Exhibit 7

Effects of Management on Carbon Sequestration in Forest Biomass in Southeast Alaska

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Wayne Leighty
University of California, Davis

Steven P. Hamburg
Environmental Defense Fund

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Effects of Management on Carbon Sequestration in Forest Biomass in Southeast Alaska

Wayne W. Leighty,[1*†] Steven P. Hamburg,[1] and John Caouette[2]

[1]*Center for Environmental Studies, Brown University, P.O. Box 1943, Providence, Rhode Island 02912, USA;* [2]*Regional Office, Wildlife, Fisheries, Ecology and Watershed, US Forest Service, P.O. Box 21628, Juneau, Alaska 99802-1628, USA*

Abstract

The Tongass National Forest (Tongass) is the largest national forest and largest area of old-growth forest in the United States. Spatial geographic information system data for the Tongass were combined with forest inventory data to estimate and map total carbon stock in the Tongass; the result was 2.8 ± 0.5 Pg C, or 8% of the total carbon in the forests of the conterminous USA and 0.25% of the carbon in global forest vegetation and soils. Cumulative net carbon loss from the Tongass due to management of the forest for the period 1900–95 was estimated at 6.4–17.2 Tg C. Using our spatially explicit data for carbon stock and net flux, we modeled the potential effect of five management regimes on future net carbon flux. Estimates of net carbon flux were sensitive to projections of the rate of carbon accumulation in second-growth forests and to the amount of carbon left in standing biomass after harvest. Projections of net carbon flux in the Tongass range from 0.33 Tg C annual sequestration to 2.3 Tg C annual emission for the period 1995–2095. For the period 1995–2195, net flux estimates range from 0.19 Tg C annual sequestration to 1.6 Tg C annual emission. If all timber harvesting in the Tongass were halted from 1995 to 2095, the economic value of the net carbon sequestered during the 100-year hiatus, assuming $20/Mg C, would be $4 to $7 million/y (1995 US dollars). If a prohibition on logging were extended to 2195, the annual economic value of the carbon sequestered would be largely unaffected ($3 to $6 million/y). The potential annual economic value of carbon sequestration with management maximizing carbon storage in the Tongass is comparable to revenue from annual timber sales historically authorized for the forest.

Key words: carbon sequestration; geographic information system; climate change; forest management; Alaska.

Introduction

Concern over rising levels of atmospheric carbon dioxide, a primary greenhouse gas (GHG), has given impetus to the construction of global carbon budgets. Forest carbon dynamics are a key component of these budgets. Although the Kyoto Protocol of the UN Framework Convention on Climate Change provides for a potentially active and regulated market in Certified Emission Reduction credits (CERs) for some types of forest management, implementing such a program has been controversial, and as of 2006 the United States has not ratified the Kyoto Protocol. Quantifying sources and sinks of carbon and the fluxes resulting from forest management is essential for the accurate estimation of national emissions and transparent functioning of a CER market that could help a country meet GHG emission reduction targets.

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**Corresponding author; e-mail:* WayneLeighty@alumni.brown.edu
Current address: P.O. Box 20993, Juneau, Alaska 99802, USA

Terrestrial vegetation and soil represent important sources and sinks of atmospheric carbon (Watson and others 2000), with land-use change accounting for 24% of net annual anthropogenic emission of GHGs to the atmosphere (Prentice and others 2001). Managing these terrestrial carbon stocks to mitigate future climate change requires information on global and national carbon budgets. Specifically, the management of public lands represents a policy challenge, because there is often a mandate to consider multiple uses, including carbon storage or reduced emissions. Consequently, estimating the potential economic value of the carbon held in these lands, and the impacts of management on carbon stocks, may become an important part of managing public lands.

It is likely that CERs would be allocated based on the change in total carbon stock caused by a shift in forest management. Consequently, quantifying net carbon flux under varied management regimes and establishing a ''business as usual'' baseline are key to planning for future uses of public lands.

We chose to study the carbon implications of forest management of the Tongass National Forest (Tongass) in southeast Alaska for several reasons. First, the Tongass is the largest national forest in the United States, and it is part of the largest intact old-growth temperate rainforest in the world (USDA Forest Service 2005). Second, few estimates of terrestrial carbon pools include Alaska, and we are aware of no estimates of net carbon flux that include the Tongass (Turner and others 1995; R. A. Birdsey personal communication). Based on studies of similar ecosystems in the US Pacific Northwest, however, it is reasonable to assume there is a large net carbon flux due to harvesting in the Tongass (Harmon and others 1990; Smithwick and others 2002). Third, the dearth of information about carbon flux in the Tongass has prevented inclusion of the economic value of carbon storage in the development of forest management policies for the Tongass. Economic value provides a common metric for comparison of the relative merits of carbon management with other goods and services provided by the forest. Finally, knowledge about the effects of management regimes on net carbon flux in the Tongass will help define the relative importance of the management of these federal lands on GHG emissions in the United States.

Commercial timber harvesting began in the Tongass in the early 20th century, and harvest intensity increased in 1954 after the granting of two 50-year timber contracts to large pulp mills (Ketchikan Pulp Corporation and the Alaska Pulp Corporation). In the 1990s, the timber volume harvested from the Tongass declined as a result of the closure of these two pulp mills. There was a net loss to the Tongass timber program in 1998 of about $29 million on $6.5 million in timber sales (USDA Forest Service 2001).

The research reported in this study was designed to assess Tongass carbon stocks in 1995, historic net carbon flux from the Tongass, effects of future management regimes on net carbon flux, and the economic value of any net carbon sequestration resulting from possible future management regimes.

In this research, existing (1995) and historic carbon stocks of the Tongass were estimated by integrating geographic information system (GIS) data with forest inventory data. Then this spatially explicit model was used with accretion data from permanent plots to examine the effects of five future management regimes on net carbon flux for the period 1995–2195.

Methods

The 70,000-km^2 Tongass National Forest lies within the Pacific Northwest coastal temperate rainforest biome, with average annual precipitation of 150–560 cm, average winter temperatures of −1° to 10°C, and average summer temperatures of 10° to 21°C (Nowacki and others 2001). Glaciers covered most of the region 14,000–20,000 y bp and are now found in some valleys (Nowacki and others 2001). Stretching 800 km along the southeast coast of Alaska, the Tongass includes 22,000 islands with forest, muskeg, alpine meadow, rock, fresh water, and ice (Nowacki and others 2001; Everest and others 1997). Twenty percent of the area of the Tongass is rock and ice, 12% is densely vegetated forestlands, 43% is moderately vegetated forestlands, and 25% is wetlands (USDA Forest Service 2000). The forest composition of the Tongass in 1995, based on species frequency in forest inventory data, was 43% Western hemlock (*Tsuga heterophylla*), 19% Alaska yellow cedar (*Chamaecyparis nootkatensis*), 16% mountain hemlock (*Tsuga mertensiana*), 9% Sitka spruce (*Picea sitchensis*), 7% western red cedar (*Thuja plicata*), 5% lodgepole pine (*Pinus contorta*), and 1% other species (USDA Forest Service 1995b). In the 1970s, over 2000 km^2 (3%) of the Tongass came under the control of Alaska Native Corporations as a result of the Alaska Native Claims Settlement Act. These lands were excluded from this study because they lack comprehensive forest inventory data.

Estimate of Existing Carbon Stocks

Calculation of Carbon Stocks at Sample Plots across the Tongass. Carbon stocks were calculated for each of the USDA Forest Service 1995 Forest Inventory Assessment (FIA) Southeast Alaska Grid Inventory's 2000 systematic sample plots using data from these plots (USDA Forest Service 1995b). Data on live and dead vegetation (including diameter, height, and species), downed woody debris, and soil (including thickness of Oi, Oe, and Oa horizons) were collected at each sampling plot (USDA Forest Service 1995b) (see Appendix 1 at <http://www.springerlink.com>).

We used these data to quantify the following seven carbon pools for each FIA sampling plot: (a) trees, (b) saplings/seedlings, (c) standing dead wood, (d) coarse woody debris (CWD) (average diameter more than 7.62 cm), (e) small woody debris (SWD) (average diameter less than 7.62 cm and large-end diameter more than 2.5 cm), (f) understory vegetation, and (g) soil.

Allometric equations were used with tree diameter and height data to estimate biomass (Mg/ha) (see Appendix 2 at <http://www.springerlink.com>). For species with more than one suitable allometric equation, biomass was estimated using equations resulting in both the lowest and highest biomass estimates (see Sensitivity Analysis). To address the need to use most of the equations beyond the range of data from which they were created, three-dimensional surface plots were created to confirm consistent behavior of the equations (for example, no inflection points) over the range of diameter at breast height (dbh) and heights to which they were applied. Additionally, the total amount of carbon in trees larger than the allometric equation bounds was estimated in our sensitivity analysis. Root-to-shoot ratios for coniferous forests (with the exception of *Pinus sylvestris*, a European species) range from 15% to 26%, so belowground biomass was assumed to be 20% of aboveground biomass (Santantonio 1977; Cairns and others 1997; Hamburg and others 1997). Additionally, belowground biomass was calculated with the range 15%–26% of aboveground biomass in our sensitivity analysis. Carbon was assumed to account for 50% of tree biomass (Hamburg and others 1997).

Standing dead biomass was calculated with the same methods used for living trees, but with a decay factor (0%–100% depending on the extent of decay and component of the tree) (see Appendix 3 at <http://www.springerlink.com>). Likewise, the same allometric equations were used to calculate the amount of carbon in seedlings and saplings (dbh less than 2.5 cm and 2.5 to dbh 12.5 cm, respectively).

The amount of carbon in CWD was calculated using FIA methods ((K. L. Waddel) public communication 2001, An application of line intersect sampling to estimate attributes of coarse woody debris in resource inventories, USDA Forest Service Pacific Northwest Research Station, Forest Sciences Laboratory) (see Appendix 4 at <http://www.springerlink.com>). The amount of carbon in SWD was calculated with the methods described by Brown (1974) (see Appendix 4 at <http://www.springerlink.com>).

Understory biomass was calculated using the foliar cover-to-biomass relationships developed in Alaska by Yarie and Mead (1988). By aggregating understory species described by Yarie and Mead into the general taxonomic categories used in the FIA, we calculated a species-weighted biomass constant for each FIA category. Biomass in understory vegetation was then calculated by multiplying these constants by foliar percent cover data from the FIA horizontal/vertical (HV) subplot data. Biomass estimates for each layer described in the FIA HV data were summed to yield total understory carbon stocks (Mg C/ha) for each FIA plot.

Soils data from the FIA Grid Inventory were inadequate for accurately estimating soil carbon in southeastern Alaska because only the top 50 cm were sampled, but organic horizons alone are often much deeper (Alexander and others 1989). Consequently, total soil carbon in organic and mineral horizons was calculated by applying the soil-category carbon stocks developed for the Tongass by Alexander and others (1989) to each of the more than 800 soil management units (SMU) in the Tongass (USDA Soil Conservation Service 1992a, 1992b; 1994; D. V. D'Amore personal communication 2001). Alexander and others used soil samples and pedon descriptions to estimate average organic carbon stock (kg C/m^2) for 10 general soil categories in the Tongass (see Appendix 5 at <http://www.springerlink.com>). The SMU scheme defines soil profiles, with the area of each SMU mapped in polygons in a GIS database (GIS polygon data define areas with defined attributes).

We began by grouping each SMU into the soil categories described by Alexander and others (1989). Then each SMU was assigned the carbon stock given by Alexander and others for its associated category. When an SMU was intermediate to two soil categories, it was assigned to the category with a lower carbon stock to ensure a conservative carbon estimate. Finally, total soil carbon in the Tongass was calculated by multiplying the carbon

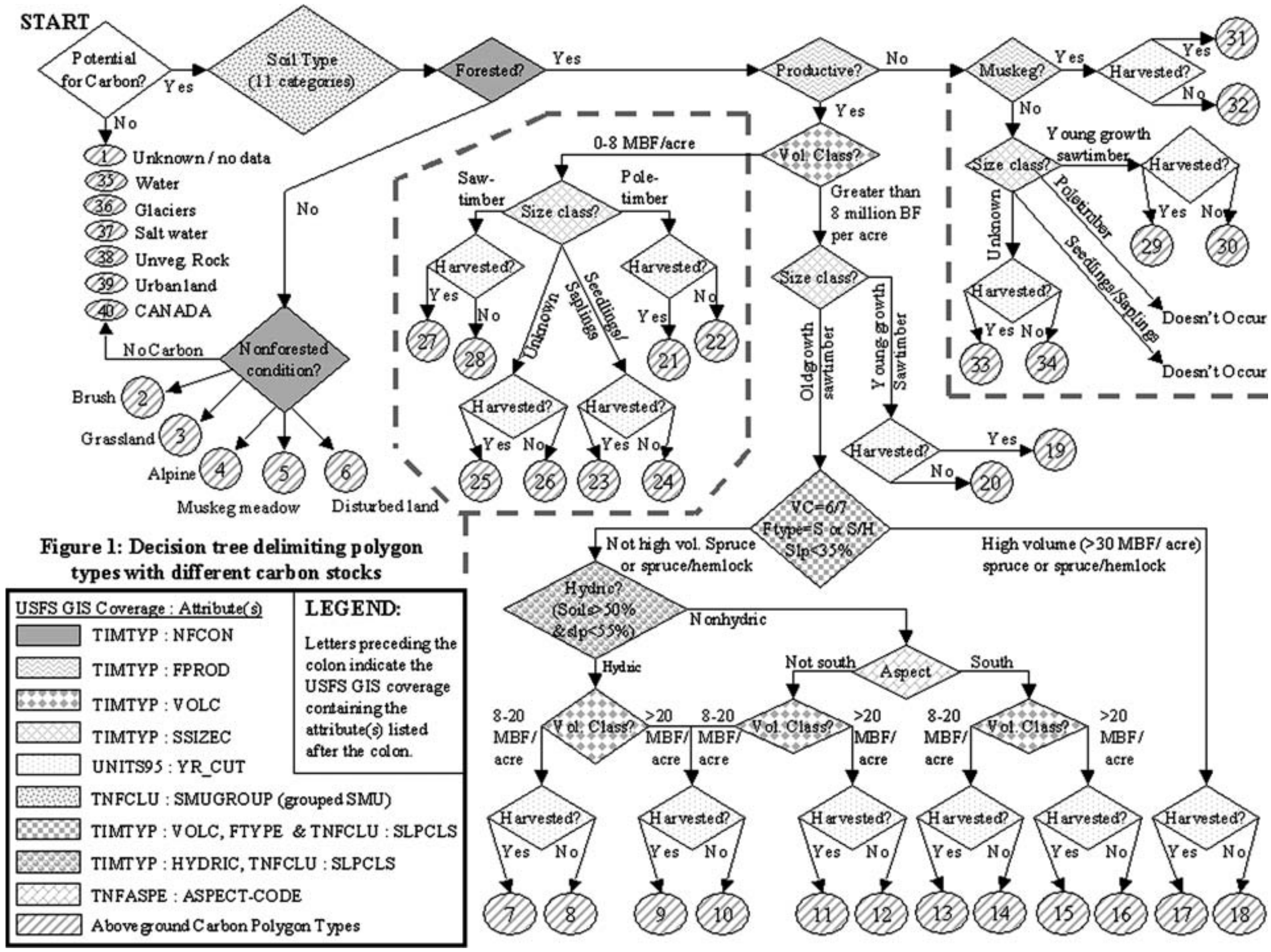

Figure 1. Decision tree delimiting polygon types with different carbon stocks. Ovals represent Aboveground Carbon Polygon Types (ACPTs). These 40 polygon types exist for each of 11 soil-type categories, for a total of 370 Total Carbon Polygon Types (TCPTs). Pattern-coded diamonds indicate data sources used in differentiating among polygons. Dotted lines divide the figure into four general classes of ACPTs for ease of interpretation. MBF, million board feet (2360 m^3); SMU, soil associations and complexes; NFCON, nonforested conditions; FPROD, expected annual growth; VOLC, timber volume; SSIZEC, dominant timber size; YR_CUT, year of timber harvest; FTYPE, general forest type; SLPCLS, slope gradient; HYDRIC, hydric and nonhydric soil conditions; ASPECT-CODE, slope aspect.

stock assigned to each SMU by its total area. In the 10% of the Tongass where soil type has not been mapped, mostly wilderness areas, soil carbon stock was assumed to be the spatially weighted average of all soil types. Total soil carbon in the Tongass was also calculated from FIA soil pit data (see Sensitivity Analysis).

Creation of Spatially Explicit Land-Cover Types and Carbon Stock Estimates. Existing USDA Forest Service GIS data (Figure 1) were combined using the computer software ArcInfo 380 New York Street Redlands, CA 92373-8100 (Environmental Systems Research Institute; Workstation ArcInfo, copyright 1982–2002, ver. 8.0). A decision tree (Figure 1) was applied to the resulting Complete Coverage for the Tongass using SAS (SAS Institute Inc; 100 SAS Campus Drive, Cary, NC 27513-2414 SAS System for Windows, copyright 1989, 1996, release 6.12) to define Total Carbon Polygon Types (TCPT) and Aboveground Carbon Polygon Types (ACPT) based on polygon attributes.

The decision tree uses available polygon attributes to predict polygon types with varying aboveground and belowground carbon stocks. For example, an unharvested, productive spruce–hemlock forest with high volume and size class (ACPT 18) contains greater aboveground carbon stocks than a harvested, productive forest with low volume and size class (ACPT 23) (Figure 1).

Next, the polygons in the Complete Coverage were aggregated based on their TCPT (370 polygon types) and ACPT (40 polygon types) designation.

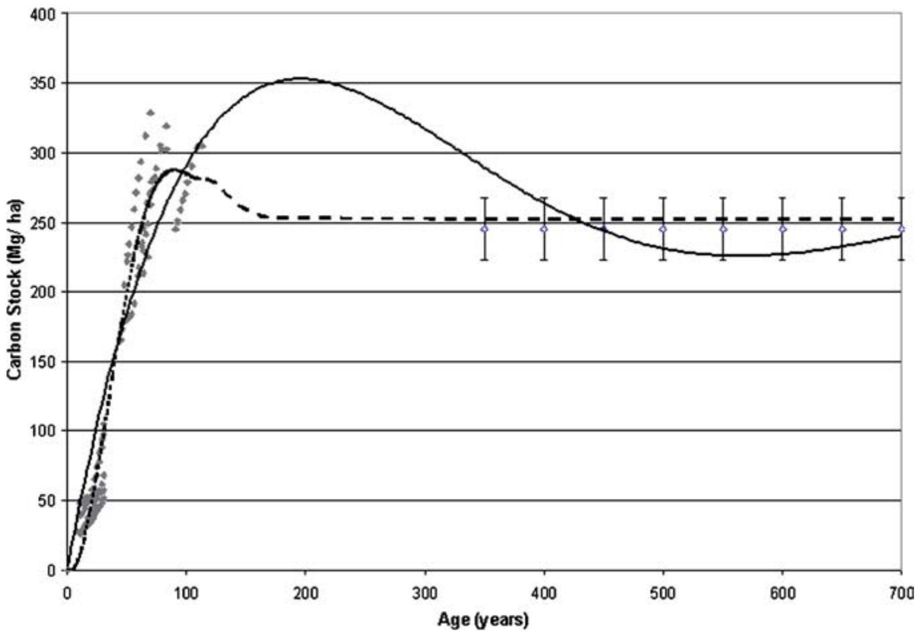

Figure 2. Carbon accretion curves for aboveground live biomass. Filled diamonds represent data from permanent plots; open diamonds are the area-weighted average of old-growth Aboveground Carbon Polygon Types (ACPTs). The solid line shows the best-fit polynomial model of carbon accretion; the dashed line is the asymptotic accretion curve. Variable site quality (site index) causes divergence among permanent plot data.

Polygon slivers caused by the aggregation processes in ArcInfo (defined as polygons with area less than 0.4 ha and *perimeter/area* ratio greater than 1) were merged with their largest neighboring polygon.

Finally, the location of each FIA plot was associated with a TCPT. The aboveground and belowground carbon stocks for each TCPT (Mg C/ha) were then calculated by averaging the carbon stocks for all FIA plots in the TCPT. The total carbon stock in the Tongass was calculated by multiplying the carbon stock for each TCPT by its area and summing all TCPTs.

Projecting Net Carbon Flux

Equations were constructed to model carbon accretion in aboveground biomass after harvesting (Figure 2). Forest inventory data from 272 permanent ''growth and yield'' plots from throughout the Tongass were used to estimate biomass accumulation over the first 100 years of regrowth (DeMars 2000). The area-weighted average aboveground carbon stock of all old-growth commercial forest ACPT was used to approximate the carbon stock of forests more than 350 years old (assumed to be in equilibrium) because prior research suggests it can take 350 years for forests in southeast Alaska to reach old-growth equilibrium (Janisch and Harmon 2002). We addressed the lack of data on biomass of stands 100 to 350 years old by employing two carbon accretion models for 500 y of forest growth: a polynomial ($y = 9 \bullet 10^{-12} \bullet x^5 - 3 \bullet 10^{-8} \bullet x^4 + 4 \bullet 10^{-5} \bullet x^3 - 0.0209x^2 + 4.6459x, R^2 = 0.8727$) and an asymptotic ($y = 10^5 \bullet x^4 - 0.0027x^3 + 0.2078x^2 - 1.0021x, R^2 = 0.9531$). Comparison between these two models enabled us to test the sensitivity of flux estimates to the uncertain shape of this accumulation curve.

Pools of CWD were assumed to increase after harvest by 40% of the preharvest aboveground standing biomass (estimated from FIA data) due to stumps and slash left on site, and then decline with decomposition (Sampson and Hair 1996). Carbon stocks in the soil before and after harvest were assumed to be unchanged due to lack of data informing us otherwise.

Past net carbon flux, since 1900, was based on historic harvest volumes. We split the harvest history in the Tongass into two time periods, 1900–54 and 1955–95, because the rate of timber harvest increased dramatically in 1954 with the initiation of two long-term timber contracts (USDA Forest Service 1995a). Because nearly all timber harvesting in the Tongass has involved clear-cutting, we assumed that this harvest method would continue in the future. Future net carbon flux was modeled for the following five forest management regimes: (a) no timber harvesting, regrowth of secondary forest, and equilibrium in unharvested areas (a lower bound for harvest intensity); (b) harvesting of all forested lands on 100-year rotations (an upper bound for harvest intensity); (c) harvesting of all forested lands on 200-year rotations (used to examine the impact of harvest rotation period); (d) harvesting of all lands currently available for harvest (exclusion of existing roadless areas) on 200-year rotations (represents an approximation of ''business as usual''); and (e) harvesting of all lands currently available for harvest (exclusion of existing roadless areas) on 100-year rotations (used to examine the impact of harvest rotation period). Current land-use designations (USDA Forest Service GIS coverage LUD99) were used to identify areas available for harvest, and projected harvests were spread evenly across available land.

Forest regrowth was assumed to follow the biomass accretion models described above, with the amount of carbon in a specific polygon dependent on stand age and precut carbon stocks. For the modeling of past net carbon flux, the total carbon stock in 1900 was calculated by assuming that all polygons were unharvested in 1900 and assigning carbon stocks to harvested polygon types equal to their unharvested equivalents (Figure 1). We allocated the total net historic flux (difference between carbon stock in 1900 and 1995) between the time periods 1900–54 and 1955–95 in proportion to the volume of timber cut in each period.

To estimate net carbon flux associated with harvesting, we calculated the forest products stream, the amount of carbon left on site as slash and stumps, and the amount of carbon sequestered annually in secondary growth at annual time steps. Net annual carbon flux from the Tongass was calculated as the total amount of carbon leaving the forest less regrowth and does not include carbon storage in forest products. Carbon storage in forest products was included in estimates of net annual carbon flux to the atmosphere, assuming that 60% of the aboveground living biomass is merchantable and the rest is left on site as slash and stumps (Sampson and Hair 1996) (Figure 3). Historically, roughly half of the merchantable volume entered the sawtimber production process, whereas the other half entered the pulpwood production process (Warren 1999).

We assumed that 90% of the carbon in sawtimber products was emitted to the atmosphere over 75 years (assuming an exponential release pattern), and that the corresponding figures were 50 years for pulpwood products, and 100 years for slash and stumps left on site after harvesting (Skog and Nicholson 1998). The CWD and SWD present prior to harvesting was assumed to linearly lose half its carbon in the 50 years after harvesting, accounting for decreased deadwood formation in the early stages of secondary growth. These carbon pools were then increased to their preharvest stocks over the next 200 years.

Aboveground carbon stocks after harvesting were assumed to be equal to those in polygons defined as forested, productive, low-volume, harvested areas with seedlings/saplings (ACPT 23) in one set of model runs and to equal zero in another (see Sensitivity Analysis).

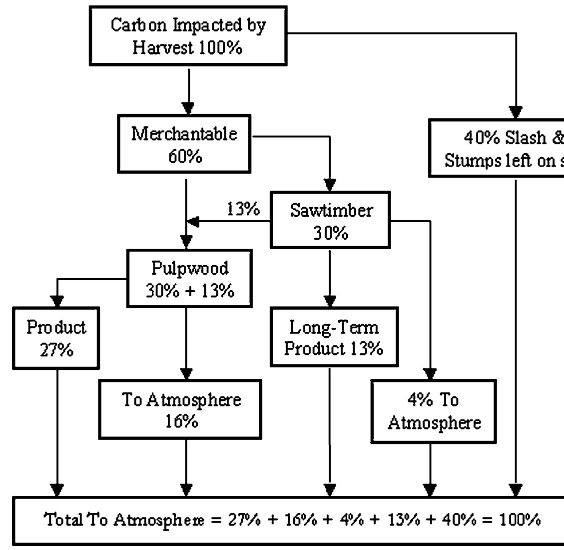

Figure 3. Product/waste flows for the southeast Alaska timber industry. The timing of carbon flux to the atmosphere varies among pathways. Percentages refer to the proportion of the total carbon impacted by harvesting in each product/waste. Figure modified from Sampson and Hair (1996).

Conversion of Net Carbon Flux to Monetary Units

Current estimates of the economic value of carbon in potential emissions trading markets vary widely, from \$5 to \$125 Mg^{-1} C (Weyant 2000); in this analysis, we assumed a market value of \$20 Mg^{-1} C for avoided emissions or sequestered carbon. We did not apply a discount factor or temporal variation in this value, so all monetary values are in 1995 US dollars. Leakage, the possibility of offsetting increases in emissions associated with increased harvest elsewhere, was not considered in estimating the economic value of different management scenarios.

Sensitivity Analysis

To test the influence of assumptions required for the analysis described above, we carried out sensitivity analyses involving the following issues: the selection of allometric equations, the use of allometric equations for trees outside their specified ranges, estimation of soil carbon, the shape of biomass accretion curves, old-growth biomass of cut-over lands, and postharvest carbon stocks. Using the results of specific sensitivity analyses, upper- and lower-bound estimates of net carbon

Table 1. Carbon Pools in the Tongass National Forest in 1995

	Model Runs			
Carbon Pool (Pg)	**1**	**2**	**3**	**4**
Roots	0.12	0.12	0.12	0.04
Soil	1.86	1.86	1.86	1.86
Total aboveground	0.87	0.85	0.82	0.38
Trees	0.42	0.42	0.53	0.18
Seedlings/saplings	0.16	0.16	0.05	0.03
Dead Snags	0.09	0.09	0.10	0.04
CWD	0.18	0.16	0.12	0.12
SWD	0.00	0.00	0.00	0.00
Understory	0.02	0.02	0.02	0.02
Total (+ 95% CI)	2.85 (0.51)	2.83 (0.48)	2.80 (0.51)	2.28 (0.40)

CWD, coarse woody debris; SWD, small woody debris; CI, confidence interval.
Six model runs were made using the following combinations of allometric equations and assumptions to quantify the sensitivity of estimation to necessary assumptions: Run 1 used allometric equations predicting low carbon contents, did not include willow or birch, and included a CWD outlier. Run 2 used allometric equations predicting low carbon contents, included willow and birch, and did not include a CWD outlier. Run 3 used allometric equations predicting high carbon contents, included willow and birch, and did not include a CWD outlier. Run 4 used allometric equations predicting low carbon contents, included willow and birch, and did not include a CWD outlier or trees with dbh greater than specified for each allometric equation.

flux were calculated. These bounds indicate the potential impact on our estimates of these key sources of uncertainty, but they do not include all possible sources of uncertainty. As such, the sensitivity analysis cannot be considered an uncertainty analysis capable of providing absolute bounds on our estimates.

Tongass carbon pools were estimated using allometric equations resulting in the lowest and highest biomass estimates for all species (Table 1). Similarly, the importance of carbon in trees larger than the size specified for the allometric models employed was examined by calculating the total amount of carbon in these trees.

Carbon in CWD at one FIA plot was an outlier (more than twice the next nearest measurement); therefore it was excluded from calculation of our best estimates of carbon in CWD for this ACPT. We included this high value in our calculations during the sensitivity analyses to verify its relative insignificance.

In addition to the calculation of soil carbon from GIS SMU data described above, total soil carbon was calculated from FIA soil pit data (thickness of soil horizons) using carbon-density estimates (Mg/m^3) for each soil horizon (Alexander and others 1989). For each FIA soil pit, horizon thicknesses were multiplied by their associated carbon density estimate, as given by Alexander and others, to estimate carbon stock. These carbon stock estimates were used to estimate the carbon stock for each SMU, which were then multiplied by the total area of each SMU to calculate total soil carbon stock in the Tongass. The total amount of soil carbon in areas lacking soil GIS data was estimated, with both methods, to gauge the size of this uncertain carbon pool.

In calculating our upper- and lower-bound carbon pool and net flux estimates, belowground biomass was calculated using the upper (26%) and lower (15%) bounds of applicable published root-to-shoot ratios.

The time periods for 90% carbon emission from the saw timber, pulp products, and slash pools were both doubled and halved to gauge the influence of these rates on the shape of projected net carbon flux curves.

Net carbon fluxes were modeled using both asymptotic and polynomial biomass accretion curves (Figure 2). Net carbon flux was also calculated using mean and 95% confidence limits (CL) for carbon stock estimates for each ACPT.

In the no-harvesting scenario, there was uncertainty as to the long-term biomass accumulation on cut-over lands. For example, will ACPT 7 eventually reach the carbon stock of ACPT 8 or 10 (Figure 1)? To test the sensitivity of net flux projections to the assumed precut carbon stock, the model was run assuming biomass accumulation to a carbon stock of the most similar ACPT, as well as to the carbon stock of a related ACPT with the highest timber volume.

The carbon stock in aboveground standing biomass of ACPT 23 was used as an estimate of the amount of carbon present immediately after harvesting. However, this ACPT is defined as con-

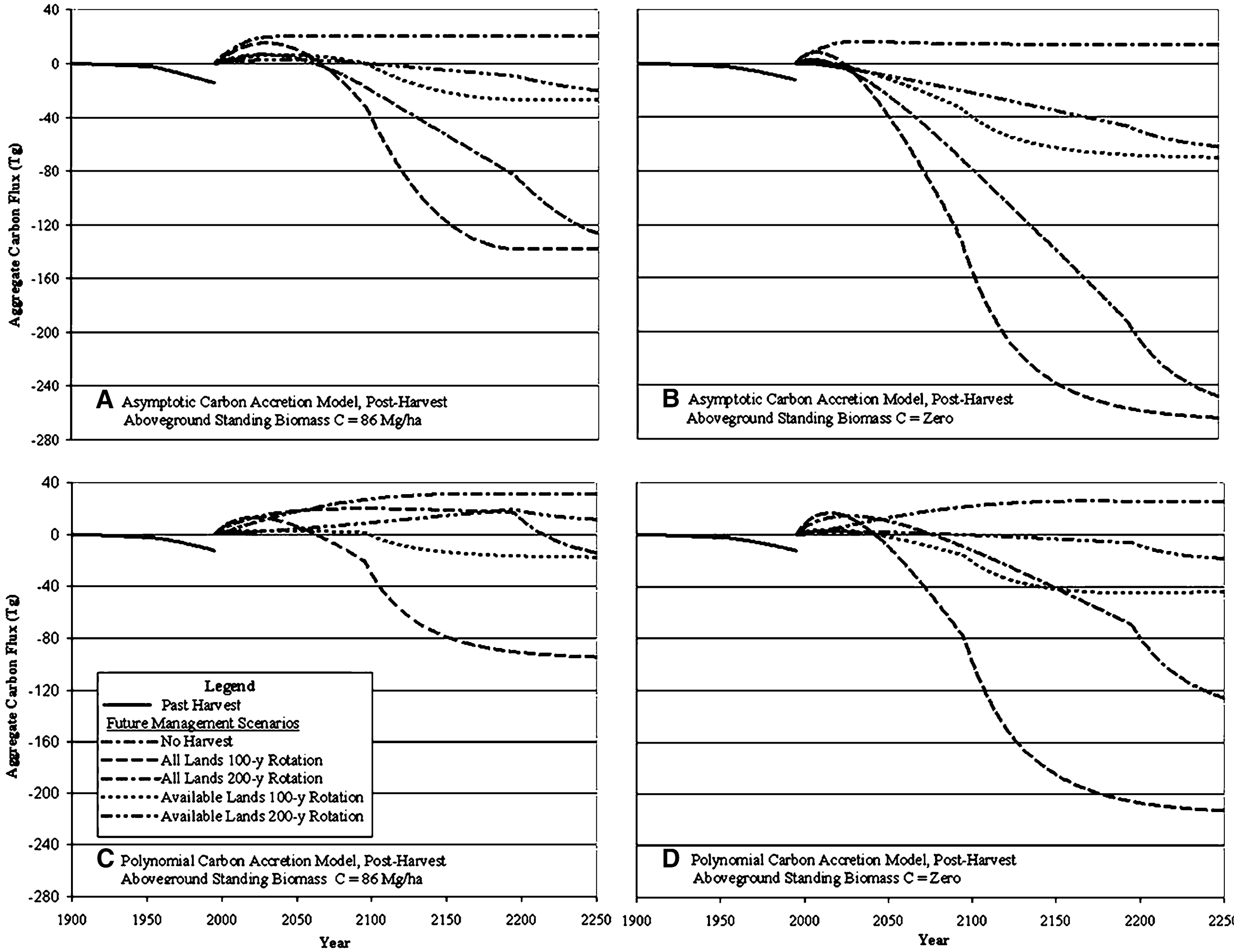

Figure 4. Past and potential future aggregate net carbon flux between the Tongass and atmosphere (excluding soils). **A–D** Aggregate net carbon flux between the Tongass and the atmosphere with each management scenario, re-zeroed in 1995. Asymptotic carbon accretion in secondary growth is assumed in A and B; polynomial carbon accretion in secondary growth is assumed in C and D. Carbon stock in standing aboveground biomass after harvesting is assumed to be equal to zero in B and D; carbon stock in standing aboveground biomass after harvesting is assumed to be equal to 86 Mg C/ha in A and C. The total carbon stock in the Tongass was estimated to be 2.83 Pg in 1995. Negative aggregate net flux indicates carbon emission from the Tongass; positive aggregate net flux indicates carbon accumulation in the Tongass.

taining forest composed of seedlings and saplings (86 Mg C/ha), which suggests that between 5 and 15 years have elapsed since harvesting in these areas. Consequently, net flux projections were also performed assuming zero carbon stocks in aboveground standing biomass after harvesting, a clear underestimate of aboveground living biomass on recently clear-cut lands.

We did not explore the effects of varying our assumptions about the forest products industry (for example, the proportion of biomass used for merchantable products or the ratio of sawtimber to pulp production) in the calculation of upper and lower bounds in our sensitivity analysis. Altering these assumptions does influence the shape of our projections of net carbon flux to the atmosphere (Figure 4) but does not impact the magnitude and was therefore not amenable to quantification in a sensitivity analysis. Changing these assumptions essentially hastens or delays carbon emission to the atmosphere depending on whether more carbon is entering product streams with longer or shorter life spans. More detailed examination of this effect is beyond the scope of this paper.

Results

Evaluation of our spatially explicit carbon stock estimates suggests that they are a realistic representation of forest structure. Comparison of GIS carbon stock coverages to aerial photographs showed a correlation between observable transi-

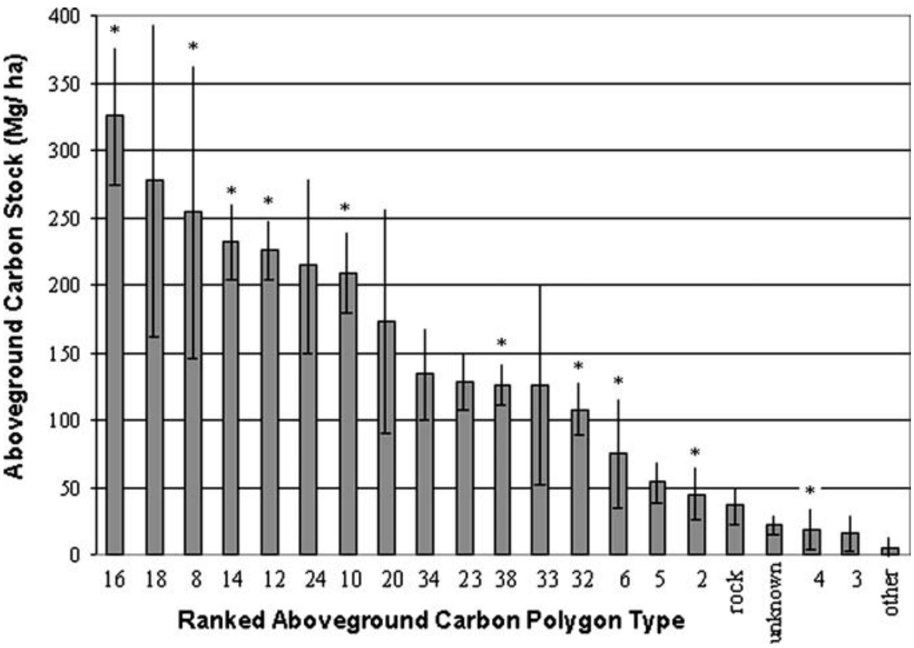

Figure 5. Aboveground carbon stock by Aboveground Carbon Polygon Type (ACPT) number, ranked by aboveground carbon stock. Carbon stocks for all ACPTs (polygon types with *n* less than 5 are omitted) are shown in gray. Asterisks identify the 10 ACPTs that account for 86% of total carbon in the Tongass (95% CI).

tions in forest characteristics and mapped carbon densities.

The creation of carbon stock polygons resulted in a limited number of distinct and unique landscape units. Twelve ACPTs account for over 90% of the area of the Tongass, and 10 of them account for 86% of the total carbon (Figure 5). Polygon types with few FIA sample plots have large uncertainty in carbon stock estimates, but they represent small land areas and contribute very little to the total carbon stock. The 17 ACPT with less than five FIA plots represent 2% of the area of the Tongass and 1% of the total carbon, whereas each of the 10 ACPTs that combine for 86% of the total carbon stock of the Tongass have between 43 and 312 FIA sample plots each.

The aboveground carbon stocks in each ACPT correspond with qualitative descriptions of the areas. Unharvested high volume old-growth forest (ACPT 18), for example, has over five times the aboveground carbon stock of a muskeg meadow (ACPT 5) (Figures 1 and 5). The influence of soil carbon, however, complicates this relationship when considering total carbon stock because the soil may contain over half of total ecosystem carbon, thereby preventing a simple relationship between the description of aboveground forest characteristics and total carbon stock. Total carbon stock in a muskeg meadow (ACPT 5), for example, averages about 1.5 times that of unharvested high volume old-growth forest (ACPT 18). However, we did find a relationship between aboveground and soil carbon stocks, one largely defined by the following ecosystem types: muskeg, forest, and alpine meadow/rock and ice (see Appendix 6 at <http://www.springerlink.com>).

Total carbon in the Tongass (soil, aboveground living biomass, and roots and dead woody debris) was estimated to be 2.8 ± 0.5 Pg (95% confidence interval [CI]) (Table 1). In all, 42% of the variability is the uncertainty in aboveground carbon stock estimates, 6% is from uncertainty in root carbon (root-to-shoot ratios), and 52% is from uncertainty in soil carbon. Assumptions about the allometric biomass equation used for willow and birch, the exclusion of an outlying CWD data point, and estimation of CIs for carbon stocks in polygons lacking sufficient data have insignificant influence on total carbon or the CI (Table 1). Trees outside the size range of the allometric models account for 19% of the total carbon estimate. Three-dimensional surface plots of the allometric equations maintained consistent shape outside the dbh range for which the equations were developed.

The carbon stock in the Tongass forest and soils (2.8 Pg) comprises 7.7% of the carbon in the forests and soils of the conterminous United States (36.7 Pg) (Turner and others 1995) and 0.25% of the carbon in the Earth's forest vegetation and soils (1,146 Pg) (Dixon and others 1994).

In all, 66% of the total carbon in the Tongass is in the soils, 30% is in aboveground biomass (15% in live trees, 6% in seedlings and saplings, 3% in standing dead wood, 6% in CWD, less than 1% in SWD, and 1% in understory vegetation), and 4% is in roots. Less than 1% of the total carbon estimates were influenced by the assumptions involved in our calculation of aboveground carbon stocks (for example, selection of allometric equations and application of these equations beyond their specified range). Uncertainty in the density and distribution of understory vegetation did not affect the analysis. Twenty-two percent of total carbon in the Tongass is in the soils of polygons where soil types have not been mapped. Comparison of the results from application of soil carbon density estimates from Alexander and others (total soil carbon = 1.9 Pg) with total soil carbon given by calculations using FIA Grid Inventory soil pit data (total soil carbon = 0.49 Pg) suggests that more than 70% of soil carbon is not reported in the FIA data.

We produced several net carbon flux projections for each management regime to capture carbon dynamics associated with the following factors: variations in the residence time of carbon in slash, long-term forest products, and short-term forest products; and effects of the carbon accretion model (polynomial or asymptotic) (Figure 4). The annual rate of net carbon flux is the first derivative of the aggregate net carbon flux presented in Figure 4. Doubling or halving the time periods for 90% carbon emission from the saw timber, pulp products, and slash pools alters the shape of projected net carbon flux curves but causes less than 0.6% change in average annual net carbon flux for all modeled management regimes.

The average annual net carbon flux from the Tongass during the period 1900–54 was 60,000 Mg C/y, and the average annual net flux from the Tongass for the subsequent 41-year period was 307,000 Mg C/y. Estimates of future net carbon fluxes are presented in Table 2; upper- and lower-bound estimates were calculated using the results of the sensitivity analyses.

Our best estimate of the net annual economic value of carbon sequestration that would result from ceasing all harvesting in the Tongass is \$4 to \$7 million/y for the 100-year period 1995–2095 and \$3 to \$6 million/y for the 200-year period 1995–2195 (Table 3). Our best estimate of the net annual economic value of carbon emission resulting from increased harvesting of administratively available forested lands is −\$3 million/y for the 100-year period 1995–2095 and −\$2 to −\$4 million/y for the 200-year period 1995–2195.

Discussion

Using GIS data in combination with FIA data proved to be an effective and robust approach to estimating carbon stocks and modeling the effects of different management regimes on future net carbon flux. New spatially explicit data could be integrated into our existing models, enabling application of the models to other areas and refinement of net carbon flux estimates if future GIS data collection is carried out with this application in mind.

A lack of data on tree size and density necessitated the use of timber volume classes in mapping carbon stocks. Although tree size and density data are preferable, timber volume is tightly correlated with carbon stocks (Hamburg and others 1997), and low variances among the 10 most important ACPTs suggest the robustness of using existing volume data to map carbon stocks.

The range in estimates of net carbon flux from ceasing all timber harvesting may overestimate the uncertainty in this projection. We aggregated uncertainties of carbon stocks, assumptions about aboveground carbon stocks postharvest, and the carbon accretion model that we used; yet it is highly likely that these uncertainties are independent, and thus not additive.

The uncertainty in net flux estimates resulted largely from selection of the biomass accretion model, asymptotic or polynomial (Figure 2). The rapidity with which carbon accretion progresses to equilibrium in the asymptotic model may be unrealistic, but the polynomial model's prediction of carbon stocks greater than those found in old-growth stands may also be unrealistic. Unfortunately, the limited availability of chronosequence data leaves a gap in our understanding of carbon accretion during the transition period from early secondary growth to old growth. Furthermore, calculation of carbon stocks for old-growth stands from area-weighted averages of old-growth polygon types is not analogous to the FIA permanent plot data used for young stands and may confound our accretion models. Data from FIA permanent plots in old-growth forest could be used to test both our assumption of steady-state carbon stocks and 250 Mg C/ha in aboveground live biomass in old-growth forest. The actual pattern of carbon accretion probably lies somewhere between the polynomial and asymptotic models, but we have insufficient data to craft a more realistic model (Janisch and Harmon 2002).

Our use of the area-weighted average aboveground carbon stocks of all old-growth commercial forest types in creating the biomass accretion models could introduce bias if remaining old-growth forests are lower in biomass than the old-growth forests already harvested. Failure to area-weight

Table 2. Average Annual Net Carbon (C) Flux Projections from the Tongass

		Average Annual Net C Flux from Tongass National Forest (000s Mg C/y)						Average Annual Net C Flux from Tongass National Forest to the Atmosphere (000s Mg C/y)					
		Aboveground Standing Biomass C after Harvest = 86 Mg C/ha			Aboveground Standing Biomass C after Harvest = 0 Mg C/ha			Aboveground Standing Biomass C after Harvest = 86 Mg C/ha			Aboveground Standing Biomass C after Harvest = 0 Mg C/ha		
Management Regime	C accretion Model	Upper Bound	Best Estimate	Lower Bound	Upper Bound	Best Estimate	Lower Bound	Upper Bound	Best Estimate	Lower Bound	Upper Bound	Best Estimate	Lower Bound
1900–95													
Historic management	Polynomial accretion	180	160	67	180	160	67	140	130	54	140	130	54
	Asymptotic accretion	200	180	74	180	160	67	170	150	63	140	130	54
1995–2095													
Cessation of all harvesting	Polynomial accretion	−330	−270	−210	−330	−270	−210	−330	−270	−210	−280	−210	−180
	Asymptotic accretion	−270	−200	−120	−210	−150	−91	−270	−200	−120	−210	−150	−91
All forested lands harvested on a 100-y rotation	Polynomial accretion	840	440	71	1700	1200	880	470	200	−65	1100	790	520
	Asymptotic accretion	1300	780	390	2300	1800	1300	530	310	130	1700	1300	910
All forested lands harvested on a 200-y rotation	Polynomial accretion	−0.59	−110	−230	410	300	180	−160	−200	−280	140	95	12
	Asymptotic accretion	640	410	210	1200	910	650	280	170	84	920	710	480
Administratively available forested lands harvested on a 100-y rotation	Polynomial accretion	160	5.4	−140	400	250	97	100	−15	−160	280	160	17
	Asymptotic accretion	280	120	−12	600	420	230	91	0.43	−69	480	330	150
Administratively available forested lands harvested on a 200-y rotation	Polynomial accretion	−40	−100	−180	81	17	−58	−39	−87	−170	51	1.7	−86
	Asymptotic accretion	150	57	−16	330	230	140	55	−1.5	−43	300	200	73
1995–2195													
Cessation of all harvesting	Polynomial accretion	−190	−160	−130	−190	−160	−130	−190	−160	−130	−170	−130	−110
	Asymptotic accretion	−140	−100	−58	−100	−70	−44	−140	−100	−58	−100	−70	−44
All forested lands harvested on a 100-y rotation	Polynomial accretion	740	430	150	1300	1000	720	770	450	160	1300	1000	740
	Asymptotic accretion	1100	680	360	1600	1300	920	1100	690	360	1700	1300	930
All forested lands harvested on a 200-y rotation	Polynomial accretion	120	−39	−180	610	450	300	42	−84	−210	470	350	220
	Asymptotic accretion	850	540	280	1400	1100	770	670	420	210	1300	960	690
Administratively available forested lands harvested on a 100-y rotation	Polynomial accretion	160	57	−47	330	230	120	190	83	−37	350	220	100
	Asymptotic accretion	250	130	27	440	310	190	260	130	28	470	340	200
Administratively available forested lands harvested on a 200-y rotation	Polynomial accretion	−30	−110	−180	120	40	−33	−29	−97	−180	100	32	−48
	Asymptotic accretion	190	76	−17	360	250	150	140	47	−30	350	230	110

Annual net carbon flux was projected for total carbon leaving (or entering) the Tongass and for the portion of this carbon exchanged with the atmosphere. To quantify the influence of two important uncertainties, carbon accretion rate and carbon stock in aboveground standing biomass left after harvesting, net carbon flux was modeled for each management regime with both polynomial and asymptotic carbon accretion curves and with carbon in aboveground standing biomass after harvesting equal to zero or 86 Mg C/ha. Our best estimate of each net flux was calculated with reasonable judgments for other required assumptions; the upper and lower bounds were calculated with the combination of assumptions that yielded the highest and lowest possible net flux estimates.

Table 3. Average Annual Economic Values for Net Carbon Flux ($ million/y) from the Tongass to the atmosphere

Management Regime Modeled	Secondary Growth Curve			
	Polynomial Accretion		Asymptotic Accretion	
	1995–2095	1995–2195	1995–2095	1995–2195
Cessation of all harvesting	3.7	2.2	2.5	1.2
100-y rotation (all forested lands)	−16	−21	−26	−26
200-y rotation (all forested lands)	−1.9	−6.9	−14	−19
100-y rotation (admin. avail. forested lands)	−3.2	−4.5	−6.6	−6.8
200-y rotation (admin. avail. forested lands)	−0.03	−0.63	−4.0	−4.7
Maximum range of net annual carbon value from ceasing harvest	3.7–20	2.9–23	6.6–29	5.9–27
Best estimate of net annual carbon value from ceasing harvest	3.7	2.9	6.6	5.9

Average annual economic value of net carbon flux for each management regime modeled was calculated using our net carbon flux estimates and a value of $20 Mg^{-1} C. The maximum range of net annual carbon value from ceasing harvest is the difference between ceasing harvest and the alternative management regime with the most carbon emission (100-year rotation of all forested lands). The best estimates of net annual economic value are the difference between ceasing harvest and 200-year rotation of administratively available forest lands (a close approximation of ''business as usual''). These estimates assume zero carbon in standing aboveground biomass after harvesting and reduction of Certified Emission Reduction Credits (CERs) by 13% to account for reduced carbon storage in long-term forest products.

these mean values, however, could give too much importance to the rare forest conditions, which have relatively few representative FIA sample plots.

Net carbon flux projections for the 200-year rotation scenarios are more strongly influenced by selection of the carbon accretion model than are the 100-year rotation scenarios because the 200-year rotations allow enough time for secondary growth to reach the peak carbon stocks predicted by the polynomial model. Net carbon flux projections for management regimes involving 100-year rotations are less sensitive to the selection of carbon accretion curve because forested lands are reharvested before there is a significant difference in the trajectories of the two models. Resolution of the uncertainty in carbon accretion rates is imperative for informing forest management policy directed at carbon sequestration.

The distribution of carbon among soils (66%), aboveground living and dead biomass (30%), and belowground living biomass (4%) is consistent with carbon inventories completed in other ecosystems (Turner and others 1995). The large proportion of the carbon stocks found in soil is due to large areas of muskeg and deep organic soils in southeast Alaska and is consistent with the average for other temperate forests (Prentice and others 2001). Our approach to estimating soil carbon resulted in conservative estimates of the total carbon stock in this pool. Mapping conventions may have underestimated the depth of hemist soils in the Tongass by classifying them as saprists (none of which are deep), which would cause underestimation of carbon stocks (D'Amore and Lynn 2002). The large discrepancy in results from our two methods of estimating soil carbon stocks suggests severe underestimation when FIA data are used. Consequently, we did not combine our estimates or use them as separate lines of evidence in our uncertainty analysis.

Uncertainty in the soil carbon stock, which represents about half of the uncertainty in total carbon stock estimates, was not incorporated into our estimates of net carbon flux because we assumed equilibrium in soil carbon stocks. Although forest harvesting has little effect on soil carbon on average, specific harvesting techniques can cause increases or decreases in soil carbon (Johnson and Curtis 2001). There is insufficient information, however, on the effects of harvesting in southeastern Alaska to include soil carbon in our net flux models. Carbon flux from soils could represent a significant addition to the net carbon flux associated with harvesting in southeastern Alaska, but the assumption of soil equilibrium is necessary until more data are available.

In defining our ''best estimates'' of net carbon flux for the management regimes modeled, we made the following assumptions: zero carbon in standing aboveground biomass after clear-cutting; 13% reduction of CER allocations for carbon sequestration associated with cessation of harvesting as a result of reduced carbon storage in long-term forest products; and the 200-year rotation represents the baseline case upon which CER allocation is based (current forest management equates to a 180-year rotation). These assumptions significantly reduce the range in our net flux estimates, but some uncertainties (for example, carbon accretion model) persist.

Net carbon flux into or out of the Tongass is not large enough to significantly impact the US carbon budget. The US Environmental Protection Agency's (EPA) 2003 inventory of GHG emissions and sinks estimated that net carbon flux from the forests of the conterminous United States amounted to 267 Tg C/y in 1995 (US Environmental Production Agency 2003). Our estimates for the Tongass of 0.13–1.8 Tg/y are 0.04%–0.7% of the EPA's inventory. Similarly, the potential for carbon sequestration due to management change in the Tongass is significantly less than that for other options for land-use change. Cessation of all harvesting of available lands in the Tongass (1.3×10^6 ha) results in annual sequestration of 0.04–0.33 Tg C/y, or 31 to 250 kg C ha^{-1} y^{-1}. By comparison, the land enrolled in the Conservation Reserve Program (CRP) in 1996 (16.2×10^6 ha) may sequester as much as 12 Tg C/y (Barker and others 1995), which is three to 30 times the rate per unit area in the Tongass. However, the economic cost of carbon sequestration in the Tongass may be significantly less than that for the CRP. Assuming that the lost revenue from US Forest Service timber sales is the cost of carbon sequestration in the Tongass, for example, the cost of carbon sequestration in the Tongass would be about one-quarter of the CRP cost (approximately \$0.02/kg C versus approximately \$0.08/kg C).

Past harvesting caused the net loss of 1.3–3.6 Tg C from the Tongass from 1900 to 1954 and 5.1–13.6 Tg from 1954 to 1995; these numbers include emissions from harvesting and sequestration from regrowth. For comparison, land use in the conterminous United States caused the loss of 27,000 ± 6000 Tg carbon from 1900 to 1945, but the regrowth of northeastern forests resulted in a net gain of 2000 ± 2000 Tg C from 1954 to 1995 (Houghton and others 1999).

The conversion of 6×10^6 ha of old-growth forest to young plantations in forests of Washington and Oregon is similar to the logging history of the Tongass, and resulted in the loss of 1500–1800 Tg C from aboveground and soil carbon pools (Harmon and others 1990). Harvesting in the Tongass has caused the loss, from aboveground carbon pools only and net of subsequent regrowth, of 13%–29% (6.4–17.2 Tg C on 0.2×10^6 ha) of the carbon per hectare released from the forests of Washington and Oregon. Harmon and others use of Covington's model of decline in O horizon soil carbon after harvesting may have led to a significant overestimate of the loss of soil carbon (Yanai and others 2003). Our estimates of net carbon flux from aboveground biomass (150–210 Mg C/ha) are similar to those of Harmon and others (187 Mg C/ha).

The economic value of carbon sequestration associated with the cessation of harvesting in the Tongass may be significant relative to the value of the timber harvested. Our best estimates of the net annual economic value of carbon sequestration resulting from cessation of all harvesting in the Tongass (\$3 to \$7 million/y) are of similar magnitude to the annual revenue from timber sales in the Tongass (\$6.5 million/y) (USDA Forest Service 2001). Potential cobenefits of harvesting timber and of ceasing harvest (for example, fisheries, tourism, timber processing) could influence the total net annual economic value for each management regime.

Some investigators have suggested that carbon sequestration from land-use change may not mitigate climate change as effectively as the reduction of GHG emissions from fossil fuel use, citing the possibility for leakage (that is, emissions associated with production may be displaced to another location). Reduced harvesting in the Tongass may require increased harvesting elsewhere to keep product supply constant. Consequently, estimates of the monetary value to Tongass managers for carbon sequestration may not reflect the net social benefit nor the benefit to the USDA Forest Service if another national forest increases its harvesting, buying CERs to do so, to keep the total product stream from national forest lands constant.

The net economic value of carbon sequestration associated with the elimination of harvesting in the Tongass clearly depends on the value of CERs. This value was assumed to be \$20 Mg^{-1} C, but estimates of the value of CERs in a regulated marketplace range from \$5 to \$125 Mg^{-1} C (Weyant 2000). Deviation in the value of CERs from \$20 Mg^{-1} C was not included in the estimated range of net economic value from carbon sequestration in the Tongass because the range scales linearly.

Some additional factors omitted from our analyses deserve mention. First, increasing atmospheric concentration of carbon dioxide and changing regional climates may alter some characteristics of the Tongass, including carbon stock and flux. However, the magnitude of changes in carbon stock caused by climate change is small compared to changes caused by land use (Caspersen and others 2000; Houghton and others 1999). Second, the assumption of steady-state carbon stocks in old-growth forests is ubiquitous, despite a dearth of data available to either confirm or disprove it, for Alaska or elsewhere. Third, young forests generally have lower levels of defect from decay than old-growth forests. Consequently, the proportions of harvested material used in forest product streams may change with conversion of forested lands in the Tongass from old-growth forest to managed younger stands, with implications for the question of whether harvesting less area more intensely results in greater carbon storage than harvesting more area less intensely. Fourth, the possibilities for improving efficiency in timber harvesting (Fahey 1983) were not included in our models because they are highly dependent on a large number of economic variables that are beyond the scope of this research. Finally, changes in species composition, caused by management or climate change, could influence carbon flux due to associated shifts in the relative importance of white and brown rots in wood decay (Kimmey 1956).

The Tongass must be included in accurate national carbon budgets. Furthermore, management of the Tongass for carbon sequestration may be of equivalent economic value to timber harvesting. Valuation of potential carbon sequestration in the Tongass from ceasing all harvesting may be amplified by indirect benefits of eliminating harvesting, such as maintenance of the southeast Alaska fisheries and tourism industries and reduced expenses for the Tongass timber program. Complete valuation of timber harvesting may be influenced by cobenefits as well. The emerging economic value of carbon sequestration requires consideration of net carbon flux in the development of future Tongass management plans.

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