A METHODOLOGY TO ESTIMATE CARBON STORAGE AND FLUX IN FORESTLAND USING EXISTING FOREST AND SOILS DATABASES

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Abstract. Sequestration of carbon through expansion and management of forestland can assist in reducing greenhouse gas concentrations in the atmosphere. Quantification of the amount of carbon presents an ongoing challenge that calls for new approaches. These new approaches must seek to simplify the science-based accounting of carbon storage and flux, while adhering to general principles of greenhouse gas accounting. Quantifying change in carbon storage and carbon flux consists of two steps: developing a baseline of carbon storage, and measuring resulting storage and flux following a change of conditions. A methodology is proposed that accomplishes both steps, applicable to an aggregate-level analysis using the state of Iowa (United States) as a case study. The method combines existing databases from the U.S. Forest Service (USFS) and U.S. Department of Agriculture (USDA), and merges these with the methods of Birdsey (USDA, 1995 and 1992); (IPCC, 1997); (EIIP, 1999) for partitioning carbon stocks into storage pools. Forested ecosystems in the study area contain approximately 137.3 metric tons organic carbon per hectare, or 114 million metric tons of carbon in aggregate. Of this total, 44.8 million tons are stored in biomass tissue, and 69.2 million tons of carbon are contained in soils. Carbon flux due to forests in the state of Iowa is estimated to be a net annual sequestration (removal from the atmosphere) of 4.3 million metric tons of CO_2-equivalent, approximately 5 percent of the net annual CO_2-equivalent emissions from the state (Ney et al, 1996).

Keywords: baseline determination, carbon sequestration, greenhouse gas, GIS, verification.

Brief title for running head: **Computing Forest Carbon Flux from Existing Data Sources**

1. Introduction

There are significant, historical stores of data describing soils and forestland that have been collected and maintained by the USDA and USFS. Traditionally these data were collected to estimate soil productivity for agricultural purposes, or for quantifying the forest resource available for timber harvest. However, increases of atmospheric greenhouse gases and the potential consequences of future climate change have generated interest in understanding and quantifying the role of terrestrial ecosystems in the carbon cycle (Birdsey, 1995). Forest ecosystems are capable of storing large quantities of carbon in trunks, limbs, roots, and soil, providing an important terrestrial sink for carbon dioxide (IPCC/UNEP/OECD/IEA, 1997). Conversion of forests to other land uses can result in net emissions of CO_2, while forest regeneration will, over time, result in uptake (Pulliam, 1996); (Fan et al, 1998). This, combined with the increase in total forest area in the United States over the past century, indicates the significance of forest resources in addressing the balance of greenhouse gas emissions. This study seeks to describe a mechanism for utilizing these existing data stores to quantify the amount of carbon sequestered by forestlands, and which, by extension, might provide tools for verifying greenhouse gas removals from current and future forest expansions. The state of Iowa is selected as a case study because it of a wealth of data on its soils and forestland, and because growth trends in Iowa forest area are believed to mirror the regeneration and expansion of forests across much of the United States.

During the 1800s prairie was the most common form of vegetation in Iowa, with forest vegetation present in the eastern valleys and along the major streams in other parts of the state (Oschwald *et al*., 1965). In the 1850s there was approximately 2.75 million hectares of forestland among Iowa's 14.6 million hectares. Deforestation progressed at a rapid rate as Iowa's rich soils were converted to agricultural production. By 1974 total forestland in Iowa stood at 0.6 million hectares. Since 1974, there has been slow, steady growth of Iowa forestland to nearly 0.85 million hectares of forestland. Figure 1 portrays the forest area of the state in the interim period of 1984, at 0.7 million hectares. Even with the return of forest area, Iowa remains one of the most environmentally altered areas of the United States, with 90% of its land in agriculture, 75% of its forests cleared, 95% of its wetlands drained, and over 99% of its original prairies vanished (Ney *et al*., 1996).

It has been said that there is insufficient data available to confidently estimate the impact of disturbance of forest ecosystems on C dynamics for major forest types in the U.S. (Serita, 1996), so there is a need to access and collate existing data into a comprehensive database to be used for evaluation of alternate land use practices. The purpose of this study is to complete the computation of annual carbon storage increments resulting from forest management and land use changes, using existing data structures. These databases have long existed in parallel. However, it is shown that they can be combined in order to establish baseline inventories of above- and below- ground carbon storage, to provide quantification of sequestration rates over an historical period, and to offer insights into methods of verifying future removals of carbon dioxide from the atmosphere.

2. Computing Forest Carbon Storage by Compartment

One of two basic approaches can be utilized for estimating carbon storage resulting from land use change. These methods are the stock approach, where standing stocks are estimated at two separate points in time, and the flow approach, where annual changes in forest carbon are estimated by comparing fluxes of carbon into and out of the forest area (EIIP, 1999 and IPCC, 1995). Under both approaches, all carbon removed from the forest area is assumed to be emitted to the atmosphere at the time of removal, resulting in an underestimate of the net removal of carbon from the atmosphere, by neglecting to credit carbon that is stored in wood used for long-term products, such as home construction. It is left to the verifier to decide which approach is to be applied, often with data availability being the determining factor. For development of our methodology, the 'stock approach' method best fits available data sets, and therefore forms the core of our approach.

2.1 Above-Ground Carbon in Trees

The stock approach was applied to data from forest timber inventories of 1974 and 1990, conducted in Iowa by the U.S. Forest Service (Spencer *et al*., 1980 and Brand *et al*., 1991 and U.S. Forest Service Inventory and Analysis (FIA) database (online query)). Total forestland area is categorized into timberland, reserved timberland, and other forestland. Timberlands are then further distinguished by forest or tree-type and are reported by USFS on a per county basis. Table I presents a summary of the coverage of each forest type within the study area (Iowa), for 1990. Comparison of these simple forest inventories between 1990 and 1974 does not provide enough information to complete calculations of carbon storage on forested lands. Following the methods of greenhouse gas accounting described by IPCC (and summarized by the Emission Inventory Improvement Program (EIIP) of US EPA), the total volume of merchantable timber of at least 12.7 cm diameter at breast height (d.b.h.) is also obtained from the USFS database, by forest type, by county. Following the methodology described by Birdsey and incorporated by IPCC and EIIP, this value must then be combined with expansion ratios, to convert the volume of merchantable timber into total tree biomass volume. Table II describes the expansion ratios for the Central Region of the United States, applicable to the case study area.

Total tree biomass volume is then converted to a mass basis by utilizing the specific gravity of each tree- or forest-type. Finally, the carbon mass is calculated using an average percent carbon for each tree or forest type (Birdsey, 1992). Equation 1 illustrates computation of a conversion factor that derives total carbon (metric ton C) from merchantable timber (m^3):

$$((TER_S \text{ x } BCF_S \text{ x } R_S)+(TER_H \text{ x } BCF_H \text{ x } R_H)) \text{ x } 0.001 = FACTOR \quad (1)$$

where,

- TER = total above- and below-ground biomass for all live and dead trees (m^3)/ total volume of merchantable timber (m^3) (expansion ratio)
- BCF = biomass conversion factor, biomass density on a dry weight basis (kg C)/total volume tree biomass (m^3) (BCF=specific gravity * 1000 kg/m^3 (water) * % carbon)
- R = fraction of hardwood or softwood per type/total volume of merchantable timber (m^3)
- $_S$ and $_H$ denote softwood and hardwood respectively
- 0.001 = weight conversion ratio (metric tons C/kg C)

Table III presents the resulting 1990 estimate of above- and below-ground carbon storage pools computed through application of equation 1 and the USFS inventory data for the case study area.

2.2 Above-Ground Carbon in Forest Understory and Floor

Following the methods of Birdsey, IPCC and EIIP, the amount of carbon stored in the living and dead plant tissues of the understory and floor is also estimated. The forest floor is defined as “all dead organic matter above the mineral soil horizons, including litter, humus, and coarse woody debris.” (Birdsey, 1992). Understory vegetation consists of all live vegetation within the forest, exclusive of trees. While it is recognized that these pools often represent short-term storage of carbon in active flux from either tree or soil to a different condition (such as atmospheric CO_2), by utilizing the stock approach these pools can be estimated and measured against the same pool size from the earlier stock period. Birdsey again provides estimated forest floor carbon storage values by forest type. Table IV provides these values, as well as the resulting estimates of the forest floor carbon pool for the 1990 data set. The understory carbon pool is more difficult to ascertain. Birdsey assumed that there was no carbon in the understory at forest age 0, that it peaked at forest age 5, and that it reached a reference level estimated equal to 2 percent of carbon in the overstory by age 55. The difficulty lies in determining the age of each parcel of forestland. For purposes of this study, and the relatively small contribution of overall carbon storage contained in the understory, it will be assumed that the reference value of 2 percent of overstory carbon is applicable. This assumption should be a conservative one, in that nearly 25 percent of the forestland in the study area is less than 16 years old, thus being closer to the peak (5 years) rather than the reference value (55 years). Using this method, total understory carbon storage in the study area is estimated to be 559,369 metric tons in 1990.

3. Computing Soil Carbon Storage Attributable to Forests

The Birdsey/IPCC/EIIP methodology relies upon a regression model to predict the amount of carbon contained in soils beneath U.S. forestland. As in the case of estimating carbon storage in understory, assumptions were made concerning the age of forest and the timing of peak soil carbon accumulation (55 years).

3.1 Baseline Estimation

The USDA soil sampling databases, SSURGO and STATSGO, were utilized to develop a baseline of soil carbon content, with STATSGO providing the primary information for soil carbon analysis. These databases present sampled organic matter contents and soil dry bulk densities, which allow computation of soil carbon content for each polygon represented in the GIS presentation of the databases. The soil surveys upon which the databases were constructed vary in date from 1919 through 1996, with a majority occurring prior to 1990. The STATSGO database can therefore serve as a rough approximation of baseline conditions for 1974. The carbon contents predicted by the Birdsey regression model will serve as estimates of 1990 soil conditions. Comparison of the two values will provide a measure of soil carbon accumulation due to the increase in forest area.

3.2 Calculation Methods

In the STATSGO database, the properties of multiple soil layers of varying depths are provided from the soil surveys. In order to calculate the carbon contained in the upper-most 30 centimeters (the requirements most frequently discussed for inclusion under the Kyoto Protocol) layers of soil data were combined and their properties combined and scaled to the required depth. The calculated 30-cm carbon values were then returned to the STATSGO GIS database as represented by Figure 2.

There is a pattern of increasing carbon in soil in northern and north-central Iowa, with values between 123.5 and 20 metric tons per hectare. The landscape originated from glacial deposits of the Des Moines lobe, and the principal surface material there is loam till. Glacial drift and loess deposits each served as the origin for about 40% of Iowa soils. The loess-derived soils are some of the most productive soils in the state (Anderson, 1983), and are used predominantly for agricultural purposes. Computation from the STATSGO database estimates an average Iowa soil carbon content of 70.7 metric tons carbon per hectare. The regression model predicts an average soil carbon content of 83.4 metric tons per hectare for central region forestland (Birdsey, 1992). With our assumption of STATSGO data as an approximate 1974 baseline value, it is inferred that the Iowa forestland added 12.7 metric tons of carbon per hectare from 1974 to 1990.

3.3 Formatting Output for Consistent Geographic Representation

Polygons from the STATSGO soils database do not neatly match the county-wise presentation of the forestland data. Further manipulation was required to derive 30-cm soil carbon values on a per-county basis for comparison with county-wise forestry figures. The 30-cm soil carbon value for each polygon was assigned to its county location. The average county soil carbon content was achieved by weighting the individual polygon soil carbon values according to the area contained in each polygon. Figure 3 presents average 30-cm soil carbon content beneath forestland, by county.

3.4 Improving Precision

The SSURGO database can also be employed to examine the sensitivity of the methodology for use on a more precise scale. On the detailed Polk county map (Figure 4), one can observe details of carbon content in soils. The average carbon concentration is approximately 76.6 tons per hectare, with lowest values localized around urban areas (Mancuso and Schnoor, 1999). Future efforts beyond this study may employ advanced GIS skills to match the forest land-use polygons (Figure 1) with the detailed soil polygons (Figure 4) to produce more robust carbon storage estimates at finer levels of detail.

3.5 Creating the GIS Presentation

The GIS presentation of above and below ground carbon storage in Iowa was accomplished using the following GIS data:

1) State Soil Geographic (STATSGO), Data Base for Iowa (1994), U.S. Department of Agriculture (USDA), National Cooperative Soil Survey (NCSS), Soil Conservation Service (SCS). Source scale was 1:250,000, based on the National Map Accuracy Standard for 1:250,000 maps. The best case accuracy would be 127 meters (USDA/NCSS/SCS, 1994).

   To make a detailed map of an individual county, we used the Soil Survey Geographic (SSURGO) Data (1998), Polk County, U.S. Department of Agriculture (USDA), National Cooperative Soil Survey (NCSS), and Soil Conservation Service (SCS). Source scale was1:24,000. The accuracy would be about 2 acre (USDA/NCSS/SCS, 1998).

   Using STATSGO and SSURGO database, we presented soil carbon storage maps (metric tons/acre). Carbon storage on the first 30 cm of soil was calculated using the GIS database including layer thickness, bulk density and percent of organic matter.
2) COUNTY (1990), Iowa Department of Natural Resources. Source scale was 1:24,000. The accuracy is 22 meters (IDNR, 1990). On this map, we displayed above ground carbon storage (tons/acre) and the values for carbon emission or

sequestration by county (metric tons/yr).

The numerical data for carbon storage for each county and polygon were estimated and entered into GIS database format using a combination of Microsoft Excel and ESRI's ARCVIEW 3.2 programs. ARCVIEW was utilized to produce output maps. Figure 5 provides a schematic of the methodology.

4. Results and Discussion

4.1. Carbon Storage in the Study Area

As of 1990, using the methodology in this paper, it is estimated that forest ecosystems in Iowa contain approximately 114.0 million metric tons of carbon above and below the ground, representing about 0.14% of all the carbon stored in U.S. forest (Birdsey, 1992). The area of Iowa forests was 0.83 million hectares in 1990, or 0.28% of U.S. forest area (Powell *et al*., 1993). The amount of forestland, 5.7% of the total land area in Iowa, has increased by approximately 0.23 million hectares between 1974 and 1990 (Brand *et al*., 1991). These changes represent an increase in forest area of approximately 2% per year.

Forests are ecosystems with several components, with each acting as a carbon storage pool: trees (providing above- and below-ground carbon), understory vegetation, forest floor and soil. The average forest in Iowa contains 137.4 metric tons organic carbon per hectare. Trees, including tree roots, account for 27% of all forest ecosystem carbon. Live and standing dead trees contain 32.3 million metric tons of carbon (above- and below-ground), an average of 38.9 metric tons per hectare. The largest carbon storage pool within Iowa forestland is the soil, which contains 69.2 million metric tons of carbon, 83.4 metric ton per hectare. On the forest floor and in understory is found 11.9 and 0.6 million metric tons of carbon, respectively. Figure 6 illustrates the average carbon distribution among the carbon storage pools, per hectare of Iowa forest.

4.2 Carbon Storage by Forest Type

There are differences in carbon storage between forest types (Table V). The highest values are found in Oak-hickory forests, with 61.85 metric tons C/hectare stored above ground, and 152.6 metric tons/hectare in total above and below ground storage. The oak-hickory forest covers more area than any other forest type in Iowa (37%) (Leatherberry *et al.*, 1992), accumulating 46% of the total carbon stock (Table V).

4.2 Conversion of Stock Change to Annual Carbon Flux

In accordance with use of the stock approach, greenhouse gas fluxes are estimated by totaling carbon stocks at two points in time, 1974 and 1990, with the difference between the two points divided by the number of intervening years. The approach produces an average value for annual carbon sequestration during the period. Total carbon stocks for each endpoint were subdivided into four forest ecosystem components: trees, understory, floor and soil. As a result of biological process and anthropogenic activities, carbon is cycled though these forest components, as well as between the forest and the atmosphere. The net change is in the amount of carbon stored in each of these pools over time (EIIP/U.S. EPA, 1998). A net increase in forest carbon stock represents net CO_2 uptake and a net sequestration of CO_2 emissions. From 1974 to 1990, timberland area in Iowa increased 33%. Most of the new forestland came from pasture areas no longer grazed (Brand *et al.*, 1991). Changes in Iowa forest stocks and land-use during this period were estimated to account for a net annual sequestration of 1.2 million metric tons carbon, or 4.5 million metric tons of CO_2–equivalent per year (Table VI). Thus the methodology estimates that an average of 4.5 million metric tons of CO_2-equivalent is removed from the atmosphere annually over the period 1974 – 1990 by the growth of existing forests and the expansion of forestland. To compute this value, the difference in carbon storage for the tree (above- and below-ground), floor and understory pools that results from the stock change between 1990 and 1974 was divided evenly over the 16-year interval. Changes in soil carbon content of 12.7 metric tons per hectare, as quantified by subtracting the STATSGO baseline from the Birdsey regression prediction, was assumed to occur beneath all acreage, and was also divided over the 16-year period.

4.3 Results by Political Unit

As described in section 3.3 above, the procedure also provides the capability of analyzing changes in carbon stock by county, within the study area. Both stock change and average annual flux were analyzed. In eight of the ninety-nine counties, decreases in forest area led to net emission of CO_2 to the atmosphere. However, improvements in management practices could increase carbon sequestration in counties with reduction in their forest areas. This is the case for Harrison county, which between 1974 and 1990 decreased the forested area by 2,000 acres, but increased above-ground carbon storage by 16.1 tons/hectare. Figure 7 depicts estimated carbon fluxes per county for the period 1974-1990.

4.4 Remaining Uncertainties

The U.S. Forest Service does not estimate standing stocks of non-forest trees (e.g., urban trees), and some forested land areas that have restricted access. The annual change in forest stocks and in forest acreage was estimated based on the net change over several years, without considering year-to-year variability. Soil polygons from the STATSGO database do not neatly follow geographic borders. Thus assignment of polygons to a county (performed by USFS) may over- or under-estimate the actual land area of the county, which through the area-weighting methodology could introduce error in the county-wise soil carbon figure.

5. Conclusions

A methodology was demonstrated to document carbon storage due to land use change, using existing databases and GIS technology. This work has shown that between 1974 and 1990, carbon stored on Iowa forestland (above- and below-ground) has increased an average of 1.2 million metric tons carbon (4.3 million metric tons CO_2) annually. The geographic representations of forest area and soil carbon contents, can be combined to provide enough information to estimate net changes in carbon sequestration rates. Continued refinement of the GIS databases, with improved resolution, could soon lead to the ability to verify project-specific carbon storage and fluxes on township, or even farm scale. Such quantifications can be made in accordance with international guidance related to trading of greenhouse gas emissions for the purposes of meeting commitments of the Kyoto Protocol or subsequent international agreements to address global climate change.

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List of Figure Captions

Table I. Area Coverage by Forest Type, 1990[1]

Forest Type		Area (ha)	Area (% of forest)
Timberland			
	Loblolly-shortleaf pine	9,231	1.11
	Oak-pine	9,636	1.16
	Oak-hickory	361,296	43.53
	Elm-ash-cottonwood	201,457	24.27
	Maple-beech-birch	190,972	23.01
	Aspen-birch	4,777	0.58
	Non-typed	850	0.10
	Others[2]	8,623	1.04
Reserve/Other Forestland		43,198	5.20
All Forest Land		830,040	100.00

[1] Data from USFS, 1990.

[2] Non-specified tree types

Table II. Ratio of Total Volume to Merchantable Volume for the Central Region

	Above-Ground Ratio	Below-Ground Ratio
Softwood Species	2.159	0.170
Hardwood Species	2.240	0.155

From Birdsey, 1992

Table III. 1990 Above- and Below-Ground Carbon Storage in Iowa Forestland (metric ton C)

Forest Type[1]	Above-Ground	Below-Ground	Total
Loblolly-shortleaf pine	111,436	18,178	129,614
Oak-pine	146,523	23,711	170,234
Oak-hickory	17,119,743	2,654,243	17,773,986
Elm-ash-cottonwood	8,030,401	1,245,099	9,275,500
Maple-beech-birch	2,435,735	378,232	2,813,967
Aspen-birch	115,860	17,975	133,835
Others	8,739	1,355	10,094
TOTAL	27,968,437	4,338,792	32,307,229

[1] Forest type classification from FIA (USFS).

Table IV. The 1990 Forest Floor Carbon Storage Pool by Forest Type (metric ton C)

Forest Type[1]	Carbon (kg/ha)	Total (metric ton C)
Loblolly-shortleaf pine	25,838	294,520
Oak-pine[2]	19,666	190,027
Oak-hickory	13,495	4,885,956
Elm-ash-cottonwood	13,495	2,724,157
Maple-beech-birch	18,669	3,572,494
Aspen-birch	18,669	89,283
Others	13,495	99,366
TOTAL		11,855,804

[1] Forest type classification from FIA (USFS)

Table V. Carbon Content by Forest Type (metric ton C/hectare)

Forest type	Above ground[1]	Below ground[2]	Total
Loblolly-shortleaf pine	38.21	85.39	123.60
Oak-pine	35.20	85.88	121.08
Oak-hickory	61.85	90.75	152.60
Elm-ash-cottonwood	54.19	89.59	143.78
Maple-beech-birch	31.71	85.39	117.10
Aspen-birch	43.47	87.17	130.64
Others	14.75	83.58	98.33

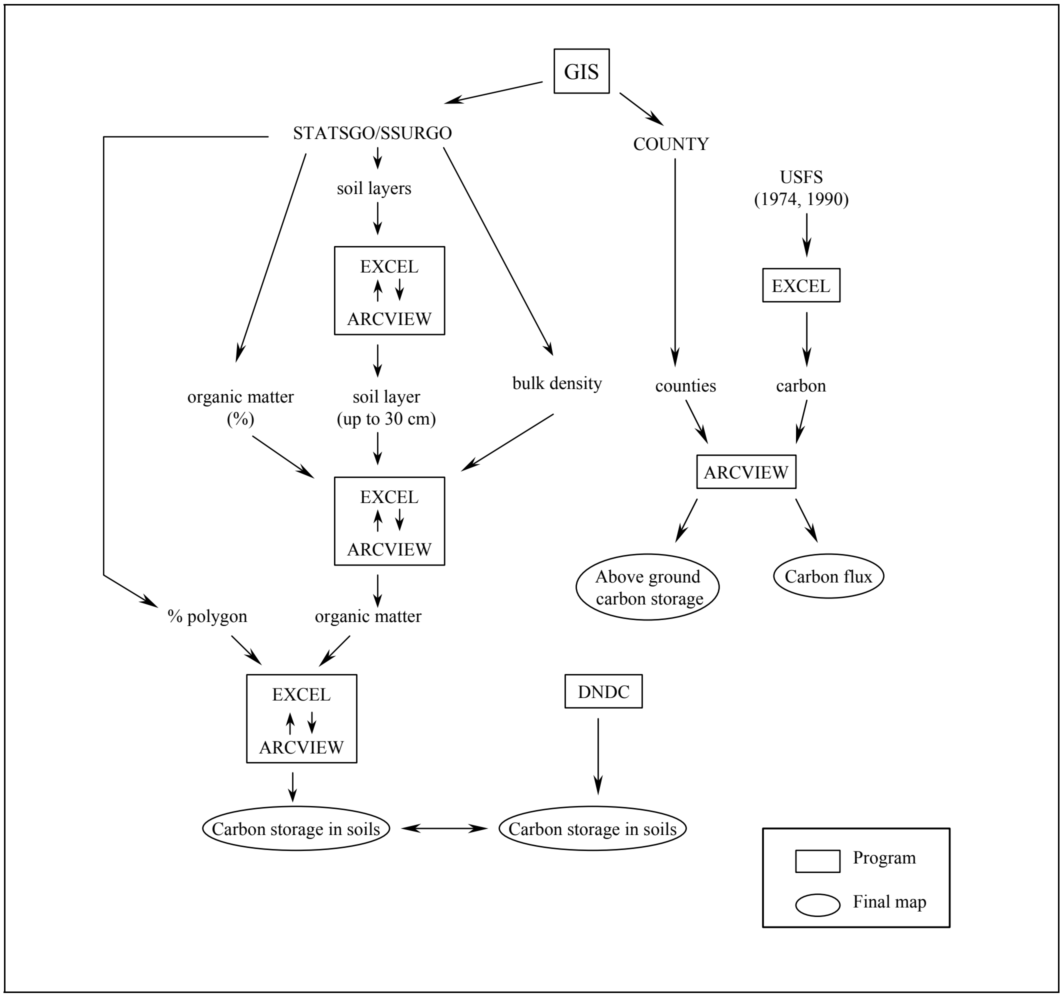
[1] includes tree, understory and floor

[2] includes tree roots and soil

Table VI. Change in Forest Area and Apparent Average Annual CO_2 Flux (1974-1990)

Forest type[1]	Change in Area 1990 - 1974	Avg CO_2 Flux[2]
	(hectare)	(Metric ton/yr)
Loblolly-shortleaf pine	+2,109	-52,577
Oak-pine	+3,452	-57,904
Oak-hickory	+48,251	-1,818,430
Elm-ash-cottonwood	+56,885	-1,374,173
Maple-beech-birch	+79,290	-1,169,002
Aspen-birch	+1,855	-33,989
Others[3]	+6,093	-36,577
All forest land	+197,935	-4,542,653

[1] Forest type classification from FIA (USFS).
[2] CO_2 emission: positive value. CO_2 uptake: negative value.


GIS
STATSGO/SSURGO
COUNTY
soil layers
USFS
(1974, 1990)
EXCEL
ARCVIEW
EXCEL
organic matter
(%)
soil layer
(up to 30 cm)
bulk density
counties
carbon
ARCVIEW
EXCEL
ARCVIEW
Above ground
carbon storage
Carbon flux
% polygon
organic matter
EXCEL
ARCVIEW
DNDC
Carbon storage in soils
Carbon storage in soils
Program
Final map