

4.0 MEASURING AND MONITORING FOREST CARBON STOCKS AND FLUXES

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Measuring and monitoring forest productivity and carbon (C) is of growing concern for natural resource managers and policymakers. With the Delaware River Basin (DRB) as a pilot region, this subproject of the CEMRI sought to:

- Improve the ability of the ground-based Forest Inventory and Analysis (FIA) networks to more completely assess forest C stocks and fluxes
- Integrate estimates of forest biomass and net primary production (NPP) from available remote sensing products with FIA data
- Characterize the effects of land use change and forest fragmentation on cumulative C stocks and fluxes
- Integrate disparate monitoring networks to develop complete site-level and Basin-level C budgets including C loss by water transport

4.1 Background

Human activities, primarily burning fossil fuels and changing land use and land cover, are increasing atmospheric concentrations of greenhouse gases, which alter the radiative balances in Earth's atmosphere. Global mean temperatures increased by 0.6 °C in the 20th century, and climate models predict a further increase as large as 5.8 °C by 2100 (Intergovernmental Panel on Climate Change 2001), suggesting the potential for substantial changes in food and fiber production, hydrologic regimes, coastal resources, and other natural resource sectors.

Carbon dioxide (CO₂) is an important greenhouse gas produced as a byproduct of fossil fuel burning, but it is also taken up and released during growth and metabolism by photosynthetic organisms. Because forests are thought to store close to 90 percent of Earth's terrestrial vegetation biomass (Dixon et al. 1994), they are important controllers of atmospheric CO₂ concentrations and are thus critical components in the global C cycle. Current interest in forest C cycling rates is especially intense because of some uncertainty in the magnitudes of terrestrial sources and sinks, as well as continued uncertainty about the lasting effects of land use change and forest disturbance on forest C cycling rates. Furthermore, international agreements such as the Kyoto Protocol, intended to curb greenhouse gas emissions and slow the pace of climate change, require accurate inventories of forest C stocks and fluxes.

In addition to driving the atmospheric C balance, the rate of forest growth may help determine the quality and quantity of water reaching streams. For example, photosynthetic rates are directly proportional to water use by plants, and thus the rate of tree growth may help determine streamwater quantity. Dissolved organic carbon (DOC) is also an important source of nutrients for soil microbes.

At larger scales, C export from the land to surface waters may also be a significant component of the regional C budget. Global estimates suggest that C fluxes from erosion and weathering may transport up to 0.8 Gt C yr⁻¹ (Carbon and Climate Working Group 1999) from streams

and rivers. Carbon burial in lakes, reservoirs, and peatlands may exceed four times the burial rate in oceans (Dean and Gorham 1998, U.S. Geological Survey 1999).

In terms of human health, DOC in streamwater may compromise water quality for human consumption. Increased export of C from forested landscapes will increase the pool of C available for developing tri-halomethanes in drinking water supplies. Tri-halomethanes are a chlorination byproduct that may pose a human cancer risk. This is a particular concern in the DRB, which supplies drinking water to New York City and northern New Jersey.

4.2 Measurement of Forest and Aquatic Carbon Stocks and Fluxes

Vegetation contains roughly 50 percent C; live trees are thus important C reservoirs in forests. However, significant amounts of C may be stored in harvested wood products, in dead trees, or belowground in roots and soils. In addition, C is released back to the atmosphere as a byproduct of metabolism, and as organic matter decays, the decay rates of different types of organic matter must be taken into account for a complete C budget for forested land. The C cycle is further complicated by changes in land use, which release C to the atmosphere from deforestation or store additional C as vegetation regrows on land that reverts back to forest.

Two kinds of measurements are required to estimate C cycling rates in forests. First, estimates of the total amount of C stored in a forest ecosystem (C stocks) are important because total C stocks represent the amount of C available for harvest or decomposition. Comparisons between C stocks in different forest types, or in similar forests on different site types, and analysis of trends in total C stocks with forest age can also help determine what the total C storage capacity might be for a forested landscape. In addition, it is important to understand the rate of change in different forest compartments (C fluxes) because the sum of these movements of C into and out of the terrestrial system represents net C exchange between forests and the atmosphere.

To accurately quantify forest C stocks at the plot level, detailed information must be collected on: tree dimensions for all trees, soil C pools (including roots), and dead organic matter (including standing and downed dead trees and stumps). The information on tree dimensions can be translated to C terms using conversion factors based on tree allometry. Although collecting the required information to assess aboveground C stocks is fairly straightforward, quantifying C stocks belowground in soil and roots is much more difficult and time consuming.

Quantifying C fluxes accurately is even more difficult because: a) net annual C changes are made up of a series of fluxes controlled by a wide variety of factors; and b) year-to-year C fluxes are difficult to detect because they are often much smaller in magnitude than total C stocks. To quantify annual C fluxes in a forested system, we must collect information on changes in tree dimensions, changes in soil C stocks, total fine and coarse root production, and production of dead material from tree damage or mortality (both large and small material, such as stumps, branches, and twigs as well as leaves and needles). In addition, we must collect information on C lost from the soil as CO₂ via metabolism of soil organisms. Finally, land use change and harvesting for timber products may translocate C to other pools. Each of these fluxes may be controlled by a different factor, such as climate, nutrient

availability, and disturbance regime—as a result, net annual C sequestration rates can vary dramatically in space and time.

In research studies, ecologists typically gather information on a subset of fluxes at a series of experimental plots within a larger forest landscape. One common measure of forest productivity is NPP, an important aspect of the role of vegetation in the global C cycle. NPP is defined as the net rate of C accumulated by vegetation per unit area per year—or, in other words, the difference between the total C fixed from the atmosphere and the portion of that C used by plants in metabolism. Net ecosystem production (NEP) is the difference between NPP and the C used by animals in metabolism—NEP is thus the net rate of C sequestration by a forest system. If we assume our study plots have characteristics representative of the surrounding area, we can then translate plot-level information to the landscape level (for example, if there is a total of 100 Mg C in all forest compartments on a 1-ha plot, we can say there is likely to be 1,000 Mg C in the surrounding 10-ha forest). Finally, we note that net ecosystem C balance is the net result of NEP and any other C losses. This is important because lateral transfers of C between forest stands within a landscape are not captured by physiological measurements such as NEP and NPP. For example, if DOC is leached in ground water from forest soil, it will be lost from the biomass pool and will eventually emerge in streamwater where it can be measured.

As applied in standard research settings, this approach has limitations. First, it is usually impractical, if not impossible, to measure all the relevant fluxes in a standard research study. For example, measuring the C lost from soil typically requires complicated and expensive equipment not easily available to all researchers. Measuring root production is also quite time consuming and expensive. Second, many of the fluxes may vary substantially from site to site (and even from point to point within one site), making it difficult to adequately capture the status and trends in the C resource with scattered site-level studies. Finally, the plots chosen by researchers for detailed study are few in number and represent only selected characteristics of the surrounding forest. When C fluxes from a plot are scaled up to a landscape, this bias usually results in overestimates of C cycling rates because ecologists tend to choose plots covered more densely with forest than the surrounding areas, which tend to have a history of frequent disturbance.

Three types of measurements are commonly used to assess C fluxes in aquatic systems: water quantity, sediment load, and C concentrations in water and in sediment. Together, these measurements provide an integrated picture of the total C transported out of a watershed in streamwater. A fourth measurement, gas flux from the river's surface, is important for C budgets of large, slow-moving rivers, but was not included for the Delaware CEMRI.

Water quantity in rivers of the Northeastern U.S. varies significantly between seasons and is controlled by several factors, including plant photosynthesis, precipitation, bedrock and surficial geology, and soil porosity. The most common way to measure water quantity is by installing a gauge at a point along a river where changes in stream depth are gradual and directly proportional to stream volume. This type of measurement requires expensive installations and labor-intensive calibration and is thus practical only for a finite number of the existing river reaches in the United States. The Delaware River has several stream gauges

4.3 Existing Monitoring Programs and Regional Assessment Capability

established, including the main-stem river at the head-of-tide upstream of the Delaware Bay at Trenton, New Jersey, and on numerous small and large tributaries throughout the watershed.

Carbon concentrations can also vary dramatically in surface waters and are dependent on factors such as water quantity, in-stream nutrient processing, watershed sediment yield, and temperature. As with water quantity, continuous monitoring is the most accurate method for assessing streamwater concentrations. Again, this type of intensive measurement is not practical except under very limited circumstances.

The USFS FIA program provides a comprehensive sample of forests in the United States and is the accepted basis for national statistics about C sequestration in forests (Birdsey 1992, Birdsey et al. 1993, Birdsey and Heath 1995). However, the program measures only a subset of the relevant stocks and fluxes; the remainder must be estimated from measurements made during more detailed plot sampling.

To estimate C storage, the forest ecosystem is partitioned into separate components. One possible way to define these is live trees, dead trees, coarse woody debris, forest floor, soil, and understory vegetation. These definitions of ecosystem components are broad enough to include all sources of organic C in the forest ecosystem. As defined here the tree portion includes all aboveground and belowground portions of all live and dead trees and saplings greater than 1 inch d.b.h., including the merchantable stem, limbs, tops, cull sections, stump, foliage, bark and root bark, and coarse tree roots (greater than 2 mm). The soil component includes organic C in mineral horizons to a depth of 20 cm, excluding coarse tree roots. The forest floor includes all dead organic matter above the mineral soil horizons except standing dead trees and coarse woody debris. Understory vegetation includes live vegetation other than live trees.

Using data from forest inventories and intensive-site ecosystem studies, estimates of average C storage by age or volume classes of forest stands (analogous to a forest yield table) are made for each ecosystem component for forest classes defined by region, forest type, productivity class, and land use history. Equations are derived to estimate C storage in the forest floor, soil, and understory vegetation for each forest class (Table 4.1). Additional details about estimating C storage for different regions, forest types, site productivity class, and past land use are provided in Smith et al. 2006.

The USGS National Water Quality Assessment program (NAWQA) collects data on streamwater DOC concentrations in several locations within the DRB (Fig. 3.2). However, these measurements are mostly limited to medium to large catchments; land use in these catchments varies so much that it is difficult to draw cause-and-effect relationships between terrestrial condition and aquatic DOC export. The USGS Basic Data program periodically collects total C and sediment data from the Delaware River at Trenton, New Jersey, and from the Neversink River at Claryville, New York.

Table 4.1.—Average carbon uptake after reforestation, by region—includes all forest types and ecosystem carbon pools ($\text{t ha}^{-1} \text{y}^{-1}$)

Age	Southeast	South Central	Northeast	North Central	Rocky Mountain	Pacific Coast
0-5	-1.9	-3.4	-0.2	-0.2	1.3	0.5
6-10	-1.8	-2.0	0.7	0.5	0.4	1.0
11-15	2.2	2.4	0.9	0.7	0.2	1.0
16-20	3.4	4.6	1.4	1.3	0.6	1.9
21-25	4.0	5.0	1.3	1.4	0.6	2.0
26-30	3.4	4.2	1.6	1.6	0.8	3.4
31-35	2.8	3.2	1.5	1.8	1.0	3.4
36-40	2.8	2.8	1.7	1.8	1.6	4.0
41-45	2.1	2.7	1.6	1.8	1.5	3.9
46-50	2.2	2.5	1.6	2.0	2.0	3.7

4.4 Gaps in Evaluation of Forest and Aquatic Carbon Stocks and Fluxes

Although FIA-based forest C estimates are accurate at regional scales, they do contain critical gaps in estimating C stocks and fluxes at smaller scales. Generalized relationships based on geographic region, forest type, and volume must be used to develop estimates of soil and forest-floor C, standing dead biomass, and coarse woody debris. These FIA-based forest C estimates also lack accurate spatially explicit accounting for land use change and other annual dynamics that reflect growth and disturbance.

Important steps have been taken toward addressing these concerns. Studies of dead organic matter dynamics have begun for specific areas, with an eye toward extending them nationwide (Fig. 4.1). Efforts to quantify with more certainty the relationships between tree diameter and tree biomass have yielded a set of national regression equations currently being implemented as part of the USFS national C budget effort (Jenkins et al. 2003). Coarse-

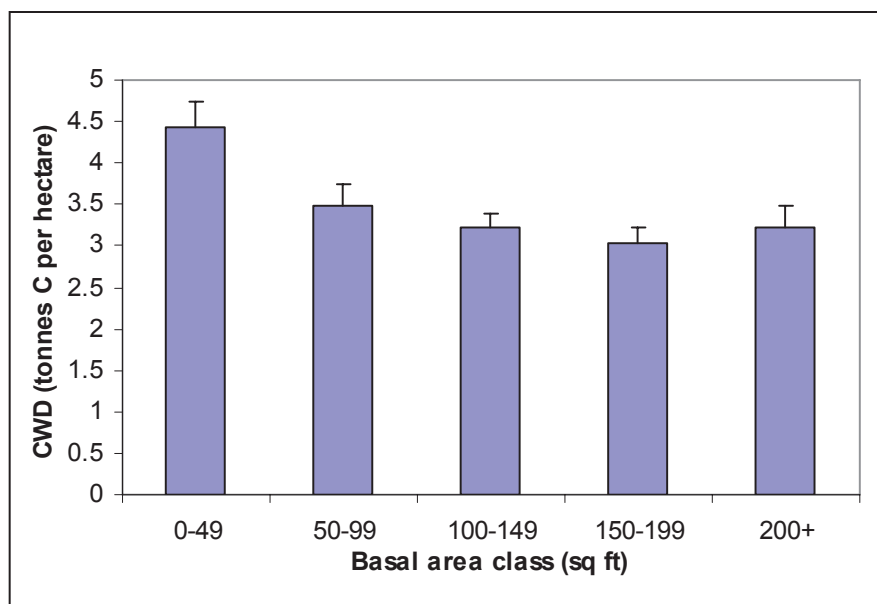


Figure 4.1.—Down coarse woody debris as a function of basal area class for Maine timberlands (Heath and Chojnacky 2000).

Table 4.2.—Key variables and analyses for assessing carbon stocks and fluxes in the Delaware River Basin, by monitoring tier

Tier 1: Intensive sites
Foliar litterfall
Root production
Soil carbon dioxide flux
Relationships between forest type, soil chemistry, and forest carbon stocks and fluxes
Relationships between forest productivity and water quality and quantity
Tier 3: Regional surveys
Forest inventory sample plots: biomass and other forest carbon stock variables
Streamwater organic and inorganic carbon
Tier 4: Remote sensing
Forest species distribution/type (from Landsat Thematic Mapper)
Land cover classification (from Landsat Thematic Mapper)
Satellite-based net primary production estimates (from MODIS)
Fragmentation and historical land use change statistics (from color infrared aerial photos)

gridded estimates of forest biomass and forest NPP have also been developed based on the tree measurements made during the FIA sample (Jenkins et al. 2001) (Fig. 3.3). However, these estimates are limited by what is currently available in the FIA sample: they are based on broad, generalized relationships about quantities such as fine root and litter production, the resolution is still quite coarse, and they do not account for coarse woody debris dynamics, soil C efflux, or soil C stocks and fluxes.

Additional gaps are evident in monitoring the relationships between aquatic and terrestrial resources. Data on aquatic C concentrations in the DRB are limited, and the available data are collected at monitoring stations on medium to large rivers (Ward Hicks, 2000, written communication). Although these medium to large stream C concentrations are influenced by soil C flux from forested landscapes, the number of mostly forested watersheds that could be used to give a signal of the C leaching from forest soil to streams is inadequate for use in regional assessments.

In addition, information about terrestrial processes that control C flux on nonforest land is needed, as streamwater C concentrations in the region are influenced by agricultural and urban/suburban runoff from nonforest land. Forest growth and water quality and quantity are interconnected: a change in one results in changes in the others. However, the lack of data sharing and field collaboration among existing terrestrial and aquatic monitoring programs has limited our ability to track these relationships.

Finally, the science of DOC is still limited: very little is known about the sources, dynamics, and effects of DOC in terrestrial and aquatic systems on a regional scale. An integrated strategy for monitoring this potentially important compound can be achieved only by a multiresource monitoring effort. Our strategy for achieving this important goal is described below.

4.5 The CEMRI Integrated Monitoring Program for Carbon Cycling

Integration of foundation and new data collection programs was tested at two scales—within the IMRAs and for the entire watershed above the stream gauge at Trenton, New Jersey. In each case, supplemental data collection was required at each tier of the monitoring framework to allow for linked terrestrial-aquatic C budgets to be developed (Table 4.2). The integrated data collection strategy is provided here for each monitoring tier.

4.5.1 Intensive Site Research (Tier 1)

At intensive research and monitoring areas (IMRAs), we developed a system for integrating process-level information on C cycling rates with the regionally extensive forest monitoring network and the USGS surface water monitoring programs. At the three IMRAs, plots were established at a finer spatial resolution than in the Tier 3 monitoring programs. At these intensive sites terrestrial variables such as fine foliar litterfall, coarse woody debris stocks, foliar chemistry, and soil C and N stocks were measured. Relationships between these variables and the measurements typically made at FIA plots, such as forest type and basal area, were developed and applied to Tier 3 FIA plots in the region to generate regional estimates of C dynamics. Stream export of C from the watersheds containing these research plots was computed at selected USGS water quality and discharge monitoring stations. The watersheds represented by these stations are nested upstream of large river monitoring stations operated by the USGS NAWQA program, where C flux estimates were also developed.

At the Neversink IMRA site, detailed information about terrestrial C and nitrogen (N) stocks and fluxes was combined with data on deposition, surface water quality and quantity, and soil water quality and quantity collected by the USGS district research program to develop annual input/output budgets for C and N in the Neversink Watershed (Jenkins et al. 2005). Surface water samples were collected at both the nested USGS research and monitoring stations within the Neversink Watershed and the first-order streams that drain the hillslopes containing the FIA forest plots. This combination of the linked-terrestrial/aquatic surveys and the nested-watershed budget approaches tested two different strategies for linking USFS and USGS monitoring data.

Additional Tier 1 assessments of C stocks are associated with the research on forest fragmentation and land use change. This research takes place primarily within the Delaware Gap IMRA and incorporates the monitoring programs of the USGS, USFS, and NPS.

4.5.2 Regional Survey Monitoring (Tier 3)

Information from existing Tier 3 monitoring programs was used to create a large-scale input-output budget of forest C from the full DRB. For this purpose, FIA data from plots falling inside the DRB were analyzed to develop estimates of forest NPP. These were combined with remotely sensed land cover change information and NAWQA data from the Delaware River at Trenton to provide a C input-output budget for the full DRB, integrating terrestrial and aquatic data from the wide variety of land cover types found within the basin.

Regional surveys of first-order streams within the IMRAs and in the Appalachian Plateau Province of the upper DRB were conducted by the USGS as an enhancement of the NAWQA sampling program. The surveys were designed to test linkages between aquatic and terrestrial monitoring for nutrient flux; sampling points were located on the nearest first-order stream to the FIA forest plots throughout the Appalachian Plateau and were thus a random sample associated with the FIA forest plot data. Surveys within the IMRAs were linked to the intensified FIA sampling network. The FIA program also added the collection

of three soil samples at three depths at each FIA plot within the DRB above the Trenton gauge, and these soils were analyzed for total C and N. These data supplement streamwater C concentration data from NAWQA survey stations selected to represent a range of landscape disturbance and development. Data from the IMRA studies were linked to the regional surveys through common sampling and analysis protocols and common parameters measured and through consistent protocols for selecting sampling locations both within and outside of the IMRAs. This information was used to develop the first integrated monitoring plan in the U.S. that can help us understand the relationships between forest productivity, soil C, and water quality and quantity.

4.5.3 Remote Sensing and Mapping (Tier 4)

Remotely sensed information was used to develop an updated land use classification map for the DRB, to assess past rates of land use change in selected urban and suburban portions of the basin, and to develop methods for assessing the contribution of forest fragmentation to forest C dynamics. In addition, the ground-based plot network provided validation data for satellite remote sensing instruments as well as parameterization and validation data for ecosystem process models. Remote sensing indicators for fragmentation and C sequestration were developed at the French Creek and Delaware Gap IMRAs, applied throughout the upper DRB, and tested through ground-truthing at selected FIA plots and associated small watersheds defined by the USGS stream monitoring stations. Validation areas included the stations sampled during the urban gradient survey of the NAWQA program, thus also linking terrestrial and aquatic monitoring within the NAWQA study basins.

4.5.4 Modeling

A modeling approach was used to develop spatially explicit estimates of forest productivity at the regional scale (Fig. 4.2). First, field data collected at Tiers 1 and 2 were stratified into forest types and used to parameterize the PnET-II model to predict forest NPP for each of the forest types (Aber and Federer 1992, Aber et al. 1996, Ollinger et al. 1998). A remotely sensed land cover classification was used to assign forest types to fine-resolution pixels, and the model was then run on a forest-type basis (using the parameterizations developed from the Tier 1 and Tier 3 information) for each individual pixel. In this way, we combined Tier 1, 3, and 4 information in our model parameterization strategy for large-scale C cycle estimation.

A model validation step was part of the CEMRI strategy in the DRB. Carbon cycling data (such as foliar litterfall and soil CO₂ flux) collected at IMRAs, as well as at a separate set of randomly chosen forest plots in the Allegheny Plateau, were compared against the PnET predictions developed using the parameterizations described above. As part of the NASA-funded C cycling initiative, we also used CEMRI field data to validate NPP predictions from NASA's new MODIS sensor, a high-spectral remote sensing instrument developed to provide real-time measured information about forest processes (Pan et al. 2006). For this part of the study we used a different variant of the PnET family of models, PnET-CN (Pan et al. 2004).

4.6 Preliminary Results

We combined integrated measurement and monitoring of vegetation, soil, and water with process and empirical models to estimate C stocks and dynamics of the DRB. At the largest scale of the whole river basin, we used remote sensing (Tier 4) and data from existing sample plot networks maintained by the USFS and USDA Natural Resources Conservation Service (Tier 3). We used estimators from the FORCARB-2 carbon accounting model to estimate basinwide change in forest C stocks (Smith and Heath 2005). At the IMRA scale, we added land and water measurements to existing intensive monitoring sites maintained by the USGS

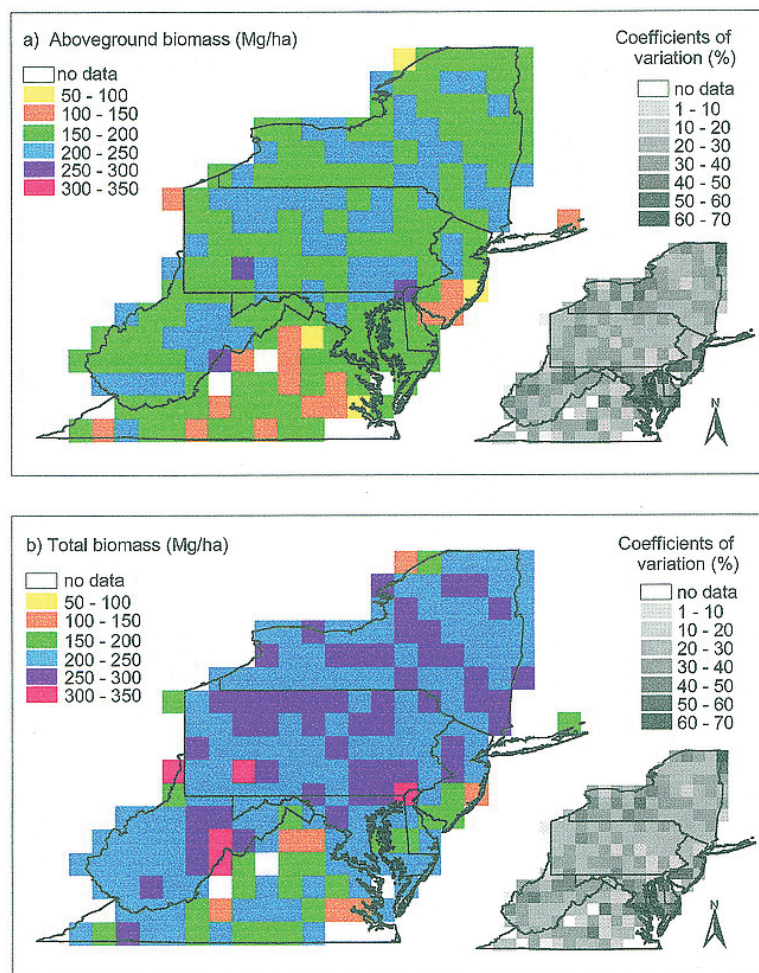


Figure 4.2.—Estimates of carbon cycling rates for the mid-Atlantic region (USA) at the 0.5 scale developed from Forest Inventory and Analysis data (coefficients of variation calculated from data for the plots falling within each 0.5 degree grid cell). A) Aboveground biomass. B) Total net primary productivity (aboveground plus belowground).

and the NPS and we estimated complete land and water C budgets. At an intermediate scale, we used remote sensing and intensive sampling of selected small watersheds that had contrasting conditions defined primarily by degree of residential development. At all scales, we used the PnET-CN ecosystem process model to estimate and map biomass and productivity, and the SPARROW empirical model to estimate C transport by water. Initial results show the basin is a small net C source, although within the basin, southern areas are losing C while northern areas are gaining C primarily because of historical patterns of land use change (Table 4.3). Initial estimates of transfer of C via streams show small quantities relative to uptake by trees.

Table 4.3.—Total stock of carbon, and change in carbon stock by forest type, in teragrams, 2000

Forest type	Total carbon	Change since 1990
White/red/jack pine	13.0	-25.4
Spruce-fir	1.8	-0.3
Loblolly pine	8.8	-6.4
Eastern redcedar	0.1	0.1
Exotic softwoods	1.1	0.0
Oak-pine	13.4	-7.0
Oak-hickory	165.6	8.4
Oak-gum-cypress	5.2	-1.2
Elm-ash-cottonwood	17.3	-3.2
Maple-beech-birch	188.0	28.1
Aspen-birch	4.1	-0.2
Nonstocked	1.0	1.0
Total	419.4	-6.0