

Science Plan:
Mid-Continent Intensive Campaign of the
North American Carbon Program
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Summary

The Mid-Continent Regional Intensive Campaign is primarily a large-scale test to compare and reconcile, to the extent possible, regional carbon fluxes on hourly to annual time scales using “top-down” atmospheric budgets versus “bottom-up” ecosystem model-based inventories. A secondary goal is to identify the mechanisms governing the regional fluxes. The intensive will focus on comparisons of CO₂ flux estimates, but CH₄ may also be included in the evaluation depending on the availability of data. The experimental design includes four general steps: 1) develop the “top-down” atmospheric budgets and “bottom-up” inventories to estimate fluxes and their associated uncertainties, 2) evaluate the top-down budgets and bottom-up inventories using independent data that, for example, overlap a subset of the domain in space and/or time; 3) compare and contrast validated bottom-up and top-down approaches and reconcile differences to the extent possible by making incremental improvements through further evaluation and improvements in both methods, and 4) quantify sources and sinks during the campaign as well as the mechanisms governing those fluxes. The intensive will support goals of the North American Carbon Program by establishing methodology for making regional flux estimates with greater accuracy using “top-down”, “bottom-up”, or a combination of the two approaches.

I. Introduction

The Mid-Continent Intensive (MCI) is an element of the North American Carbon Program (NACP). In general, intensives are intended to be campaigns within sub-regions of North America that improve our understanding and the methods for estimating carbon exchange between the earth’s surface and atmosphere. Knowledge gained from the intensives will be employed in the long-term study of the continental carbon cycle envisioned by the NACP. Intensive campaigns may involve ground sampling, flux tower measurements, aircraft measurements, remote sensing and modeling to estimate fluxes of CO₂ and CH₄ and elucidate the underlying controls on the fluxes. Each intensive will likely have its own focus in terms of research objectives and study area, but the combined effort is expected to provide improved methods needed for a continental synthesis with unprecedented accuracy in support of the NACP. **For the MCI, the overarching goal is to validate and compare regional carbon flux estimates derived from “top-down” atmospheric budgets and “bottom-up” ecosystem inventories, facilitating further evaluation and improvement of both approaches.**

¹ Mid-Continent Intensive Campaign Task Force was formed by the Scientific Steering Group of the North American Carbon Program to facilitate and coordinate research associated with the Mid-Continent Intensive Campaign. Task Force members are Stephen Ogle and Ken Davis (co-chairs), Arlyn Andrews, Kevin Gurney, Tristram West, Robert Cook, Tim Parkin, Jeff Morissette, Shashi Verma and Steve Wofsy.

“Bottom-up” approaches use ecosystem models with activity and environmental data to simulate carbon fluxes. Activity data typically include anthropogenic activities known to influence fluxes, such as land use change, while environmental data may include micrometeorological records, soil characteristics, topography, and other surface characteristics. Models are developed through a combination of field studies, laboratory or field experiments and theoretical constructs, and the resulting algorithms are evaluated using flux measurements (e.g., measurements from eddy-covariance towers in the Ameriflux network), and/or measured trends in carbon stocks (e.g., measurements of carbon stocks stored in soil, plant and litter pools). “Bottom-up” flux estimates can also be constructed from spatial extrapolation of flux measurements such as eddy-covariance flux towers, or from networks of carbon stock measurement data. To the extent that the processes governing carbon fluxes are understood, bottom-up approaches allow for an evaluation of the mechanisms controlling carbon sources and sinks, and also enable future trends to be predicted. Possible mechanisms are land use change, land management, commodity production, waste management, energy production, and responses of terrestrial ecosystems to increasing concentrations of greenhouse gases including climate change and CO₂ fertilization. Remote sensing of the land surface and geographically distributed databases allow bottom-up approaches to be extended over large domains.

“Top-down” approaches use atmospheric measurements of CO₂, CH₄, and related tracers, along with simulations of atmospheric transport to estimate fluxes consistent with the observed spatial and temporal patterns of atmospheric concentrations. The atmospheric inversion methods are based on tracer measurements from tower data and aircraft measurements, remote sensing data defining the spatiotemporal state of the vegetation, and assimilated meteorological fields. These approaches have traditionally been used for resolving continental scale fluxes over monthly time periods. This is due to limits on the spatiotemporal resolution of the transport models and the mismatch between the scale of transport simulations and the tracer measurements. Consequently, inverse modeling has been employed to study net fluxes for the whole earth or for latitudinal bands, given that pole-to-pole mixing is much slower than zonal transport, because data have been limited, and resolution of atmospheric transport has been relatively coarse and uncertain. Without further progress in tracer measurements and transport simulations, resolving sub-continental fluxes remains a significant challenge.

The MCI is aimed at improving our ability to determine CO₂ fluxes at regional spatial scales, and daily to annual temporal scales. CH₄ will also be evaluated, but not to the extent of CO₂, because of limited measurements and modeling that will not support the same level of comparison. Bottom-up approaches, whether based on measurement of carbon stocks, process models, direct flux measurements, or a combination thereof, are built upon data that are local in scale, and must be extrapolated over space. Direct flux measurements can yield high temporal resolution, but may not effectively capture, at least over a large region, the slower time-scale processes that govern annual changes in carbon stocks. Process models can provide more detailed accounting of fluxes to the extent that the underlying mechanisms are represented in the model framework. However, parameterization is often difficult for capturing the spatiotemporal heterogeneity over

large regions, and validation of results requires independent data from model development and parameterization that are often not available. Measurement-based inventories of carbon stocks have very low temporal resolution by nature, and obtaining broad spatial coverage is very labor intensive. Although there are several long-term experiments in the region with a time series of C stock measurements, a network of monitoring sites does not currently exist with the spatial density needed for generating an inventory of carbon stock changes in the Mid-Continent region. Consequently, current approaches for bottom-up inventories rely on a combination of modeling and measurements, and such large-scale inventories have been difficult to validate. Top-down approaches, as noted above, have not typically been applied to continental or sub-continental domains due to limited atmospheric data and difficulty in obtaining accurate, high-resolution atmospheric transport fields. Thus to date we are unable to produce a definitive carbon budget and understanding of the processes governing those budgets at the continental to sub-continental scales.

The NACP science plan calls for a multi-tiered observational network that would provide this capability. To date, however, the proposed observational design remains uncertain, and multiple top-down and bottom-up approaches have not yet been brought to bear upon a common region in a study spanning at least one full annual cycle. The MCI is intended to provide an initial test of the proposed NACP observational network, and demonstrate this capability, thus supporting the long-term goals of the NACP.

A primary building-block of the MCI is the National Oceanic and Atmospheric Administration's emerging tall-tower and aircraft trace gas sampling network. This network, which is under construction, is initially being developed in the Mid-Continent (to be completed in early 2007) and then is anticipated to expand for eventual continental coverage. The network is proposed as a long-term atmospheric measurement system that will enable inverse studies of the North American carbon cycle. This intensive is intended to test the efficacy of the NOAA sampling approach and to assess plans for site selections. The major challenge will be to demonstrate that the network is capable of providing an accurate carbon budget for the region based on the density and suite of measurements that are being taken during the campaign. The findings will be critical for supporting or possibly modifying the design of the continental-scale network. The region also hosts relatively dense networks of eddy-covariance flux towers, several long-term agricultural experimental sites with time series of C stocks, forestry data collected through the FIA program, annual crop yield data collected by USDA-NASS, and atmospheric transport measurements, thus providing an excellent location for testing multiple methods.

There is one large component of the carbon cycle that is already very well quantified at the national level, but somewhat less well at the regional level, and that is the combustion of fossil fuels. This study offers an opportunity for validation of the top-down method specifically for monitoring fossil emissions, and in the future a successful top-down method could provide an independent check on the effectiveness of policies to decrease fossil emissions in addition to the success of policies encouraging carbon sequestration.

Another key component of the MCI is a data management plan that will guide production, documentation, and distribution of data products. A NACP data management system is currently in the planning phase and is anticipated to support data needs for the overall research program including the MCI (<http://www.nacarbon.org/nacp/documents.html>). As part of the initial planning, data requirements and recommended approaches have been developed that are expected to provide a robust structure for data management in the NACP.

II. Objectives and Hypotheses for the Mid-Continent Intensive

The primary objectives of the Mid-Continent Intensive (MCI) Campaign include:

- 1) Develop approaches to estimate fluxes using “top-down” atmospheric budgets and “bottom-up” inventories,**
- 2) Provide both “top-down” and “bottom-up” flux estimates and associated uncertainties for the MCI study region, including a separate analysis for the fossil fuel component,**
- 3) Provide independent validation data and error analysis for both approaches, and**
- 4) Evaluate discrepancies between the two approaches, diagnose problems, and iteratively improve estimates for both approaches through mutual “learning”.**

The MCI also has secondary objectives that will provide additional information in support of the continental synthesis, including:

- 5) Provide the basis for optimization of field, satellite and atmospheric sampling schemes,**
- 6) Determine mechanisms driving regional net fluxes patterns in the MC region,**
- 7) Assemble data products required for the “bottom-up” and “top-down” approaches, and**
- 8) Provide guidance to future intensives.**

To the extent allowed by funding, “bottom-up” approaches will be used to estimate CO₂ emission and uptake based on observations and modeling of plant, soil, livestock, and wetlands systems, in addition to human-induced emissions from energy use, industrial processes and waste management. “Top-down” approaches will be used to estimate fluxes from atmospheric concentration measures and inverse modeling. Both of these approaches will be evaluated with independent validation data, and in turn, the “bottom-up” inventories will be compared to “top-down” flux estimates. Through iterative improvements in each approach, the campaign is expected to provide flux estimates and attribution of sinks and sources with greater certainty than previous analyses, which is a primary objective of the NACP. The success of the MCI campaign is predicated on several underlying assumptions, which have been formulated as testable hypotheses, including:

- 1) *Increased spatial and temporal coverage of atmospheric trace gas measurements and improved simulation of atmospheric transport and mixing processes will enable regional, weekly to annual net carbon fluxes to be determined using “top-down” approaches at a sufficient level of accuracy to detect regional responses in flux patterns associated with climatic variability and changes in land use (estimated at approximately $\pm 20 \text{ gC m}^{-2} \text{ yr}^{-1}$)². To date atmospheric budgets coupled with inverse modeling have been more successful at estimating longer term trends across continental domains. The intensive will provide a landmark methodological test by applying these methods in a rigorous manner to resolve fluxes at the finer regional scale.*

- 2) *A hierarchy of field and remote sensing observations will enable further process model development and/or data assimilation techniques that reduce uncertainties in “bottom-up” flux estimates. Regional flux estimates will have uncertainty levels comparable to those described for ‘top-down’ approaches. Remote sensing and field observations provide the basis for “bottom-up” methods and a goal of the intensive is to make better use of this information in the modeling activities. Moreover, data assimilation techniques show considerable promise to improve model simulations by adjusting parameters based on new information. Modeling activities will occur at different spatial scales that will be compared to refine methods at each level in the hierarchy.*

- 3) *Comparison of “top-down” and “bottom-up” results will lead to iterative improvement of each independent regional approach, leading to estimates of fluxes and stock changes that are consistent among the approaches. Flux estimates will be compared between top-down and bottom-up approaches to determine consistencies and inconsistencies across the region and throughout the duration of the MCI. Model assumptions will be tested to the extent possible and the modeling approaches will be improved based on these comparisons.*

- 4) *The “bottom-up” methods, including carbon flux and stock measurements and models, will yield a quantitative understanding of the environmental conditions, agricultural management, and ecosystem processes responsible for the observed regional CO_2 and CH_4 flux estimates. “Bottom-up” estimates will be used to quantify sources and sinks from specific land surfaces and the underlying causal factors will be elucidated through sensitivity analyses.*

The MCI is expected to contribute to the longer term goals of the NACP by providing improved modeling approaches with less uncertainty for quantifying CO_2 fluxes between the atmosphere and terrestrial ecosystems. The refined modeling approaches will be integrated with improvements and knowledge gained through other intensives to provide a more robust continental analysis of CO_2 fluxes in North America and surrounding

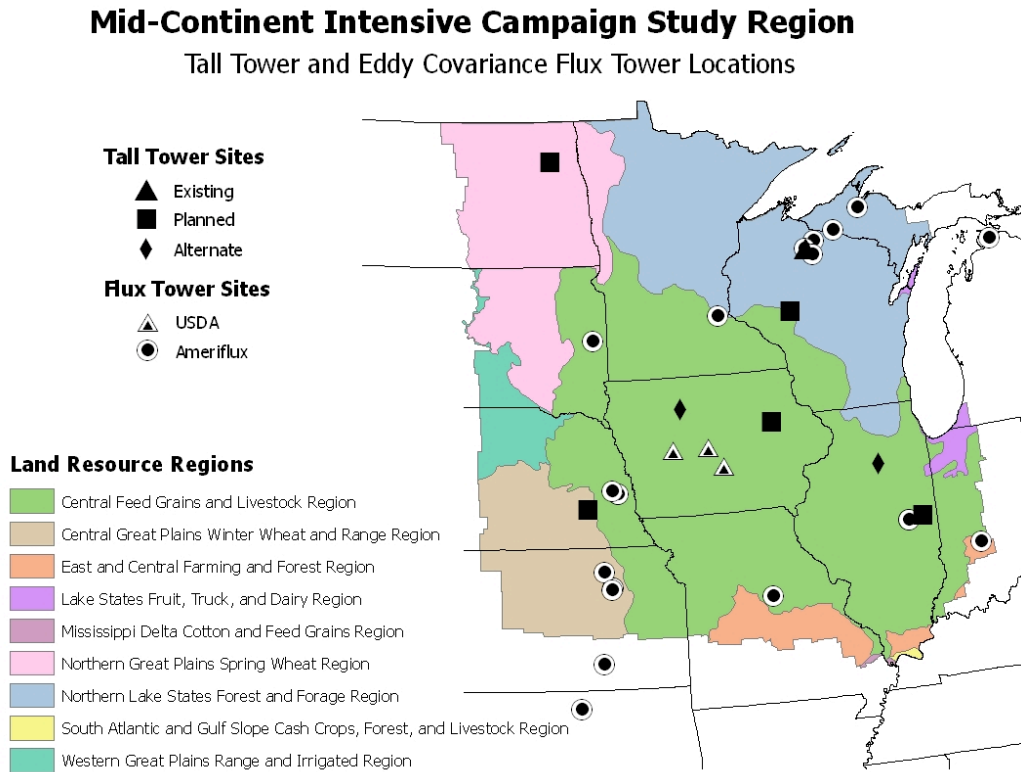
² Interannual variability in fluxes observed at several AmeriFlux towers typically ranges from 50-100 $\text{gC m}^{-2} \text{ yr}^{-1}$, thus an accuracy of $\pm 20 \text{ gC m}^{-2} \text{ yr}^{-1}$ would be sufficient to resolve interannual variability in terrestrial C fluxes, assuming the tower measurements are representative of regional flux patterns.

ocean basins. These activities are being done in parallel with projects on other continents, such as European regional research (<http://carboregional.mediasfrance.org/campagne/index>), and may also lead to larger scale syntheses in the future.

III. Spatial and Temporal Domain

Atmospheric measurements integrate the influence of surface processes over a wide area, and this region of influence shifts through time. Therefore, it is not possible to define a relatively small region in which the “footprint” for atmospheric measurement is fixed. However, a study area has been delineated that is considered the focal region for the MCI based on the most likely land surface “footprint” that will influence atmospheric concentration measurements on the tall tower network established by NOAA CMDL investigators (Figure 1).

Figure 1. Focal Study Region for the Mid-Continent Intensive Campaign.



The core “bottom-up” and “top-down” modeling activities are expected to focus their efforts in this region. The center of the study area is largely dominated by agricultural land, but significant areas of forest lands occur in the northern and southern portions of this region. There are also some metropolitan areas in the region such as Minneapolis-St. Paul in Minnesota, and a significant number of wetlands are found in the area, particularly in Minnesota and North Dakota. Furthermore, the northeastern and eastern boundaries include the Great Lakes Superior and Michigan. Investigators will study the

flux patterns from all of these regions to the extent possible with the goal of producing a regional and subregional budget of carbon fluxes. In addition, complementary studies are ongoing in the Canadian portion of the Mid-Continent that may be incorporated into the campaign.

While some components of the study began in 2005, including intensive studies of bottom-up methodologies in subsets of the domain, the key atmospheric sampling year is expected to occur in 2007 because the NOAA CMDL CO₂ mixing ratio network for the region is projected for completion in 2006. In addition, we anticipate that independent validation data will be acquired in campaigns to measure CO₂ mixing ratios (airborne, temporary tower deployments), and possibly airborne fluxes, at high temporal and spatial resolution in 2007.

IV. Experimental Design

A generalized experimental design for the MCI is provided in this section. It is important to realize that this is a broad overview for planning purposes. Not all of the activities envisioned here are currently funded; moreover, there may be additional studies that contribute to the intensive using experimental designs not described in this section.

*Step 1: Develop “Top-Down” Atmospheric Budgets and “Bottom-Up” Inventories to estimate CO₂ Fluxes*³. A spatial hierarchy is inherent in the study design for the intensive. At the smallest scale, are individual stand- or field-level studies, which can be long-term experiments or short-term studies. At the next scale are sub-regional studies such as those with a watershed focus; these are likely to be mini-intensives with “top-down” and “bottom-up” approaches. At the top level of the hierarchy are studies that will estimate fluxes across the entire Mid-Continent study region. Beyond the hierarchy of the intensive are larger continental and global scale influences on atmospheric CO₂ concentrations that are currently under evaluation in other projects and are anticipated to contribute information on boundary conditions. There is also a temporal hierarchy beginning with variation in day/night fluxes to daily, seasonal and annual fluxes, which will be studied across these spatial scales, and both net and gross fluxes will be quantified.

While subsets of the entire region will be more intensively studied, the ultimate goal is to determine the net flux over the entire region using atmospheric budget approaches, and to compare the resulting atmospheric budget (inversion) estimates with independent, “bottom-up” inventories, leading to incremental improvements. Stand and field-scale experiments included in the campaign as well as sub-region intensive studies are all in support of this primary, overarching goal. Summary points are provided in Box 1 for each spatial scale in the hierarchy.

The anticipated needs for “top-down” approaches include 1) long-term atmospheric mixing ratio data from the NOAA tall tower and aircraft profiling network as well as

³ Note that CH₄ will be evaluated to the extent possible, even though it is not discussed in the experimental design.

selected AmeriFlux sites, 2) campaign-style oversampling of atmospheric mixing ratios using temporary tower-based measurements and aircraft, 3) atmospheric transport fields including boundary conditions, and 4) inverse modeling.

Box 1: Summary of data collection and modeling at whole region, sub-region and stand/plot scales

Whole Mid-Continent region

- Annual to daily focus, high spatial resolution. Independent top-down and bottom-up approaches.
- Tall tower and flux tower mixing ratio measurement network, including supporting measurements to enable quantification of the fossil fuel component, such as CO, SF₆, and others, including carbon-14.
- Periodic tower and aircraft measurements with dense, comprehensive observations in time and space (validation data)
- Flux tower network
- Ecosystem modeling focused on Mid-Continent Study Area for one or more sink/source categories (i.e., plant, soils, fossil emissions, waste management, livestock, land-lake coupled carbon flux, etc.)

Sub-regional intensive domains

- Evaluate bottom-up approaches within coherent Land Resource Regions and/or Ecoregions.
- Seasonal to daily focus, very high spatial resolution. Independent top-down fluxes.
- Aircraft, flux tower, and ground-based inventory and component flux measurements
- Net carbon fluxes over Lakes Michigan and Superior
- Sites include Bondville, Mead-NB, SMEX05/Iowa-USDA, ARM-CART, and the ChEAS

Stand-level or field-scale studies and other plot-scale data

- Flux towers, ‘tier 3 and tier 2’ plots, etc.
- Used to calibrate ecosystem models for up-scaling.
- Annual to daily focus, but may provide long-term data
- Single points in space
- Measurements of stocks and/or fluxes. Typically designed to test the influence of specific driving variables on stock changes or fluxes, such as the effect of land use change
- Examples of studies include Ameriflux Network, Long-term field experiments (e.g., USDA-ARS experiments), Forest Inventory Analysis data

The anticipated needs for development of bottom-up inventories include 1) regional modeling applications addressing fluxes of CO₂, 2) a flux measurement network (e.g., flux towers, aircraft flux measurements, component flux measurements, such as soil and

leaf level, in addition to air-water exchange in Lakes Michigan and Superior), and supporting biological data for process models (e.g. LAI, leaf nitrogen, soil carbon), 3) soil characteristics (soil type, drainage, texture, bulk density), 4) land use and management histories for sites, 5) spatially detailed process-based estimates of fossil fuel combustion over diurnal, weekly, and seasonal cycles (point sources, urban emissions, traffic corridors, etc.), 6) spatially-distributed production estimates (crop yield data, forage production, forest Inventory data, and turfgrass production, primary production and carbon loss to sediments in lakes), and 7) land surface information to support bottom-up modeling applications (crop, grassland, wetland, forest and impervious surfaces; locations of livestock operations, power plants, landfills and waste management facilities; spatially-explicit data on fire occurrence, tillage/residue management, and fertilizer use; digital elevation model; MODIS Vegetation Index, LAI, FPAR, GPP, and PSN products; as well as weather and (DayMet) soils data (Statsgo).

In order to fulfill some of the anticipated needs, data from field investigations as well as data required as inputs to process-based and inverse modeling will presumably be compiled, documented and made available to MCI investigators. These data as well as data products generated through the study (e.g., flux estimates and inventories) will be made available for distribution through an integrated NACP data and information management system, which is currently being developed (<http://www.nacarbon.org/nacp/documents.html>).

Step 2. Compare Results Among Bottom-Up and Top-Down Inventories. Once the initial atmospheric budgets and “bottom-up” inventories are developed, the information will be incorporated into databases and results will be compared.

“Bottom-up” inventory comparisons will focus on evaluation of model output relative to measurements from stand/field experiments, such as measured trends in fluxes from eddy-covariance towers in the Ameriflux network. This analysis will confirm that ecosystem models adequately represent processes before attempting to simulate region-wide fluxes or stock changes. Some modeling projects may incorporate data assimilation at this scale.

Validation data for concentrations with comprehensive spatio-temporal coverage will be used to examine key features of the top-down budget models. All top-down budgets predict, or can predict, the complete 4-dimensional concentration field. Independent validation data provide tests for these predictions, highlighting discrepancies that can reveal deficiencies in the spatio-temporal distributions of flux or in the transport fields. The ability to quantitatively assess transport errors is a key function of the validation data, since inaccurate simulation of transport is the largest source of error and the least amenable to quantification using statistical methods. Validation data using ultralight aircraft to measure flux can also assess the spatial pattern of fluxes predicted by bottom-up models.

Anticipated needs to accomplish this step include: 1) Ameriflux and long-term experimental data to test “bottom-up” approaches, 2) aircraft campaign to develop

validation datasets for “top-down” approaches, and 3) a synthesis activity to make comparisons.

Step 3: Compare validated top-down and bottom-up methods.

Two levels of comparison will be used in Step 3. At the first level, sub-regional results will be compared to the results from associated areas in the whole region analysis. To the extent possible, differences will be reconciled between the mini-intensives and regional analyses, and the “top-down” atmospheric budgets and “bottom-up” inventories will be revised.

The second level of the analysis will evaluate consistencies as well as anomalies between the “top-down” atmospheric budgets/inversions and “bottom-up” inventories from the whole region analysis. Investigators will work collaboratively to make incremental improvements in their respective approaches. In some cases, further investigation will be needed to address anomalies, and therefore some inconsistencies may remain following the MCI. It is anticipated that inconsistencies will become key research topics for future intensives and associated research funded through the NACP. A synthesis activity will be needed to make comparisons, determining consistencies and inconsistencies, which will build on research activities in Step 2.

The goal of these comparisons is not to “average” the results between the two methods, or assume that one method is always correct, but rather to reconcile the differences to the extent possible. Comparisons will focus on the uncertainty ranges, and the overlap or lack thereof between the two approaches. Consequently, a rigorous uncertainty analysis is essential for making these comparisons. It should also be recognized that all inconsistencies may not be resolved, requiring further investigation in the future.

Step 4: Determine Sources and Sinks of CO₂ fluxes during MCI. “Bottom-up” inventories and “top-down” atmospheric budgets/inversions will be used to determine spatio-temporal sources and sinks in the Mid-Continent Region. Inconsistencies between the two approaches will be highlighted in the resulting products. Bottom-up inventories will be used to further elucidate the underlying mechanisms controlling fluxes, particularly the influence of anthropogenic activity. A synthesis activity will finalize estimates given improvements that were made in Steps 2, 3 and 4.

V. Deliverables

The main deliverable of the Mid-Continent Intensive Campaign will be a synthesis report. The report will include a discussion of differences across the spatial hierarchies, incremental improvements and final results for regional CO₂ and CH₄ (depending on the level of measurement and modeling for the latter) fluxes during the MCI campaign. Underlying mechanisms creating sources and sinks across the spatio-temporal domain will also be discussed, including the anthropogenic influences. The report will also highlight inconsistencies that remain unresolved for future investigation.

Guidance to future intensives will also be provided including discussion of strengths and weaknesses of the MCI campaign and recommendations for improving the operational aspects of this type of collaborative effort. Moreover, the resulting flux estimates are expected to provide a fourth level of testing and incremental improvements through a comparison of the Mid-Continent flux maps with flux estimates from the continental scale analyses.

Depending on funding availability for various components of the MCI, the intensive is anticipated to provide the following specific items in support of the continental synthesis for the NACP:

- 1) Validated methods,
- 2) MCI region stock change/flux maps and mechanistic explanation of patterns,
- 3) Methods for optimization of field, satellite and atmospheric sampling schemes,
- 4) Assembly of data products required to produce “bottom-up”/“top-down” methods for the MCI Region, and
- 5) Guidance for future intensives
 - Synthesis report with a summary of research findings, unresolved research issues and data needs
 - Discussion of operational strengths and weaknesses of campaign