State of Wisconsin
Department of Administration
Division of Energy

Environmental Research Program

Final Report

April 2004

Quantifying Carbon Storage in Wisconsin Forests

Prepared by:
Elliot Campbell, Graduate Student
Jeremie Moen, Information Technology Support
Prof. Jerald L. Schnoor, Co-Director
Center for Global and Regional Environmental Research,
The University of Iowa, Iowa City, Iowa
Dr. Richard A. Ney, Senior Environmental
Sebesta Blomberg & Associates, Inc., Iowa City, Iowa

This report in whole is the property of the State of Wisconsin, Department of Administration, Division of Energy, and was funded through the FOCUS ON ENERGY program.

focus on energy[sm]
The power is within you.

EXECUTIVE SUMMARY

Date of Report April 15, 2004

Title of Project Quantifying Carbon Storage in Wisconsin Forests

Investigators

- Jerald L. Schnoor- Professor, Department of Civil and Environmental Engineering; Co-Director, Center for Global and Regional Environmental Research, The University of Iowa
- Dr. Richard A. Ney- Senior Environmental, Sebesta Blomberg & Associates, Inc.
- Elliott Campbell- Graduate Student, Center for Global and Regional Environmental Research, The University of Iowa
- Jeremie Moen- Information Technology Support, Center for Global and Regional Environmental Research, The University of Iowa

Research Category Carbon Sequestration/Greenhouse Gas Emissions- Carbon and Greenhouse Gases Inventory

Project Period Fiscal Year 2002-2003

Object of Research

State-level greenhouse gas emission inventories typically have done a good job of capturing energy-related emissions, but could use improved information concerning the carbon sequestration benefits that accrue within natural systems. The object of our research is to quantify these benefits in Wisconsin's forestlands.

Our primary goal is to determine the volume and annual change of carbon stocks in Wisconsin forestlands. To communicate these results, we provide gross statewide and mapped regional values for soil carbon and biomass carbon. Quality assurance is another goal that we seek to achieve by validating our methodology against published carbon sequestration results for different regions and methodologies.

Summary of Results/Accomplishments:

We designed a relational database to calculate the baseline carbon stocks using published methodologies and data from the U.S. Department of Agriculture and the Wisconsin Department of Natural Resources (WDNR). Soil organic carbon (SOC) was computed from soil surveys of the USDA State Soil Geographic (STATSGO) database. The SOC results were mapped (Figure 1) and overlayed onto a Wisconsin land cover map obtained from the WDNR. The baseline forestland soil carbon density was calculated for each forest type, and the overall average was 48 metric tons/hectare. Baseline forest soil carbon was calculated as 262 million metric tons of carbon (MMTC) for soil depths up to 1 meter and 160 MMTC for soil depths up to 25 cm.

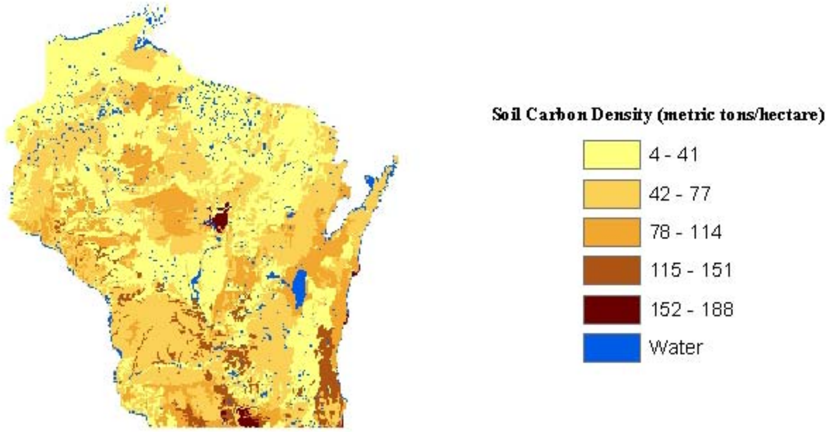

Figure 1. Statewide soil carbon density (metric ton/hectare) for soil depths to 1 meter.

We calculate annual soil carbon stocks by multiplying the baseline density results by U.S. Forest Service Forest Inventory Analysis (FIA) forest type areas for 1983, 1996, and 2001. Soil stocks are 277 MMTC, 290 MMTC, and 288 MMTC for 1983, 1996, and 2001 respectively. A linear regression indicates a net increase in forest SOC of 0.7 MMTC/yr. It is important to note that these changes are due to a transfer between land types in addition to a transfer from the atmosphere to the soil. These validated results are significantly different from results for Wisconsin from outdated methodologies that have been published and recently sited.

The relational database was also designed to automate tree biomass carbon calculations based on biomass volume data from the FIA program. Forest biomass carbon was calculated at 283 MMTC, 345 MMTC, and 350 MMTC for FIA data from 1983, 1996, and 2001 respectively. This represents a net annual biomass sequestration of 4 MMTC per year. Sequestration rates are summarized by county in Figure 2. The biomass sequestration represents a transfer of carbon from atmospheric CO_2 to forest biomass and is 11% of electricity greenhouse gas emission in Wisconsin in 2000.

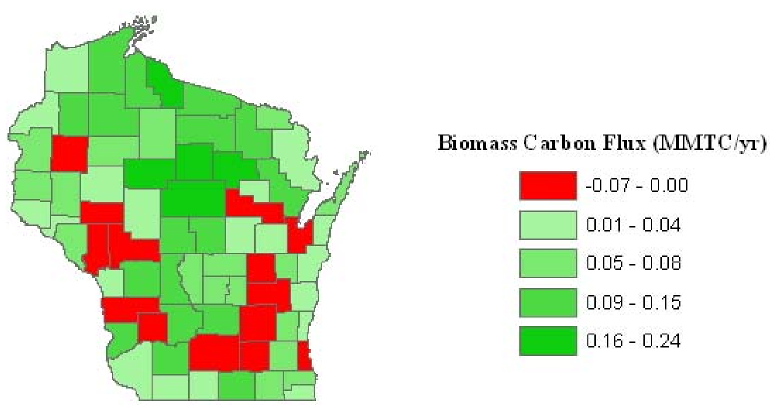

Figure 2. Biomass carbon flux (MMTC/year).

Results are verified through quality assurance measures including comparison with published results from related studies, edge matching of maps, and comparison of

SOC results with known geologic trends. The project goals of quantifying and validating forest carbon in Wisconsin were achieved. Work progressed in line with the original schedule.

TABLE OF CONTENTS

1.0 INTRODUCTION

As the world draws nearer to addressing the prospect of global climate change, greenhouse gas emitters, principally electric utilities, will need to have access to low-cost means of reducing net emissions to the atmosphere. Terrestrial sequestration of atmospheric carbon in forestlands is a viable method for offsetting emissions from the generation and/or transmission of electricity, but quantifying these benefits remains challenging.

Terrestrial ecosystems are estimated to contain nearly twice the amount of carbon held by the atmosphere. The atmospheric pool contains approximately 750 billion metric tons of carbon (Schimel 1995), while terrestrial soils contains 1200 to 1600 billon metric tons (Schlesinger 1997), and 610 billion metric tons in biomass (Schimel 1995). Attempts to balance the input and output of carbon between the atmosphere, terrestrial ecosystems, and the ocean have revealed a “missing sink” (Houghton, Davidson et al. 1998). This sink is likely to exist in the soils and biomass of the Northern Hemisphere (Pacala, Hurtt et al. 2001). A better understanding of carbon stocks and changes in Wisconsin can contribute to our attempts to balance the carbon cycle.

The ongoing trend of increasing sequestration as forest area increases within the United States has been recognized as providing potential for significant sequestration of carbon. Approximately 46% of Wisconsin’s 35 million acres is forested. This area, primarily in the northern region of the state, has been increasing since 1968, due to conversion of marginal agricultural land back into forests. Since 1983, forestland has increased about four percent, or 640,000 acres (WDNR 2003). Improved estimates of state-level forest carbon sequestration could be useful in developing greenhouse gas emission inventories.

The rate of sequestration can become important for both the state and private forest owners as actions are undertaken within the United States to reduce net greenhouse gas emissions. As a result of the information provided by this project, the state of Wisconsin will possess a tool for analyzing future forest management policy and its impact on statewide sequestration of carbon. Knowledge of the magnitude of forest carbon sequestration and of methods to improve sequestration rates will provide Wisconsin with the ability to at least partially address growing emissions of carbon from electric utilities, as well as from the industrial and transportation sectors.

The research presented in this report quantifies carbon stocks and trends in soil organic carbon (SOC) and biomass of Wisconsin forestlands. Published methodologies are applied to existing data sets including the Natural Resources Conservation Service (NRCS) State Soil Geographic (STATSGO) database, the Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND) Land Cover Data, the U.S. Forest Service (USFS) Forest Inventory Analysis (FIA) data, and the NRCS Natural Resources Inventory (NRI).

Overall results indicate annual carbon accumulation in forestlands of 0.7 million metric tons of carbon (MMTC) per year in soils and 4 MMTC/yr in biomass. This is approximately 13% of greenhouse gas emissions from electricity generation in Wisconsin in 2000 (Kerr 2004). The following sections of this report provide a methodology for estimating carbon in forestlands, a summary of statewide and mapped results, and a discussion of the implication of these findings.

2.0 METHODOLOGY

Forest carbon stocks and trends are estimated separately for SOC and biomass. While standardized methodologies have not been created for carbon sequestration measurements, the methods outlined in this section are based on state of the art techniques published in peer reviewed journals.

2.1 SOIL METHODOLOGY

To quantify soil organic carbon (SOC) stocks and trends beneath Wisconsin forestlands, we used a technique that applies GIS tools to geospatial data sets from the U.S. Department of Agriculture (USDA) and the Wisconsin Department of Natural Resources (WDNR). This approach uses soil survey data and land cover data to estimate baseline soil carbon stocks. Changes in soil carbon over time are calculated by applying land use change information to our baseline estimates.

2.1.1 Baseline SOC Stock

Baseline SOC stocks in forestlands are calculated from geospatial data from soil surveys and land cover satellite imagery. Soil survey data and GIS coverage for Wisconsin were obtained from the USDA Natural Resource Conservation Service (NRCS) State Soil Geographic (STATSGO) database. STATSGO was compiled at 1:250,000 and designed to be used primarily for regional, multi-state, state, and river basin resource planning, management and monitoring. We downloaded the most recent STATSGO coverage and attribute data for Wisconsin from the NRCS website in July 2003. This data set was last processed in 1994.

The STATSGO data is based on three levels of organization: map unit, component, and layer. Each of Wisconsin's 128 different map units represents a collection of polygons (Figure 3) that have similar landscape areas and have the same kind of component soil. Each map unit is broken down into up to 21 areas called soil series components. Each component is further divided into layers of soil of distinct depths.

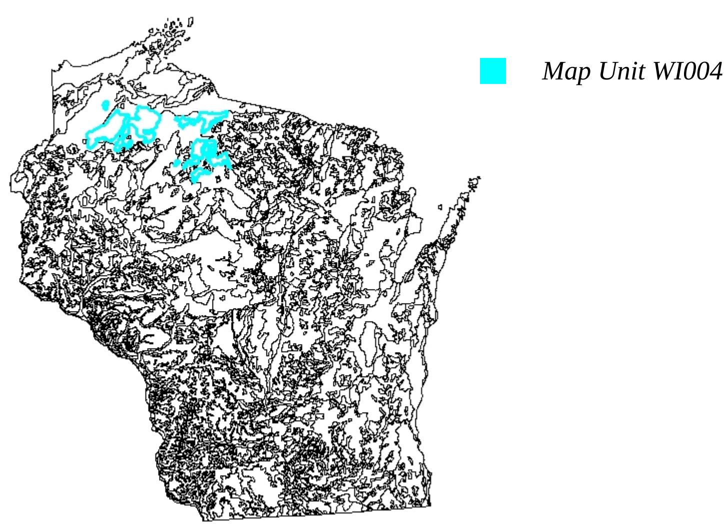

Figure 3. Outline of a single map unit from the STATSGO Wisconsin coverage.

A geospatial database was designed to store the downloaded STATSGO coverage and attribute data at the map unit, component, and layer levels. Queries were developed to automate SOC calculations based on STATSGO attribute data including bulk density, rock content, layer thickness, and organic matter content.

Methods of calculating soil carbon stocks with STATSGO data are well documented (Bliss, Waltman et al. 1995; Johnson and Kern 2002). The basic calculation carried out by the queries to obtain carbon density (metric tons/hectare) for a single map unit is as follows,

$$C_S = \sum_j \left\{ COMPPCT_j \cdot \sum_i \left[H_{i,j} \cdot BD_{i,j} \cdot OM_{i,j} \cdot FE_{i,j} \cdot U / 1.724 \right] \right\} \qquad (1)$$

where

C_s	Carbon soil density (metric tons/ha)
H	Thickness of soil layer (in)
BD	Average bulk density (g/cm^3)
OM	Average organic matter content (% by weight)
FE	Fraction of fine earth material (<2 mm)
U	Unit conversions that provide results in metric tons per hectare
COMPPCT	Percentage (by area) component of map unit (%)
1.724	Fraction carbon content to organic matter (by weight)
i	Soil layer index
j	Component index

The SOC calculation queries were run for depths to 25 centimeters and depths to 1 meter. The 0 – 25 cm layer is where carbon concentration and interactions with atmospheric carbon are thought to be greatest. Future government and carbon market policies will likely be based on these depths. The 0 – 1 meter layer is thought to include most SOC in a soil column.

The geospatial database was joined to a GIS to produce statewide soil carbon density maps. Note that these densities are for all land types, not just forestland.

Forest SOC density is obtained from an overlay of the statewide soil carbon density results and the WDNR WISCLAND Land Cover map. WISCLAND Land Cover Data (Figure 4) was derived from Landsat Thematic Mapper (TM) satellite imagery acquired from fly-overs in 1991 to 1993. TM data are stored as land cover types for pixels representing a 30-meter by 30-meter square.

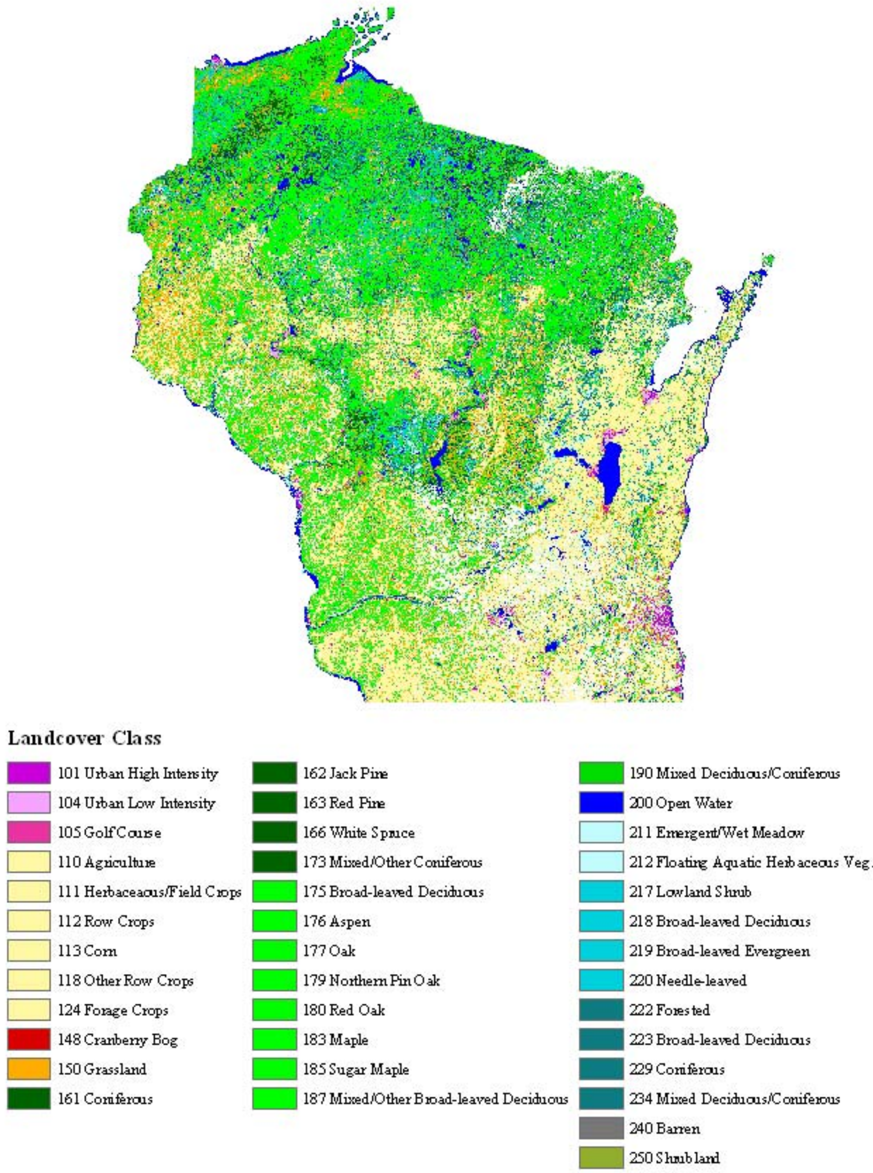

Figure 4. WISCLAND Land Cover Data grid from LANDSAT Thematic Mapper (TM) satellite imagery acquired from fly-overs in 1991 to 1993.

Total forest SOC stock is calculated by linking the geospatial database and the GIS to calculate the product of forest-type SOC densities and forest-type areas. A weighted average of SOC density by forest type is also calculated by linking the forest area and forest SOC density results.

2.1.2 SOC Stocks and Trend

SOC stocks are obtained by multiplying the baseline results and USDA U.S. Forest Service Forest Inventory Analysis (FIA) data. The baseline results provide soil carbon density (metric tons/hectare) for each forest type. The FIA data includes area estimates for each forest type by county in 1983, 1996, and 2001. The product of baseline densities and annual forest areas gives forest soil carbon stocks for the three years.

A linear regression of these stocks provides an estimate of the annual rate of carbon accumulation. It is important to note that this rate is due to the transfer of carbon between land types and the transfer of carbon between soil and the atmosphere. The increasing forest area from 1983 to 2001 clearly will result in an increase in soil carbon using this methodology. Much of this increased soil carbon was previously classified as agricultural soil carbon, therefore this accumulation rate is not a direct offset to greenhouse gas emissions, but represents a net increase in carbon stocks beneath forestland due to land-use reclassification.

2.12 SOC Trends and Land use

Further analysis of changes in SOC can be calculated by integrating baseline results, land use change data, and soil dynamics assumptions from site-specific land use studies (Heath, Birdsey et al. 2002). In this approach, soil dynamics assumptions are given as percent change in baseline depending on the land use change (ex. afforestation from cultivated land) and the area over which the land use change occurred. The baseline is assumed to be the STATSGO stock results and the land use change data is obtained from the NRCS Natural Resources Inventory (NRI).

The NRI data, revised as of December 2000, was downloaded from the Wisconsin NRCS website. NRI data contains area changes in land use from one type to another for surveys of non-Federal land in 1982, 1987, and 1997. A more detailed study of SOC dynamics is possible using the NRI forest data for forest type. However, our communication with the NRCS indicates that the NRI data for Wisconsin is not statistically reliable by forest type so we only use the aggregated NRI forest data.

The SOC dynamics assumptions are as follows. Land that is deforested and subsequently cultivated is assumed to lose 30% of baseline SOC over 25 years. Forestland that is converted to pasture or urban land is assumed to lose 15% of baseline SOC over 15 years. Afforestation from cropland, starts at 70% of baseline SOC and returns to baseline SOC levels at a constant rate over 100 years. Afforestation from pastureland, starts at 85% of baseline SOC and returns to baseline SOC levels at a constant rate over 50 years.

No change in SOC is accounted due to management and harvesting because field studies have had inconclusive results on this topic. No assumption regarding afforestation from urban land is required because there is no significant afforestation from urban land.

2.1.3 SOC Validation

A number of quality assurance measures are completed to validate results. Because the database queries automate SOC density and total stock calculations, it is easy to create sample results that follow methods used in previously published studies of SOC. A number of published studies have calculated SOC for different depths and states using older methodologies. The input datasets and query programs can be modified to create results that can be compared with these studies.

SOC results are also checked against known geologic trends by interpreting SOC density maps. Further validation is achieved by plotting the Wisconsin SOC density map next to a map of Iowa SOC densities and matching the border densities.

2.2 BIOMASS METHODOLOGY

Biomass carbon estimates of carbon in trees were estimated using a stock approach that combines U.S. Forest Service Forest Inventory Analysis (FIA) information on growing stock volume data and carbon biomass conversion factors. These results are conservative because they underestimate carbon stocks by not accounting for forest floor litter and the stocks that are removed from the forestland and stored in long-term products such as home construction.

2.2.1 Biomass Stock

Growing stock volumes on timberland were downloaded from the FIA website in July of 2003. Data was available for Wisconsin forest surveys in 1983, 1996, and 2001. These volumes are provided for each forest type and for each county. They indicate the volume of merchantable timber of at least 12.7 cm diameter at breast height (dbh).

This volume is converted to forest tree biomass using a series of conversion factors (Birdsey 1992). First, the merchantable volume is converted to total tree volume by multiplying by a factor that accounts for non-merchantable volume such as branches, foliage, and small trees. Tree biomass volume is converted to a mass basis using the specific gravity of each forest type. Tree mass is converted to carbon mass using an average percent carbon for each forest type.

2.2.2 Biomass Trend

The annual change in biomass carbon stocks is estimated by applying a linear regression analysis to the stock results for 1983, 1996, and 2001. This sequestration rate represents a transfer of carbon from the atmospheric pool to the forest biomass pool.

2.2.3 Biomass Validation

Results are validated by comparison with biomass carbon density results published for other states with related forest characteristics. Gross statewide results are also confirmed by comparison with state-level analysis by the U.S. Forest Service.

3. RESULTS

Overall results quantify the net increase in carbon in Wisconsin's forestlands. The results are successfully validated and indicate much smaller soil stocks compared to rougher approximations published in previous studies.

3.1 SOC RESULTS

The statewide SOC results for all land cover types are calculated using STATSGO data and mapped for soil depths up to 1 meter (Figures 5 and 6) and depths up to 25 cm (Figure 6). For depths up to 1 meter, SOC densities range from 4 to 188 metric tons/hectare.

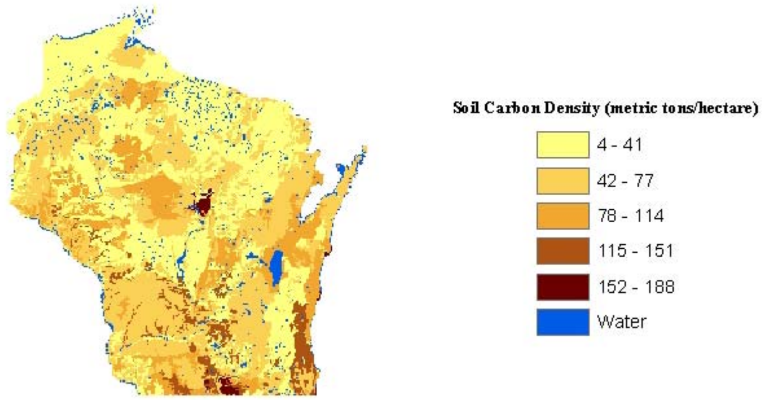

Figure 5. Wisconsin statewide soil carbon density (metric tons/hectare) using the survey methodology for soil depths up to 1 meter.

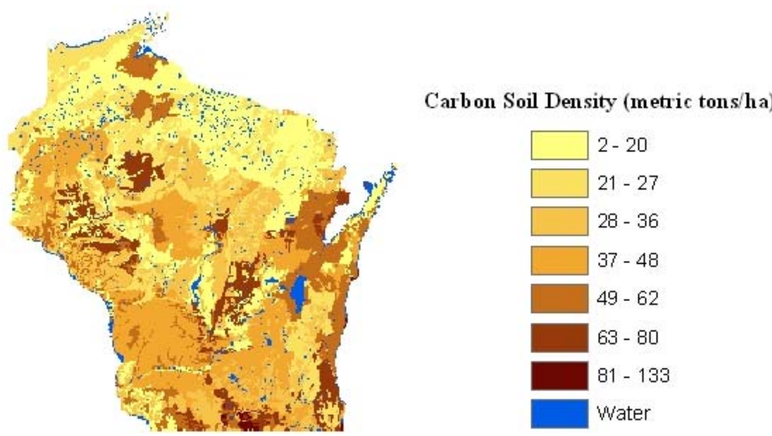

Figure 6. Wisconsin statewide soil carbon density (metric tons/hectare) using the survey methodology for soil depths up to 25 cm.

Baseline results for forest carbon are obtained by overlaying WISCLAND land cover maps and the statewide SOC maps in Figures 5 and 6 to filter out areas that are not considered forestland. The resulting map of SOC densities for forestland can be summarized by taking a weighted average of densities by forest type (Table I). Baseline results are also summarized by multiplying by their areas to obtain total forestland soil carbon values of 262 million metric tons of carbon (MMTC) for soil depths up to 1 meter and 160 MMTC for soil depths up to 25 cm.

We calculate annual soil carbon stocks by integrating the baseline results with US Forest Service Forest Inventory Analysis (FIA) forest areas for 1983, 1996, and 2001. Soil stocks are 277 MMTC, 290 MMTC, and 288 MMTC for 1983, 1996, and 2001 respectively (Table II). Forest area and SOC volumes are also broken down by forest type in Table II. A linear regression indicates a net increase in forest SOC of 0.7 MMTC/yr ($R^2 = 0.84$). It is important to note that these changes are due to a transfer between land types in addition to a transfer from the atmosphere to the soil as indicated by the large increase in forest area over this period.

Table I. Baseline SOC densities and SOC flux by land use transitions for soil depths up to 1 meter.

Forest Type	Baseline SOC Density (metric ton/ha)	SOC Annual Change (Mg C/ha/year) Crop to Forest	Pasture to Forest	Forest to Crop	Forest to Pasture or Urban
Jack Pine	42.5	0.1	0.1	-0.5	-0.3
Red Pine	43.5	0.1	0.1	-0.5	-0.3
White Spruce	44.6	0.1	0.1	-0.5	-0.3
Mixed/Other Coniferous	46.5	0.1	0.1	-0.6	-0.3
Aspen	47.2	0.1	0.1	-0.6	-0.3
Oak	46.1	0.1	0.1	-0.6	-0.3
Northern Pin Oak	38.3	0.1	0.1	-0.5	-0.2
Red Oak	36.8	0.1	0.1	-0.4	-0.2
Maple	49.4	0.1	0.1	-0.6	-0.3
Sugar Maple	43.4	0.1	0.1	-0.5	-0.3
Mixed/Other Broad-Leaved Deciduous	50.9	0.2	0.2	-0.6	-0.3
Mixed Deciduous/Coniferous	43.6	0.1	0.1	-0.5	-0.3
Average	**48.2**	**0.1**	**0.1**	**-0.6**	**-0.3**

An alternative analysis of changes in SOC can be calculated by integrating baseline densities by forest type, land use change data, and soil dynamics assumptions from site-specific land use studies. The change in SOC based on baseline densities and land use transitions are summarized in Table I. The next step is to obtain statewide estimates of forest soil carbon sequestration by applying these results to land use transition information. Currently, the NRCS National Resource Inventory (NRI) provides land use transition information, but it is not statistically accurate for forest types. In the future, improved land use transition information could permit us to extend our results to obtain statewide sequestration results using this method.

Table II. Forest area and SOC stocks by forest type for soil depths up to 1 meter.

Forest Type	Area 1983 (ha)	Area 1996 (ha)	Area 2001 (ha)	SOC Stock 1983 (MMTC)	SOC Stock 1996 (MMTC)	SOC Stock 2001 (MMTC)
White-Red-Jack Pine	519414	491530	539577	23	21	23
Spruce-Fir	658869	549692	522475	29	25	23
Oak-Hickory	1175450	1177028	1136256	47	48	46
Elm-Ash-Cottonwood	533659	622703	547494	25	29	26
Maple-Beech-Birch	1639867	2167276	2189392	76	101	102
Aspen-Birch	1614170	1403509	1437377	76	66	68
Total:	**6141428**	**6411739**	**6372571**	**277**	**290**	**288**

We validate our results through an analysis of other published studies on SOC. First we applied our GIS to map our results next to results for the state of Iowa (Ney, Schnoor et al. 2002). Inspection of the border regions of these maps (Figure 7) indicates agreement between our finding and those obtained previously for Iowa.

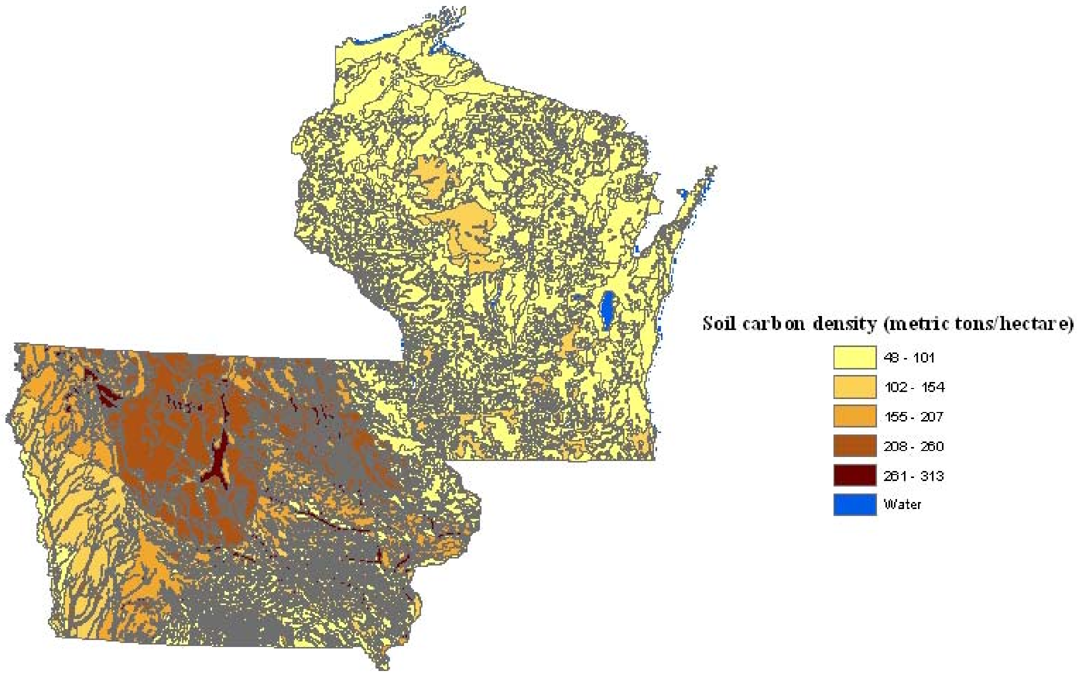

Figure 7. Validation of Wisconsin results by mapping previously published results for Iowa and comparing edges. Mapped results are for soil carbon densities (metric tons /hectare) for depths up to 1 meter.

Further validation is obtained by comparing our STATSGO-based results with SOC stock estimates using a regression approach. The regression approach provides a rough approximation of soil carbon stocks using a ratio of soil carbon to forest area for eight different regions across the U.S. (Birdsey 1992). Birdsey, the author of the regression approach, currently sites STATSGO based methods for estimating SOC stocks. However, the regression results are relevant as a basis for validation, and are currently sited in a 2004 greenhouse gas inventory for Wisconsin (Kerr 2004).

Results using the regression method were published in a national inventory of state-wide forest soil carbon stocks (Birdsey and Lewis 2000). The regression results for Wisconsin indicate forest soil carbon values of 794 MMTC, 799 MMTC, and 804 MMTC in 1987, 1992, and 1997 respectively for depths up to 1 meter. While regression results are nearly three times our STATSGO-based results, our method can be modified to obtain a close approximate to the regression results. If we drop the FE term from equation 1, our calculations do not deduct rock content from our estimate of soil carbon. This introduces rock content error into our calculations, which leads to an overestimate of SOC. Our resulting overestimate of SOC, with rock content error introduced, is within 2% of the average of the regression results for 1987, 1992, and 1997. This indicates that the regression approach, while not accounting for rock content, provides a comparable estimate of SOC stocks for Wisconsin as the STATSGO-based approach.

This same trend is observed when we repeat our analysis for the state of Maine and compare our STATSGO-based results with regression results. However when we repeat our analysis for the state of Iowa, a state with low rock content, we find that our original results (no rock error) are on the same order of magnitude as the regression results (Table III).

Table III. SOC stock estimates up to 1 meter depth for STATSGO based results, STATSGO results with rock error introduced, and regression-based results.

	STATSGO (MMTC)	STATSGO + Rock Error (MMTC)	Regression (MMTC)
Wisconsin	262	788	799
Maine	579	1071	1117
Iowa	99	101	77

Because Iowa has low rock content, there is only a small difference between the STATSGO estimate and STATSGO plus rock error estimate. This agreement between our modified results and the regression-based results validates our findings.

3.2 BIOMASS RESULTS

Tree biomass carbon calculations are developed based on biomass volume data from the FIA program and expansion coefficients (Birdsey 1992). Forest biomass carbon stocks are mapped for each county based on inventory data from 1983, 1996, and 2001 (Figure 8). For all three years, the highest biomass carbon per county area (tons/hectare) are in the northeast regions of Wisconsin and the lowest densities are in the southeast.

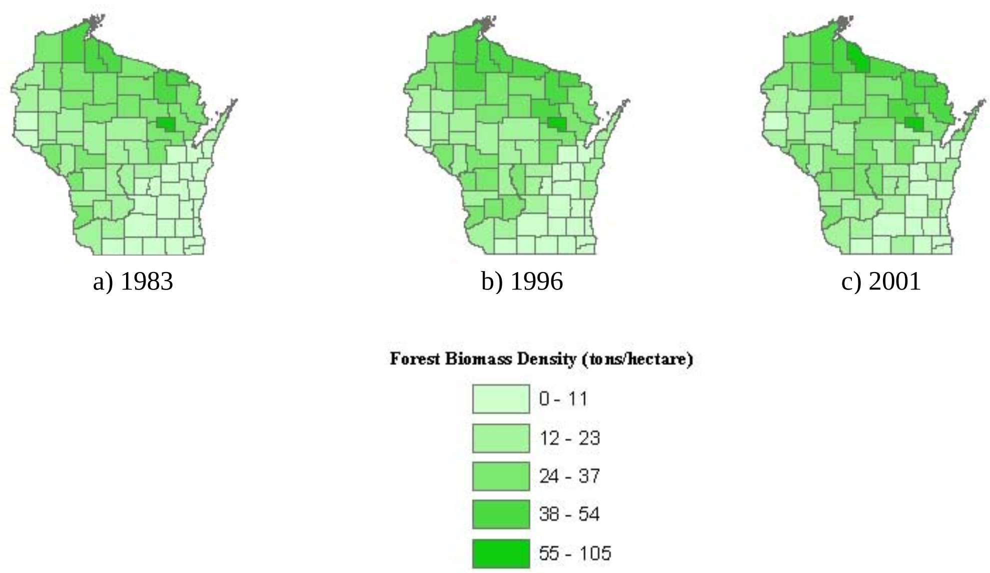

Figure 8. Biomass carbon stocks (metric tons/hectare).

Tree biomass carbon results are also calculated by forest type for each inventory year (Table IV). Maple-Beech-Birch forests have the highest biomass volume, primarily due to the large areas of this forest type and an increase in maple-beech-birch forest area of over 30% between 1983 and 1996.

Table IV. Biomass stock estimates (MMTC) and forest area (ha) by forest type for 1983, 1996, and 2001.

Forest Type	Area 1983 (ha)	Area 1996 (ha)	Area 2001 (ha)	Biomass 1983 (MMTC)	Biomass 1996 (MMTC)	Biomass 2001 (MMTC)
White-Red-Jack Pine	519414	491530	539577	25	26	36
Spruce-Fir	658869	549692	522475	17	18	15
Oak-Hickory	1175450	1177028	1136256	64	75	76
Elm-Ash-Cottonwood	533659	622703	547494	21	24	24
Maple-Beech-Birch	1639867	2167276	2189392	99	153	149
Aspen-Birch	1614170	1403509	1437377	57	47	50
Total:	**6141428**	**6411739**	**6372571**	**283**	**345**	**350**

The total biomass carbon stock was calculated as 283 MMTC, 345 MMTC, and 350 MMTC for FIA data from 1983, 1996, and 2001 respectively. A linear regression of these results provides an annual biomass sequestration of 4 MMTC per year ($R^2 = 0.89$).

The rates of biomass carbon flux by county are provided in Appendix A and are summarized by county in Figure 8. The largest rates of increase occurred in Iron County on the northern border, and in a group of adjacent counties in the north central part of Wisconsin including Marathon, Langlade, Lincoln, and Taylor counties. Increased biomass carbon in Iron County was primarily due to increases in white-red-jack pine and maple-beech-birch forest stocks. The accumulation of carbon in the north central counties was caused by a variety of forest type changes, but oak-hickory growth was significant for each. Significant decreases in biomass carbon occurred in Jackson, Vernon, and Eau Claire counties. Losses in Jackson County resulted from decreased elm-ash-cottonwood and spruce-fir volume. Vernon County had decreasing stocks of oak-hickory and aspen birch. The elm-ash-cottonwood and aspen-birch biomass in Eau Claire County decreased over the period.

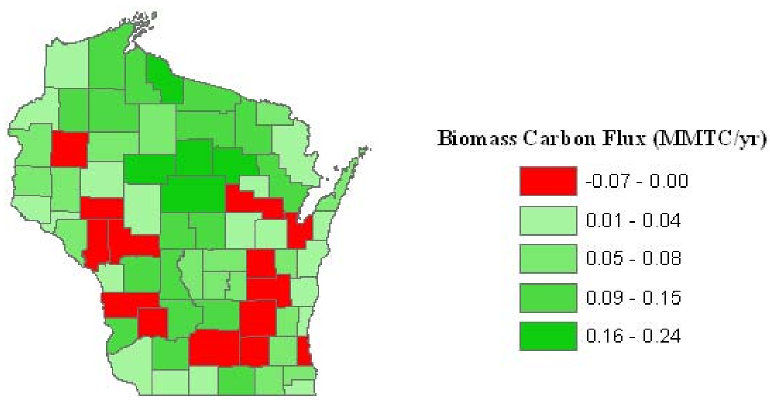

Figure 8. Biomass carbon flux (metric tons/hectare/year).

Gross statewide results are validated by comparison with a state-level report by the U.S. Forest Service (Birdsey and Lewis 2000). This report indicates comparable statewide forest biomass values of 302, 322, and 341 in 1987, 1992, and 1997 respectively.

4. Discussion

Carbon stocks and annual increments were developed for the soils and biomass of Wisconsin's forestlands. These results indicate increasing carbon volume in both soil and biomass pools over the period from 1983 to 2001. Continued analysis of the GIS produced during this study could provide insight into management strategies for continued and enhanced increases in forestland carbon.

Acknowledgments

The authors would like to thank Professor David Bennett and graduate student Chetan Tiwari from the Department of Geography at The University of Iowa for assistance with GIS development. We also appreciate assistance we received from Steve Brick at Wisconsin Focus on Energy and Mitch Moline from the Wisconsin DNR.

References

Birdsey, R. A. (1992). Carbon Storage and Accumulation in the United States Forest Ecosystems, USDA Forest Service**:** 11.

Birdsey, R. A. and G. M. Lewis (2000). Carbon in United States Forests and Wood Products, 1987-1997: State-by-State Estimates, USFS.

Bliss, N. B., S. W. Waltman, et al. (1995). Preparing a soil carbon inventory for the United States using geographic information systems. Soils and Global Change. B. Stewart. Boca Raton, FL, CRC Press Inc**:** 275-295.

Heath, L. S., R. A. Birdsey, et al. (2002). "Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001." Environmental Pollution **116**: 373-380.

Houghton, R. A., E. A. Davidson, et al. (1998). "Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance." Biogeochemical Cycles **12**: 25-34.

Johnson, M. G. and S. K. Kern (2002). Quanitfying the organic carbon held in forested soils of the United States and Puerto Rico. The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. R. Lal. Boca Raton, FL, CRC Press Inc**:** 47-71.

Kerr, S. (2004). Wisconsin's Greenhouse Gas Emissions: Trends from 1990 to 2000. Madison, Wisconsin, Wisconsin Department of Natural Resources**:** 115.

Ney, R. A., J. L. Schnoor, et al. (2002). "A methodology to estimate carbon storage and flux in forestland using existing forest and soils databases." Environmental Monitoring and Assessment **78**: 291-307.

Pacala, S. W., G. C. Hurtt, et al. (2001). "Consistent Land- and Atmosphere-Based U.S. Carbon Sink Estimates." Science **292**(5525): 2316-2320.

Schimel, D. S. (1995). "Terrestrial ecosystems and the carbon cycle." Global Change Biology **1**: 77-91.

Schlesinger, W. H. (1997). Biogeochemistry: An Analysis of Global Change. San Diego, CA, Academic Press.

WDNR (2003). Wisconsin Forest Management Guidelines. Madison, Wisconsin DNR.

Appendix A: Annual Biomass Stocks

Table V. Biomass stocks (MMTC) by county and forest type for 1983.

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
ADAMS	1.165	0.000	1.580	0.019	0.132	0.269	0.021
ASHLAND	0.489	1.893	0.063	0.590	5.845	2.461	0.000
BARRON	0.020	0.014	1.072	0.080	0.644	0.875	0.005
BAYFIELD	2.423	0.528	1.959	0.555	4.405	5.171	0.003
BROWN	0.000	0.000	0.051	0.314	0.661	0.054	0.000
BUFFALO	0.000	0.000	3.352	0.158	0.376	0.606	0.000
BURNETT	0.914	0.014	1.478	0.515	0.440	1.608	0.027
CALUMET	0.000	0.000	0.030	0.064	0.241	0.000	0.000
CHIPPEWA	0.135	0.085	0.823	0.406	1.608	0.994	0.033
CLARK	0.322	0.000	1.431	0.248	1.238	2.400	0.012
COLUMBIA	0.069	0.000	1.224	0.019	0.258	0.170	0.000
CRAWFORD	0.000	0.000	2.401	0.408	0.700	0.065	0.011
DANE	0.037	0.000	1.433	0.047	0.142	0.136	0.000
DODGE	0.025	0.000	0.156	0.054	0.097	0.030	0.000
DOOR	0.000	0.608	0.000	0.455	0.826	0.171	0.002
DOUGLAS	1.114	1.007	0.546	1.117	1.920	3.523	0.026
DUNN	0.491	0.000	1.771	0.139	0.945	0.336	0.000
EAU CLAIRE	0.610	0.000	1.685	0.055	0.339	0.549	0.000
FLORENCE	0.213	0.452	0.128	0.011	2.835	1.408	0.004
FOND DU LAC	0.115	0.017	0.185	0.076	0.350	0.004	0.000
FOREST	0.566	1.843	0.000	0.138	7.106	1.835	0.000
GRANT	0.000	0.000	2.736	0.316	0.620	0.102	0.000
GREEN	0.028	0.000	0.395	0.073	0.149	0.000	0.000
GREEN LAKE	0.030	0.037	0.295	0.000	0.050	0.000	0.000
IOWA	0.003	0.000	1.625	0.153	0.335	0.062	0.019
IRON	0.164	1.095	0.163	0.541	4.284	1.603	0.000
JACKSON	1.624	0.025	3.253	0.265	0.502	0.974	0.000
JEFFERSON	0.083	0.000	0.407	0.000	0.341	0.000	0.000
JUNEAU	0.934	0.008	2.084	0.276	0.352	0.620	0.000
KENOSHA	0.018	0.000	0.096	0.000	0.034	0.000	0.000
KEWAUNEE	0.000	0.134	0.000	0.443	0.242	0.000	0.000
LA CROSSE	0.245	0.000	2.054	0.119	0.233	0.133	0.000
LAFAYETTE	0.000	0.000	0.460	0.000	0.147	0.000	0.000
LANGLADE	0.186	0.789	0.000	0.280	4.787	1.547	0.000
LINCOLN	0.651	0.378	0.109	0.548	2.568	1.735	0.000
MANITOWOC	0.000	0.127	0.138	0.265	0.475	0.066	0.000
MARATHON	0.087	0.226	0.486	0.881	4.079	1.442	0.008
MARINETTE	1.057	1.202	1.151	0.979	3.635	3.614	0.000
MARQUETTE	0.307	0.036	0.782	0.130	0.023	0.037	0.006
MENOMINEE	0.747	0.433	0.754	0.291	5.116	0.496	0.009

Table V (Continued). Biomass stocks (MMTC) by county and forest type for 1983.

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
MONROE	0.348	0.000	2.684	0.187	0.328	0.430	0.008
OCONTO	1.145	0.685	0.679	0.770	1.868	1.824	0.000
ONEIDA	1.333	1.219	0.380	0.230	1.948	2.996	0.001
OUTAGAMIE	0.114	0.082	0.059	0.579	0.329	0.050	0.000
OZAUKEE	0.000	0.000	0.000	0.026	0.211	0.099	0.000
PEPIN	0.000	0.000	0.422	0.180	0.210	0.069	0.000
PIERCE	0.000	0.000	0.677	0.035	0.883	0.090	0.000
POLK	0.078	0.040	1.644	0.196	1.045	0.983	0.000
PORTAGE	0.570	0.065	1.201	0.320	0.599	0.393	0.010
PRICE	0.560	1.040	0.000	1.016	3.861	1.863	0.014
RACINE	0.000	0.000	0.101	0.012	0.021	0.008	0.000
RICHLAND	0.000	0.000	1.561	0.187	1.442	0.031	0.000
ROCK	0.000	0.000	0.405	0.061	0.032	0.000	0.000
RUSK	0.228	0.118	0.575	0.630	3.115	1.956	0.000
ST. CROIX	0.117	0.000	0.449	0.104	0.049	0.272	0.033
SAUK	0.186	0.000	2.508	0.009	1.139	0.125	0.014
SAWYER	0.873	0.743	0.786	0.741	6.269	2.324	0.032
SHAWANO	0.522	0.462	0.602	0.949	3.012	0.481	0.000
SHEBOYGAN	0.021	0.129	0.215	0.190	0.243	0.008	0.000
TAYLOR	0.066	0.416	0.000	0.625	4.531	0.939	0.004
TREMPEALEAU	0.252	0.000	1.818	0.162	0.230	0.298	0.012
VERNON	0.000	0.000	2.949	0.043	1.541	0.000	0.000
VILAS	1.574	0.583	0.575	0.075	2.863	2.516	0.000
WALWORTH	0.000	0.000	0.640	0.000	0.066	0.000	0.000
WASHBURN	0.686	0.126	0.843	0.367	1.373	2.338	0.004
WASHINGTON	0.000	0.014	0.080	0.373	0.182	0.004	0.005
WAUKESHA	0.000	0.000	0.374	0.088	0.000	0.018	0.000
WAUPACA	0.435	0.420	0.911	1.235	1.306	0.264	0.000
WAUSHARA	1.111	0.064	1.449	0.149	0.127	0.047	0.003
WINNEBAGO	0.000	0.000	0.077	0.031	0.401	0.000	0.000
WOOD	0.360	0.008	1.090	0.376	0.402	1.058	0.000

Table VI. Biomass stocks (MMTC) by county and forest type for 1996

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
ADAMS	0.835	0.000	3.035	0.225	0.060	0.192	0.000
ASHLAND	0.103	1.569	0.000	0.717	6.989	2.085	0.000
BARRON	0.210	0.051	1.714	0.098	0.860	0.704	0.000
BAYFIELD	2.093	0.545	1.571	0.630	6.113	5.447	0.000
BROWN	0.000	0.009	0.023	0.175	0.575	0.105	0.000
BUFFALO	0.000	0.000	3.390	0.169	0.578	0.684	0.000
BURNETT	0.615	0.164	2.830	0.237	1.454	0.918	0.000
CALUMET	0.000	0.000	0.062	0.100	0.242	0.007	0.000
CHIPPEWA	0.200	0.002	1.386	0.360	2.920	0.368	0.000
CLARK	0.394	0.000	1.787	0.456	2.039	0.883	0.000
COLUMBIA	0.551	0.000	1.755	0.069	0.192	0.048	0.000
CRAWFORD	0.000	0.000	2.781	0.520	0.837	0.096	0.000
DANE	0.007	0.000	0.978	0.000	0.932	0.062	0.000
DODGE	0.010	0.000	0.054	0.253	0.342	0.034	0.000
DOOR	0.006	0.284	0.000	0.556	1.243	0.330	0.000
DOUGLAS	1.453	0.954	0.678	0.551	2.862	3.018	0.000
DUNN	0.303	0.000	1.553	0.344	1.498	0.096	0.000
EAU CLAIRE	0.271	0.000	1.793	0.027	0.382	0.137	0.000
FLORENCE	0.687	0.559	0.162	0.073	3.980	1.467	0.000
FOND DU LAC	0.042	0.009	0.137	0.136	0.407	0.000	0.000
FOREST	0.361	1.286	0.000	0.424	10.907	1.351	0.000
GRANT	0.000	0.000	2.270	0.430	1.498	0.023	0.000
GREEN	0.002	0.000	0.406	0.071	0.370	0.000	0.000
GREEN LAKE	0.052	0.026	0.323	0.018	0.177	0.000	0.000
IOWA	0.070	0.000	1.970	0.184	0.532	0.228	0.000
IRON	0.439	1.046	0.122	0.923	7.387	1.158	0.000
JACKSON	0.840	0.032	3.162	0.421	0.988	0.664	0.000
JEFFERSON	0.000	0.017	0.247	0.216	0.157	0.000	0.000
JUNEAU	0.659	0.000	2.803	0.293	0.742	0.205	0.000
KENOSHA	0.000	0.000	0.436	0.004	0.000	0.000	0.000
KEWAUNEE	0.000	0.056	0.000	0.551	0.662	0.076	0.006
LA CROSSE	0.285	0.000	1.853	0.309	0.519	0.175	0.000
LAFAYETTE	0.000	0.000	0.544	0.054	0.161	0.000	0.000
LANGLADE	0.093	0.949	0.090	0.510	6.515	1.384	0.019
LINCOLN	1.200	0.498	0.046	0.232	3.754	1.381	0.000
MANITOWOC	0.061	0.022	0.000	0.435	1.147	0.124	0.000
MARATHON	0.234	0.195	0.588	0.793	5.805	0.792	0.005
MARINETTE	1.309	1.396	1.609	0.682	5.954	2.642	0.000
MARQUETTE	0.240	0.027	0.963	0.036	0.249	0.051	0.000
MENOMINEE	0.866	0.431	1.102	0.053	7.090	0.390	0.000
MILWAUKEE	0.000	0.000	0.000	0.000	0.294	0.000	0.000

Table VI (Continued). Biomass stocks (MMTC) by county and forest type for 1996.

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
MONROE	0.475	0.000	3.423	0.103	1.181	0.332	0.000
OCONTO	1.070	1.116	0.687	0.691	4.034	1.572	0.000
ONEIDA	1.838	0.893	0.784	0.469	3.256	2.931	0.000
OUTAGAMIE	0.057	0.051	0.105	0.586	0.360	0.143	0.000
OZAUKEE	0.000	0.003	0.000	0.083	0.382	0.000	0.000
PEPIN	0.061	0.000	0.522	0.118	0.475	0.027	0.000
PIERCE	0.000	0.000	0.263	0.349	0.827	0.191	0.000
POLK	0.217	0.000	2.051	0.078	1.689	0.840	0.000
PORTAGE	0.986	0.019	0.864	0.744	1.217	0.160	0.000
PRICE	0.323	1.638	0.000	1.575	5.916	1.798	0.000
RACINE	0.000	0.000	0.341	0.196	0.013	0.000	0.000
RICHLAND	0.000	0.000	1.586	0.107	2.213	0.253	0.000
ROCK	0.082	0.000	0.501	0.062	0.321	0.000	0.000
RUSK	0.176	0.084	1.722	0.418	5.150	1.189	0.000
ST. CROIX	0.035	0.031	0.849	0.020	0.805	0.181	0.000
SAUK	0.130	0.000	3.545	0.219	1.332	0.009	0.000
SAWYER	0.797	0.674	1.207	0.768	8.884	2.611	0.016
SHAWANO	0.359	0.851	0.665	0.862	4.573	0.555	0.000
SHEBOYGAN	0.048	0.136	0.428	0.404	0.645	0.000	0.000
TAYLOR	0.006	0.416	0.078	0.971	5.734	1.008	0.035
TREMPEALEAU	0.246	0.000	2.368	0.438	0.488	0.185	0.000
VERNON	0.103	0.000	2.258	0.268	1.932	0.176	0.000
VILAS	2.060	1.099	0.365	0.127	4.416	3.399	0.000
WALWORTH	0.015	0.000	0.657	0.017	0.305	0.025	0.000
WASHBURN	1.015	0.267	2.139	0.489	2.237	1.601	0.000
WASHINGTON	0.040	0.003	0.000	0.157	0.695	0.061	0.000
WAUKESHA	0.000	0.000	0.361	0.131	0.236	0.000	0.000
WAUPACA	0.594	0.242	1.056	1.149	2.137	0.132	0.000
WAUSHARA	0.687	0.087	1.449	0.118	0.467	0.062	0.000
WINNEBAGO	0.000	0.000	0.000	0.033	0.489	0.000	0.000
WOOD	0.313	0.083	0.998	0.394	1.260	0.727	0.000

Table VII. Biomass stocks (MMTC) by county and forest type for 2001.

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
ADAMS	1.396	0.000	1.686	0.112	0.569	0.503	0.000
ASHLAND	0.831	0.483	0.568	0.186	6.961	1.896	0.000
BARRON	0.000	0.000	1.891	0.056	1.000	0.503	0.000
BAYFIELD	2.897	0.159	0.813	0.732	5.794	6.448	0.000
BROWN	0.000	0.000	0.172	0.122	0.696	0.000	0.000
BUFFALO	0.000	0.178	2.246	1.109	0.805	1.285	0.002
BURNETT	1.875	0.018	1.365	0.349	1.720	0.752	0.000
CALUMET	0.000	0.164	0.827	0.194	0.000	0.000	0.000
CHIPPEWA	0.308	0.062	1.953	0.138	1.253	0.545	0.000
CLARK	0.579	0.020	1.909	0.485	1.995	1.054	0.000
COLUMBIA	0.057	0.000	2.168	0.286	0.396	0.234	0.000
CRAWFORD	0.000	0.000	2.492	0.949	1.175	0.574	0.000
DANE	0.000	0.000	0.929	0.068	0.761	0.000	0.000
DODGE	0.000	0.000	0.000	0.130	0.166	0.000	0.000
DOOR	0.046	0.606	0.246	0.288	1.391	0.761	0.000
DOUGLAS	1.082	0.491	1.222	1.703	1.785	3.465	0.020
DUNN	0.165	0.000	1.925	0.000	1.511	0.044	0.000
EAU CLAIRE	0.293	0.000	1.304	0.004	1.198	0.000	0.000
FLORENCE	0.102	0.391	0.000	0.000	4.483	1.083	0.000
FOND DU LAC	0.000	0.000	0.071	0.318	0.004	0.000	0.000
FOREST	0.493	1.416	0.000	0.483	10.627	1.442	0.000
GRANT	0.155	0.000	3.002	0.089	0.838	0.144	0.002
GREEN	0.000	0.000	0.181	0.075	0.674	0.000	0.002
GREEN LAKE	0.214	0.000	0.383	0.000	0.508	0.000	0.000
IOWA	0.135	0.000	2.411	0.318	0.839	0.154	0.000
IRON	0.550	1.309	0.000	0.724	7.922	1.161	0.000
JACKSON	1.880	0.006	2.435	0.072	1.242	0.336	0.000
JEFFERSON	0.000	0.000	0.352	0.094	0.159	0.000	0.000
JUNEAU	0.962	0.000	3.151	0.553	0.545	0.474	0.000
KENOSHA	0.000	0.000	0.081	0.000	0.231	0.000	0.000
KEWAUNEE	0.000	0.000	0.000	0.189	0.482	0.000	0.000
LA CROSSE	0.000	0.000	2.885	0.124	0.371	0.426	0.000
LAFAYETTE	0.000	0.000	0.440	0.056	0.542	0.000	0.000
LANGLADE	0.015	0.738	0.188	0.220	8.568	1.515	0.000
LINCOLN	1.363	0.828	0.354	0.239	4.401	1.467	0.003
MANITOWOC	0.000	0.252	0.000	0.322	2.370	0.053	0.000
MARATHON	0.146	0.120	0.795	1.428	6.653	0.623	0.000
MARINETTE	2.096	1.128	0.953	0.949	6.654	2.530	0.000
MARQUETTE	0.711	0.153	0.798	0.000	0.000	0.082	0.000
MENOMINEE	1.586	0.135	1.003	0.385	4.908	0.754	0.000
MILWAUKEE	0.000	0.000	0.281	0.003	0.000	0.000	0.000

Table VII (Continued). Biomass stocks (MMTC) by county and forest type for 2001.

County	White-Red-Jack Pine	Spruce-Fir	Oak-Hickory	Elm-Ash-Cottonwood	Maple-Beech-Birch	Aspen-Birch	Nonstocked East
MONROE	1.008	0.000	3.776	0.059	2.048	0.256	0.000
OCONTO	1.148	0.667	0.514	0.942	3.196	1.730	0.000
ONEIDA	1.871	0.931	1.593	0.306	1.727	3.312	0.000
OUTAGAMIE	0.000	0.088	0.000	0.721	0.446	0.000	0.001
OZAUKEE	0.000	0.014	0.000	0.338	0.141	0.000	0.000
PEPIN	0.000	0.000	0.416	0.661	0.503	0.000	0.000
PIERCE	0.083	0.063	1.227	0.048	0.825	0.056	0.000
POLK	0.000	0.000	1.244	0.209	1.417	1.278	0.000
PORTAGE	1.372	0.034	1.380	0.206	0.671	0.236	0.000
PRICE	0.100	0.881	0.000	0.555	6.407	2.085	0.015
RACINE	0.000	0.000	0.359	0.000	0.000	0.000	0.000
RICHLAND	0.132	0.000	0.734	0.028	1.252	0.372	0.000
ROCK	0.000	0.000	2.309	0.014	0.361	0.000	0.000
RUSK	0.000	0.102	1.055	0.461	5.635	1.213	0.000
ST. CROIX	0.000	0.000	0.770	0.275	0.469	0.113	0.000
SAUK	0.000	0.000	2.642	0.124	2.085	0.171	0.000
SAWYER	2.693	0.977	1.860	0.677	7.758	1.362	0.000
SHAWANO	0.526	0.526	0.000	0.362	3.031	0.594	0.002
SHEBOYGAN	0.234	0.000	0.000	0.372	0.700	0.085	0.000
TAYLOR	0.457	0.356	0.356	0.592	5.528	0.528	0.000
TREMPEALEAU	0.244	0.000	1.993	0.261	0.183	0.117	0.000
VERNON	0.113	0.000	1.665	0.462	1.386	0.108	0.005
VILAS	3.042	0.732	1.650	0.021	4.189	3.249	0.001
WALWORTH	0.149	0.000	0.778	0.000	0.104	0.000	0.000
WASHBURN	0.685	0.204	1.670	0.673	1.637	1.666	0.000
WASHINGTON	0.126	0.007	0.708	0.152	0.527	0.039	0.000
WAUKESHA	0.202	0.000	0.591	0.176	0.502	0.036	0.000
WAUPACA	0.195	0.609	1.024	1.053	1.956	0.109	0.000
WAUSHARA	0.688	0.362	1.063	0.223	0.302	0.432	0.012
WINNEBAGO	0.000	0.000	0.000	0.049	0.000	0.000	0.000
WOOD	0.522	0.000	1.529	0.364	2.049	0.448	0.008