As scientists we are expected to provide answers to the three major questions (not repeated here) posed in the NACP plan (Wofsy and Harris, 2002, p. 2). The answers have to be robust enough to inform policy in the near future. Uncertainty estimates need to be well defined and scientifically defensible. This is a formidable task and we are not being given a whole lot of time in the President's Carbon Cycle Science Plan.

The primary issue of both the magnitude and the possible mechanisms of the northern hemisphere terrestrial carbon sink have remained unsettled for well over a decade. Typically, "bottom up" estimates based on ecosystem models and/or inventories have tended to come up with magnitudes for the sink substantially smaller than what we deduce from "top-down" inverse models used to interpret atmospheric concentration patterns, at least when the evidence is not mixed through the use of "prior estimates". As long as these different approaches independently produce quite divergent answers, we can have no real confidence in any of the estimates. Thus far, atmospheric data have always been too sparse to be conclusive on a regional or even continental scale, and they have additionally been hampered by atmospheric model shortcomings. From the other side, it has proven very hard to sufficiently verify the scaling up of local measurements using models, or to validate satellite-based estimates for large regions. To make progress the different approaches need to be confronted in a region and at a time where we can maximize the information content and credibility of each method, so that the independent approaches can be assessed. Multiple models will be applied to both the top-down and bottom-up data sets. Needed areas of improvement will then be apparent, and we will be in a much better position to see how the approaches can strengthen each other.

Goal 1. Develop optimized sampling schemes for field and atmospheric measurements to efficiently monitor regional carbon stocks and fluxes.

Goal 2. Use "top-down" approaches to provide a region-level estimate of net carbon fluxes during short periods (weeks) with an accuracy of 10% by increasing spatial and temporal coverage of atmospheric measurements and by enabling improvements in the parameterization of transport/mixing processes in the lower atmosphere.

Goal 3. Use a variety of "bottom up" techniques to provide daily to annual estimates of carbon stocks and fluxes over a region by improving process model structure and parameterization. A hierarchy of field and remote sensing observations should be used for model testing, development of data assimilation techniques, and model parameterization.

Goal 4. Compare the top-down and bottom-up approaches and iteratively improve the independent approaches on daily to annual time scales.

Goal 5. Produce “carbon stocks and flux maps” at various levels of spatial and temporal detail, and compare the results of the top-down and bottom-up approaches to diagnose methods.

### ***B. Place and time.***

The center of the North American continent, the Midwest agricultural belt in the northern U.S. and Canada, is a large region in which the daunting complexities and the small-scale variability of ecosystems, soils, microclimates, topography, land use and land use history, are perhaps a bit more manageable. The area of the campaign will be eastern South Dakota, eastern Nebraska, eastern Kansas, northern Missouri, Iowa, southern Minnesota, southern Wisconsin, and Illinois (Figure 1). The difficulties of interpreting atmospheric measurements with transport models are minimized over flat terrain. The area is covered by the NOAA wind profiler network ([www.profiler.noaa.gov/jsp/profiler.jsp](http://www.profiler.noaa.gov/jsp/profiler.jsp)), which provides hourly wind velocities from 500 m above the surface to 16 km altitude. The area is also a significant portion of the most intensively farmed region of the continent, with relatively low population density, but with several concentrated metropolitan centers. Crop growth models making use of satellite imagery have been applied to a part of Iowa, and have been compared to end-of-season yield statistics. Daily estimates of evapotranspiration are already routinely available for a large part of the area ([www.soils.wisc.edu/wimnext/water.html](http://www.soils.wisc.edu/wimnext/water.html)), although they need to be evaluated with flux measurements. In the Carbon Sequestration Rural Appraisal, carried out in Iowa, it was estimated that on cropland under no-till the net annual carbon uptake is about 0.6 ton C/ha/year, and on land in the Conservation Reserve Program about 1.3 ton C/ha/year. The highest participation in the CRP occurs in the area straddling the state border with Missouri.

There will be an intensive during the peak season of CO<sub>2</sub> uptake (July) and in the fall when CO<sub>2</sub> respiration continues but most plant photosynthesis has ceased (October–November). In July the leaf cover is fairly uniform between corn and soybeans, which avoids non-linearity effects in averaging over remote sensing pixels. The campaign will be embedded both in space and time within a long-term observing system that is being developed to detect net annual sources/sinks. For example, ecosystem process models will require at least a year of meteorological driver data for the full year of the intensive to “spin-up” the model to equilibrium and to calculate stocks. Other field data (e.g. inventories) for estimating stocks in bottom-up approaches are only available for 5–10 year means.

### ***C. Requirements***

*1. Long-term atmospheric monitoring.* Species concentrations in the atmospheric boundary layer tend to be offset from those in the free troposphere as they “integrate” the effect of sources/sinks over large regions to varying degrees. There is significantly more variance in boundary layer concentrations than in the free troposphere. For these reason boundary layer atmospheric sampling will be more intense than in the free troposphere.

During the growing season peak, daily average depletion of CO<sub>2</sub>, if confined to the lowest 1.5 km of the atmosphere, is about 6 ppm, which includes respiration at night.

In the area of the campaign NOAA/CMDL expects to instrument 6 tall towers starting in 2004 with high accuracy continuous CO<sub>2</sub> measurements, meteorological variables, and daily flask sampling (CO<sub>2</sub>, CH<sub>4</sub>, CO, H<sub>2</sub>, N<sub>2</sub>O, SF<sub>6</sub>, and isotopic ratios). Thus, estimates of N<sub>2</sub>O and CH<sub>4</sub> fluxes will also be produced from the monitoring system. CMDL expects to fly vertical profiles twice a week with flask samples and continuous CO<sub>2</sub>, water vapor, temperature and ozone. Vertical profile locations will be coordinated with tall tower and flux measurement sites (Figure 1). Additional measurements on the tall towers will be CO and Radon-222, but both are contingent on the availability of suitable robust instrumentation. Development work is ongoing for the analysis of a suite of volatile organic compounds in the flask samples in addition to the species already measured. Perhaps additional tall towers will be added as a test of possible long-term sampling strategies.

In order to better define the large scale atmospheric concentration fields used by atmospheric models, CMDL has started in late 2003 two regular vertical profiles sites on the west coast, one in Texas on the Gulf coast, two on the east coast, and expects to add profiles over the BERMS site in Saskatchewan. The ground-based measurements elsewhere in the world will continue, with the addition of several volunteer observing ships (commercial vessels on regular routes) and NOAA hopes to add continuous CO<sub>2</sub> and delta-pCO<sub>2</sub> measurements on buoys in the coastal waters of North America.

A subset of the eddy covariance flux sites in the region will start making high accuracy CO<sub>2</sub> mole fraction measurements by adopting careful calibration procedures. These measurements will be used to define mid-boundary layer concentrations under well-mixed conditions. The values will be compared to tall tower measurements and aircraft profiles in several cases.

*2. Dedicated scientific aircraft.* Two types of dedicated aircraft will play a role. A highly capable aircraft outfitted with a large suite of chemical measurements will probe the large-scale atmospheric variance of multiple species and their relationships. For example, CO and CH<sub>3</sub>CN are tracers for biomass burning, CO is in many cases also a good proxy for the recent addition of fossil fuel derived CO<sub>2</sub>, there is a whole series of anthropogenic tracers such as PCE, benzene, toluene, chlorinated compounds, certain ratios of hydrocarbons, and likewise plants and soils have their own characteristic emissions and deposition. In principle this allows for a considerable amount of air mass characterization, which will sharpen up the attribution for carbon sources/sinks (and will also have implications for air quality research). A second role for the “chemistry” aircraft is to fly patterns that will allow direct estimates of net CO<sub>2</sub> uptake. An aircraft such as the Lear Jet is rated to fly in all weather conditions, and may need to fill in some of the large scale patterns when the airplanes regularly rented by CMDL can not fly. A second type of aircraft, especially the low- and slow flying Ultra-lights such as Sky Arrow, Long-EZ, can measure fluxes of CO<sub>2</sub> and water vapor on relatively small scales. These results will be compared with flux measurement sites, crop model predictions and estimated patterns of evapotranspiration.

3. *Biological measurements at intensive sites.* Measurements at flux sites and other intensive sites should be made to develop biometric estimates of annual NEP, to estimate carbon stocks in soils to 1 m depth (labile and recalcitrant pools) and live and dead biomass, and to provide model parameters for the major biomes. Key variables for model parameters include leaf area index (summer maximum, timing of phenological changes), leaf and fine root C:N, litter quality, percent of leaf N in Rubisco, maximum stomatal conductance, leaf mass per unit leaf area (LMA), and others yet to be defined by the modeling community.

4. *Long-term biological measurements at sites intermediate to inventories and intensive sites.* The purpose of this level of intensity is to improve spatial representativeness of a limited set of more easily measured variables, such as aboveground biomass, tree height, leaf area index, and cover type. It will be coupled with remote sensing and modeling to reduce uncertainty in annual estimates of net carbon flux for geographic regions and land classes. Bottom-up models have difficulties incorporating site history effects on the spin-up to current carbon pools, thus carbon stocks in major components are needed for model improvement and data assimilation. Soil respiration is a vital component of carbon fluxes, and is not easily accessible to observation from space. It is being measured at eddy covariance sites and with closed and open chamber methods. A possible strategy would be to measure CO<sub>2</sub> at three depths within the soil, at ground level, just above the canopy, and at three heights up to 20 m. This could provide the capacity for continuous, robust measurements at a larger number of sites. It should be tested at an Ameriflux site and an automated soil chamber site. If satisfactory, such systems could be placed at existing sites of the USDA Soil Climate Analysis Network and a subset of the benchmark sites (see below). The systems should operate throughout the year, helping to separate root respiration from soil respiration. The measurements at different depths help determine the site of root heterotrophic activity to assist in model development.

5. *Inventories of carbon stocks.* Benchmark permanent soil quality (low frequency) monitoring sites will, with sufficient spatial density, be able to detect 5-10 year trends in soil organic carbon that could result from changing management practices or other causes. They will be representative of the various soil types, climate, management regimes, and vegetation classes. Instrumentation and measurement techniques will be standardized for comparisons between sites. The grid setup will build on presently available long-term sites such as LTER and university and federal research stations. The latter sites have a wealth of long-term crop and soils data and in some cases ecosystem process data as well. Data from the new sites should greatly improve existing inventories.

6. *Bottom-up models.* Some examples of the type of modeling approaches that will be necessary are given here. A crop growth model was run during the SMEX02 soil moisture investigation in Iowa. Inputs were detailed LANDSAT vegetation classification, MODIS 8-day composite reflectance, soil physical and chemical properties available from the STATSGO database, initial soil moisture status, and weather and climate data. Measured yields on selected fields were used to calibrate model yield parameters, and at the Walnut Creek Watershed crop yields have been compared with

cumulative eddy covariance and soil flux measurements. A different type of model, the Century soil organic matter model uses databases for climate, soil properties, topography, and land use history, has crop growth and water submodels, predicts yields to estimate residue input to the soil, and predicts carbon and nitrogen in various soil compartments. The Atmosphere-Land Exchange Inverse (ALEXI) model uses GOES data, vegetation cover from satellites, and weather data (temperature, pressure, humidity) to estimate fluxes of sensible heat and water vapor on a daily basis. Visible in the resulting evapotranspiration maps are patterns that are coherent over large areas, sometimes as elongated bands more than a thousand km long and a few hundred km wide. When integrated with a canopy resistance model, daily predictions of carbon assimilation can be made. This approach has been developed furthest for crop systems. Coupling ALEXI with a Disaggregation approach (DisALEXI) using satellites with higher spatial resolution (Landsat, MODIS, ASTER) could provide real-time calibration of ALEXI using surface flux measurements by eddy covariance or gradient methods. Thus ground-based measurements could be integrated directly into large-scale flux estimates. In yet another possible approach, BIOME-BGC has been used to estimate daily GPP, NPP, and evapotranspiration, based in part on MODIS observations. Thus far it has been mostly applied to forested land, and more recently to grassland. A model such as SiB-2 simulates stomatal conductance, and thus the latent heat flux and the partitioning between latent and sensible heat fluxes, which has a significant influence on atmospheric dynamics. At the same time it provides GPP.

To the east and to the north of the intensive are extensive grassland and forested areas respectively. The atmospheric data will register the impact of those areas. Modeling of those ecosystems, including the use of flux measurements, maximizes use of the data gathered in the campaign and likely improves the results for cropland areas.

*5. Transport models.* Needed for converting observed concentration patterns into source estimates are atmospheric transport models. Assimilated meteorological data at the highest resolution available from weather forecast models will be essential. Important current weaknesses are convective mixing, detailed land surface description including the physiological response of vegetation, mixing and stability of the nocturnal boundary layer, (lack of) conservation of tracer mass, representation and impact of cloud systems. The meteorological fields and mixing schemes will be used to calculate the transport of species in global models, high-resolution regional models, and in nested models (e.g. MM5, RAMS, TM5), all run in inverse mode. Receptor models such as STILT also use assimilated meteorological data, and they provide yet another way to estimate sources.

#### *6. Land use and history*

The Landsat Thematic Mapper has been in use since 1982, and can give a comprehensive picture for the last two decades. USDA Forest Service inventory data for forests (FIA), county level data from the National Resource Inventory and the USDA National Agricultural Statistics Service can be used for data before 1982, and as a crosscheck of the Landsat data. MODIS data also give a comprehensive view of current land use, but there are only a few classes.

### 7. *Fossil fuel inventory*

Data for fossil fuel use need to be separated by type (coal, oil, and natural gas), and algorithms need to be developed to disaggregate their use into more detailed spatial and temporal patterns, including large point sources such as power plants. It may help that in the area of the intensive campaign the population density is relatively low, and that there are some very concentrated metropolitan areas nearby (Minneapolis/St. Paul, Chicago, St. Louis, Kansas City). This will give opportunities for verification of the use algorithms, chemical signatures, and perhaps even the magnitude of the emissions. The large fossil fuel component will have to be quantitatively accounted for when annual estimates of carbon sequestration/loss are made for a region. In addition, since September 2000 there is an ongoing geological sequestration project whereby CO<sub>2</sub> from a synfuels plant in Beulah, N. Dakota, is injected into the Weyburn oil field in south eastern Saskatchewan. Every day, the emissions equivalent of 100,000 people is injected into the 180 km<sup>2</sup> oil field. If there are significant leaks they would be detectable in the amount of CO<sub>2</sub> and possibly its isotopic signature.

Figure 1. U.S. upper Midwest and southern Canada. Yellow dots: metropolitan areas; red squares: eddy covariance flux measurement sites; blue: TV and FM towers taller than 800 ft and up to 2000 ft, with length of vertical line indicating height of tower; numerals 2,3,5,7 indicating the (possible) location of frequent vertical profiles by aircraft, existing before 2002, starting in 2003, etc.

