Final Report

ROLE OF NORTHEASTERN FORESTS AND WOOD PRODUCTS IN CARBON SEQUESTRATION

Report to Northeast Regional Biomass Program
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HIGHLIGHTS

1. This report summarizes existing information on the potential role of forests, forest management and forest products in public policy on the carbon cycle.

2. Existing information and analyses give limited emphasis to the Northeast, since the large-scale opportunities lie elsewhere.

3. The northeastern forests are now gaining carbon each year. This rate of accumulation cannot be increased very much, or very rapidly, as only 2% of the area is cut each year. Yet, opportunities do exist for boosting stand growth rates, retaining forest, establishing fuel plantations, and using forests such as planted streamside buffers to serve multiple purposes. These need to be identified and evaluated at state levels.

4. Still, the information supports the view that state carbon plans should consider and account for the potential role of forests, forest management, and wood products.

5. A considerable body of scientific and professional opinion holds that replacing fossil fuels with biomass, and employing more wood for long-lived uses such as building material, is useful from a carbon cycle standpoint.

6. State policies in the area of forestry, waste management, and energy may all have unintended effects on carbon cycle outcomes. Planners need to assess such effects carefully.

7. State-level estimates on many points will be needed to develop sound, databased plans.

8. Several comprehensive carbon models have been developed to analyze complex scenarios of management, utilization, disposal, recycling, and re-use. These models, however, are better suited to research than to application in state-level planning. Publications describing the models provide abundant detail on the issues, concepts, and data that could be used in state-level assessment and planning.

9. In this report, separate consideration for environmental impacts is not provided. This is for several reasons. First, such impacts are activity- and site-specific and hard to discuss on a regional basis. Second, impacts of the various practices being considered are well developed in the literature.

10. Many scientists believe that future climate change could considerably change the species composition, structure, and productivity of northeastern forests. To the extent that this may be true, it creates an additional complexity for climate change planning. These issues are not considered in this report.

PREFACE

This report was prepared as a background document for a CONEG conference held in May 1998 at Saratoga Springs, New York. The purpose of the conference was to provide information to state and federal officials involved in carbon offset planning about the opportunities in the forest management and wood products sectors. To facilitate the transfer of information and discussion of issues, this background document was prepared. A Conference Summary has also been assembled.

We would like to acknowledge helpful comments on early drafts of this report by Jim Connors of the Maine State Planning Office; Ed White, State University of New York, College of Environmental Science and Forestry; Rich Birdsey, USDA Forest Service, Northeastern Forest Experiment Station; Jeff Peterson of the New York State Energy and Research Development Authority; and Neil Sampson of The Sampson Group.

The paper provides an overview of the forest resource and forest products industry in the region, and offers an entry into the technical and scientific literature of the field. This literature is found in many documents of limited circulation and in highly technical form in scientific journals. We have taken special interest in summarizing information on how forest planting and management, and changes in wood use, can affect carbon storage. The paper closes with a general overview of policy options available to state governments.

We include a brief glossary to technical terms. Many readers will have need for only portions of this document. To keep separate chapters more self-contained, we have kept literature citations at the end of each; this results in some duplication of citations but should make it easier for readers to find citations they need quickly. Because this is not a technical manual for calculations or a scientific report, we have not converted all measurements used into a single common set of units. Rather, we have largely left them in the terms in which they are

used in the applicable literature, e.g. cubic ft. per acre for forest inventory, pounds or tons per acre for biomass, and teragrams when aggregates of carbon flows are being considered.

A primary concern is to assist planners in conducting the Assessment phase of any planning or policy analysis they are undertaking. The observations made in no sense represent policy or program proposals. Further, the views and conclusions expressed are those of the authors and not of CONEG or any of its members or funding sources.

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I. INTRODUCTION TO NORTHEASTERN FORESTS AND THEIR USES

This chapter provides a brief overview of forest conditions is the study area focusing on a regional perspective. Specifics about growth rate, policies, management, and utilizations appear in later chapters.

The region's forests account for significant economic activity in rural areas. In portions of the region, total dollar sales per acre derived from recreation and tourism are roughly equal to those derived from wood products manufacturing (NEFA, n.d.).

The forests of the Northeastern states cover a large share of the region's land surface, in proportions ranging from 89% in Maine to less than 30% in Delaware. In total, the region contains 73 million acres of forest (10% of the nation's total), of which 67.5 million is defined as "timberland" by U.S. Forest Service definition. Timberland is forest that can grow 20 cubic feet (about 1/4 cord) per acre per year of commercial wood and is legally available for timber harvesting.

Chapter Outline

A. Climate, Physiography, and Productivity
B. Forest Landbase and Condition
C. Ownership
D. Growth
E. Current Forest Uses
F. Recreation
G. Suburban or Recreational Backdrop
H. Wilderness
I. Implications Relative to Carbon Storage
J. References

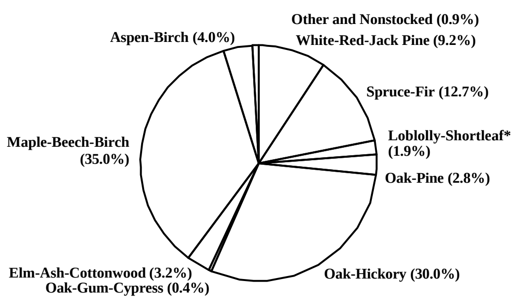
Large areas of forest in this region are secondary forests on lands once cleared for farming and pasture. In the 9 New England and Mid-Atlantic States alone, about 17 million acres of farmland returned to forest from 1909 to 1992. This area is roughly equal to the total forest area of Maine. So, in little more than 80 years, the region gained an additional "Maine" in terms of forest area.

The regional increase in forest acreage is probably about over, though locally important increases or decreases will likely

occur. This increase in forest cover has had a number of favorable effects on waterways and fish resources. It has restored cover to first-order watersheds, especially in lowland areas where the landscape had been extensively farmed (Irland, 1995). At the same time, riparian vegetation has returned to benefit wildlife and fish habitat.

Forests in this region are dominated by hardwood types. The leading type is maple-beech-birch, often termed northern hardwoods. This type is common from the glaciated northern half of Pennsylvania to northern Maine. Oak-hickory is the second most common type, occurring from southern New England and New York's southern tier southward. Softwood types account for only 24% of the forest area of the Northeast (Fig. 1.1).

Figure 1.1
Forest Types, Public and Private Land, Northeastern U.S., 1992
(unreserved only)
Total = 80,544



Source: Powell, et al., 1993, p. 26.
* Mostly pitch pine.

	Acres (1,000)
White-Red-Jack Pine	7,437
Spruce-Fir	10,203
Loblolly-Shortleaf*	1,538
Oak-Pine	2,220
Oak-Hickory	24,157
Oak-Gum-Cypress	329
Elm-Ash-Cottonwood	2,567
Maple-Beech-Birch	28,205
Aspen-Birch	3,195
Other and Nonstocked	693
Total	80,544

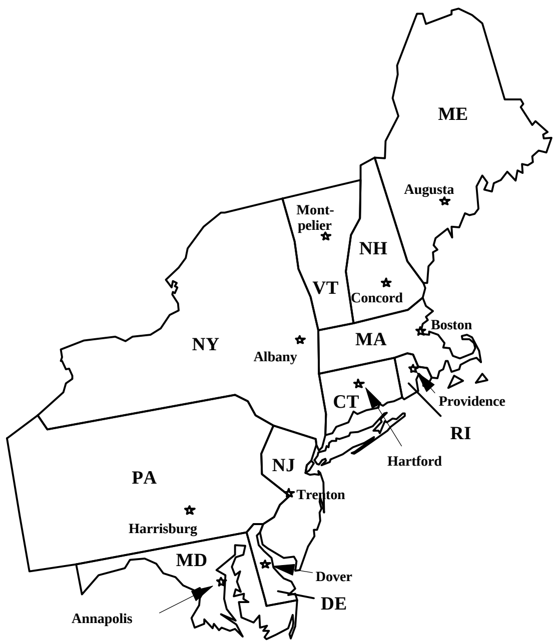
The maple-beech-birch type includes a number of valuable hardwood species, and on good sites it can produce high growth rates. Valuable softwoods such as white pine or spruce often intermix with this type.

The oak-hickory type includes more southerly species, many of high commercial value. Portions of this forest have suffered heavy gypsy moth damage in recent decades.

Spruce-fir types occur on moist and lowland sites in the northerly portion of the region. A montane variant is found in the Catskills and spreads at high elevations down the Appalachians. The trees in this type are highly valued for pulp and lumber; Maine suffered severe losses in this type to the spruce budworm from about 1975-85.

The white-red-jack pine type is diverse, and includes the visually prominent white pine as its dominant constituent, while red and jack pines are of limited distribution in the northeast. Pine stands can produce very high rates of growth, even with little management effort. Pines have been widely planted on old fields.

Figure 1.2



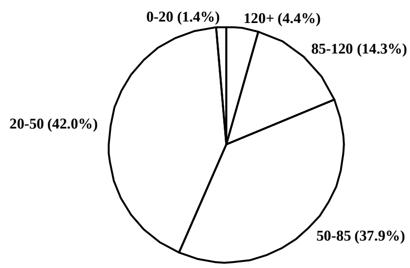
Regional definitions used in this paper will vary depending on data availability and the purpose of the moment. “The Region” refers to the 11 states shown. Northern New England is the northernmost 3 states; So. New England is the southerly 3 New England states; “Mid-Atlantic” means New York, Pennsylvania, and New Jersey. In some tables, we describe West Virginia, Maryland, and Delaware as “border states.” Forest Service and other sources often provide data for a “Northeastern” region that also includes West Virginia; this will be used where it is the only information conveniently available.

A. CLIMATE, PHYSIOGRAPHY, AND PRODUCTIVITY

The region's climate is quite diverse, ranging from short growing seasons of northern Maine and the Adirondacks to the humid mild climate of Delaware and Maryland. In terms of physiography, the region encompasses the Atlantic coastal plain, the mountain ranges of the Allegheny Plateau, and rolling uplands of New England and the Mid Atlantic States. Soils are also diverse. In the southerly portion of the region are the productive limestone based soils of southeastern Pennsylvania. Scattered through the rest of the region are former lake plains, alluvial soils, or regions of especially favorable conditions for particular crops. Yet by reason of slope, stoniness, and drainage, much of the region's land is ill suited to agriculture. Much of this land has returned to forest after futile efforts to farm it in the 19th and early 20th centuries. With its small farm units and high cost labor, the region is not well suited to most forms of livestock production other than dairying. Forest soils that were once pastured may currently contain more carbon per acre than the previous forest soils. This is because decaying root masses of pasture grasses build up deep organic horizons that were not present in forest soils.

The forests of this region include significant areas of high productivity for timber growing (Fig. 1.3). Just over half of the region's forest land, if properly managed, will grow wood at rates above 0.6 cord per acre per year. Because of ownership sizes, topography, riparian areas, and wetlands, however, not all of this land is actually available for harvesting and active management. In various local areas, studies of this "availability" issue have been conducted but there is no regional overview.

Figure 1.3
Forest Land by Productivity Class
Northeastern U.S., 1992
Total = 80,545
(cubic feet per acre per year)



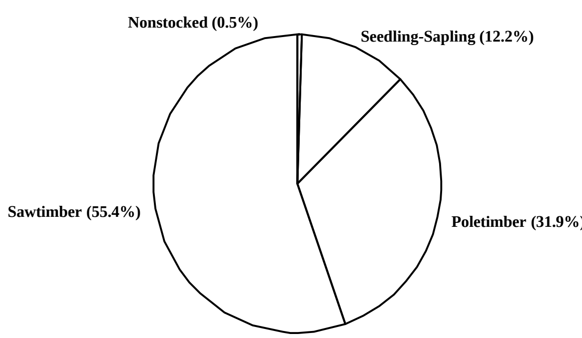
Source: Powell, et al., 1993, p. 24.

Note: productivity classes are defined in terms of cubic feet of wood grown per acre per year.

B. FOREST LANDBASE AND CONDITION

Two-thirds of the northeast's total timberland area of 67.5 million acres is found in just three states: New York, Pennsylvania, and Maine. Regionally, roughly one-third of the forest area is in poletimber stands, which are at a fast-growing stage of their life cycles. About one acre in eight is in very young sizes, and more than half is in sawtimber stages, where stands are maturing (Fig. 1.4).

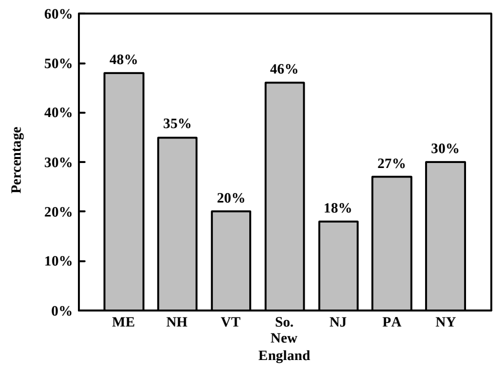
Figure 1.4
Northeastern Forest Area
by Stand-Size Class, 1992
Total = 79,449



Source: Powell, et al., 1993, p. 44.

Much of the poletimber and sawtimber area is overstocked with total growing stock by stand and stocking guides (Fig. 1.5). These are guides specifying the volume and number of stems per acre that provide best conditions for commercial timber growing. But considering trees of desirable species and quality, many acres are actually understocked. To bring them into condition to maximize value growth, they will need one or more improvement cuts. This means reducing their current volume and stock of carbon.

Figure 1.5
Percent of Forest Acreage Overstocked, Latest Year



Source: State resource bulletins.

Note: For Maine, method of classifying for stocking was changed for the 1995 Survey.

BUT: MANY OF THESE ACRES ARE UNDERSTOCKED WITH QUALITY, VIGOROUS TREES OF DESIRED SPECIES!

C. OWNERSHIP

Forestlands of the 11-state region are primarily privately owned, with public ownership accounting for only 7.5 million acres of timberland (Powell, et al., 1993, p. 37):

	Million Acres
Federal	1.5
State	5.0
County & Munic.	1.0
Forest Industry	10.9
Farmers	8.8
Misc. Private	40.2
Total	67.5

States and other governments own far more land than does the federal government. Farm ownership has declined dramatically since the early 1950's, while industry ownership increased. The bulk of industry ownership is in northern New England, New York, and Pennsylvania.

The region's private ownership pattern has recently been surveyed by the Northeastern Forest Experiment Station. Several features of the ownership pattern (Figs. 1.6 and 1.7) have implications for management:

- More than 60% of the private forestland is in ownerships larger than 100 acres, and 30% is in ownerships larger than 1,000 acres.
- Parcels larger than 100 acres account for only 6% of the total population of owners, so management activities need only involve a fraction of the owners to influence a large land area.
- Owners are heavily dominated by the age 40 and older group, and many parcels have been held a long time. Further fragmentation and turnover in ownership are likely on much of this land in the coming few decades.
- Timber management is not a prominent motivation for forest landownership, as reported by owners in surveys. This does not mean that owners would necessarily resist management, however.
- Other surveys have suggested that owner willingness to manage has been increasing. Also, other research suggests that most woodlots will be harvested at some time in the future, even if their owners report an unwillingness to cut.

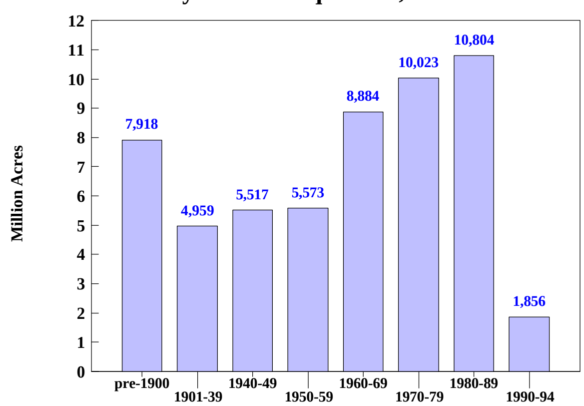
Table 1.1
Owners and Acres by Size Class, Northeast, 1993

Size Class	# Owners	Percent of Total	# Acres	Percent of Total
1-9	1,103,200	60%	3,031	5%
10-49	492,500	27%	10,468	18%
50-99	130,900	7%	8,684	15%
100-499	105,100	6%	15,512	27%
500-999	5,100	0%	2,935	5%
1000+	2,806	0%	17,261	30%
Totals	1,839,606	100%	57,891	100%

Source: Birch, 1995, op. cit.

Figure 1.6

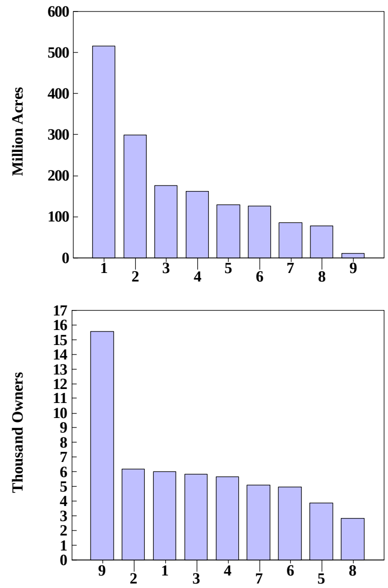
Estimated Number of Forest Land Acres by Date of Acquisition, 1993



Source: T. W. Birch, op. cit.

Figure 1.7

Estimated Number of Ownership Units and Acres of Forest Land, by Primary Reason for Owning Forest Land, 1993



1. Part of Residence
2. Esthetic Enjoyment
3. Recreation
4. Other and No Answer
5. Part of Farm
6. Farm and Domestic Use
7. Land Investment
8. Estate
9. Timber Production

Source: T. W. Birch, op. cit.

D. GROWTH

From 1952 to 1991, net annual growth in the Northeast increased from 2 million cu. ft./yr. to 3.1 million. This is due to three factors:

1) increasing forest area;

2) most stands have been in a young, rapidly growing condition; and

3) harvest has been well below growth.

In 1991, the region's timber balance was comfortably in surplus:

	1991
Net growth	3.1 MMCF
Removals	1.3
Mortality	0.8

Above removals and mortality, there was an annual surplus of 1 MMCF, according to these estimates. Recent inventories show significant increases in all states except Maine (see Sec. VI below).

E. CURRENT FOREST USES

Use patterns differ between hard and softwood species (Table 1.2, Figs. 1.8 and 1.9). For hardwood, more than half of roundwood removals are for fuel, while for softwood, sawlogs are the most important product. Strong markets for pulpwood and fuelwood are major advantages for this region in supporting quality forest management.

Table 1.2
Volume of Roundwood Products Harvested in the Northeast

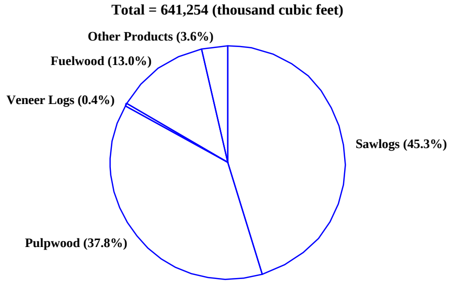
	Softwoods	Hardwoods
Sawlogs	294,742	381,515
Pulpwood	246,167	275,736
Veneer Logs	2,409	21,401
Fuelwood	84,473	855,181
Other Products	23,463	21,678
Total	651,254	1,555,511

Source: Powell, et al., 1993, p. 110.

Figure 1.8

Volume of Softwood Roundwood Products Harvested in the Northeastern U.S.

Total = 641,254 (thousand cubic feet)

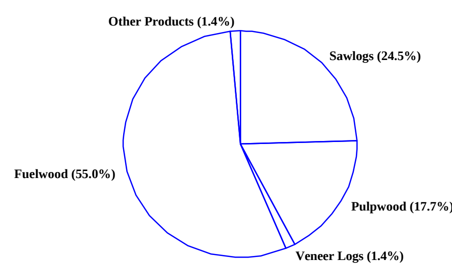


Source: Powell, et al., 1993, p. 110.

Figure 1.9

Volume of Hardwood Roundwood Products Harvested in the Northeastern U.S.

Total = 1,555,511 (thousand cubic feet)



Source: Powell, et al., 1993, p. 110.

The patterns of wood usage and relations between growth and cut vary widely within the region. For example, in the southerly portion of the CONEG region, pulpwood markets are virtually nonexistent, except in the vicinity of a pulpmill. In the more suburbanized areas, wood markets are so weak that developers have to pay clearing contractors to remove wood and stumps. In rural portions of the region, from north to south, in many areas firewood is still used seasonally as a heating fuel, and in areas with active camping, sporting camp, and leisure properties, significant volumes of firewood are burned for aesthetic purposes.

Usage of forest biomass for energy production varies across the region, based on a variety of factors. In some states, paper mills and lumber mills use their own residuals for energy or purchase residues from others for fuel. Across the region there is an active market for bark in the landscaping industry, but bark is often used for industrial fuel as well. Stand-alone wood-fired electric plants are mostly concentrated in New York and northern New England, due to past public policies there favoring investment in such facilities. Some of these plants are being closed as high-cost supply contracts are bought out or otherwise modified.

Many of these plants were expected to operate entirely from wholetree forest biomass or logging residues. Instead, many of them rely heavily on industrial residues or even urban woodwaste from landclearing, demolition, and small woodworking shops.

Increasingly, wood materials are being diverted from landfills and into fuel uses or other outlets such as landscape bark. In limited instances, recycling into specialties such as auto parts or other items is occurring. A fiberboard plant in New York is said to be completing financing. This plant will utilize 100% urban woodwaste.

F. RECREATION

Outdoor recreation in its many forms is an extremely important use of the forests of this region, especially the public lands. Some of the most heavily visited National Forests in the country are in this region. Public use of private lands for hunting, fishing, walking, wildlife observation, and water-oriented uses is extensive. The public values are high, as are the economic impacts. For example, in Maine, total tourism spending per acre of forestland was almost one-third as large as total manufacturing shipments of wood and paper products:

	Dollars Per Acre of Forestland (1987)
Manufacturing Shipments	260/A.
Gross State Product	90
Manufacturing Payroll	34
Value of Delivered Roundwood	26
Tourism Spending	97

Source: NEFA, n.d., p. 2.

G. SUBURBAN OR RECREATIONAL BACKDROP

Large areas of forestland in suburban areas, and surrounding developed resorts and extensive cottage development are essentially managed as a “green backdrop” for these other uses. That is, their owners pay no particular attention to active management. They may be indifferent to the income opportunities, or their primary ownership motive may be to protect their view and provide a buffer against nearby development. In many instances, public recreation uses may not be permitted. When oil costs are high, such lands often produce firewood for their owners, however.

Lands in this “backdrop” category undoubtedly account for many millions of acres across the region, though the amount has never been measured. As development patterns continue to decentralize, this “backdrop” will grow significantly over the coming half century.

H. WILDERNESS

According to Powell (1993, p. 22), there are about 5.7 million acres of forest in this region that are not considered "timberland." Much of this is in areas designated for preservation or similar management, while some is simply nonproductive. A comprehensive and current database on lands answering to the general description of wilderness is not available. The forest inventory has generally not taken data in these areas. There are many categories of lands like State Parks, watershed lands, and land trust preserves which are in a wilderness-like condition even though they may not precisely fit U.S. Forest Service definitions (Irland, 1996). Accounting for these would increase the above area estimate. The forests in these areas can be expected to slowly accumulate carbon, especially in forest floors and down woody debris, until they reach whatever natural level of biomass accumulation is permitted by the local soils, climate, and disturbance regimes.

I. IMPLICATIONS RELATIVE TO CARBON STORAGE

Some general implications include:

- The region as a whole is gaining carbon, except for Maine (see ch. 2 below).
- Opportunities for adding to forest area are limited but worth examining.
- State and municipal lands far outweigh Federal lands in acreage, giving certain states a significant role as landowners.
- Though there are 1.8 million private owners, about 62% of the forest is in ownerships of 100 acres and larger (6% of the owners).

J. CLIMATE CHANGE: FUTURE IMPACT ON NORTHEASTERN FORESTS

If future climates change as anticipated by recent IPCC assessments, forests of the northeast will change in many ways. Attempting to judge the likelihood of such climate changes, and the degree of impact that will result, imposes a new layer of complexity on this process. Considerable work has been done on this topic, but disagreements remain. Currently, a

national assessment of climate change impacts on U.S. regions is being initiated by the U.S. Global Change Program. Hopefully, that effort will clarify some of the uncertainties.

Because of the complexities of this topic and limits of our own backgrounds, we have left the subject outside the scope of this review. Interested readers may consult Pitelka, 1997; Aber, et al., 1995; Birdsey, 1997; Foster, et al., 1997; Loehle and LeBlanc, 1996; Hamburg, 1998; and Davis and Zabinski, 1992.

Note: Finding Forest Resource Data

The publication Forest Resources of the U.S., 1992 (Powell, et al., 1993), is a useful source of consistent information across states. It is now being updated to year 1997.

For detailed work, more detailed information will be needed. It can be obtained from “Survey Bulletins” published for each state by the USDA Forest Service’s FIA Unit at Radnor, Pennsylvania. State forester’s offices usually have copies and staff people familiar with the information and the issues.

The detailed information can be obtained on a CD-ROM and is also posted on the Web, and the Eastwide Database, at http://srsfia.usfs.msstate.edu/wo/WOFIA.HTM (case sensitive).

The following chapter will discuss carbon sequestration in relation to forest types in the Northeast, as well as the influence of other factors such as stand age and climate. These basic concepts will be important to further discussions of forest management and forest carbon modeling.

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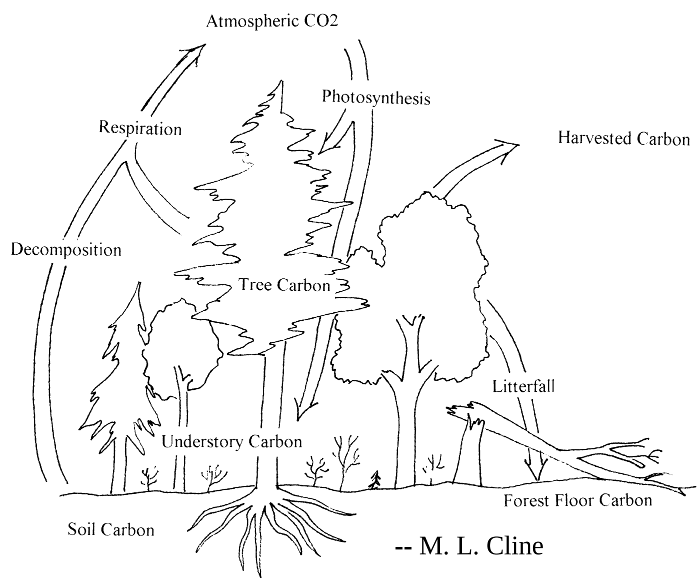
II. CARBON STORAGE IN FOREST SYSTEMS

This chapter reviews how carbon is stored in forest ecosystems, where that carbon occurs, and provides examples. Carbon stored in the trees is most directly affected by forest management (Figure 2.1). This is where we begin the discussion. We then consider the herb layer, the forest floor, and belowground stocks.

Figure 2.1
Simplified Scheme of CarbonFlow in a Forest Ecosystem



-- M. L. Cline

Terminology used in discussing the carbon cycle varies and no standard approach seems to have emerged. Fundamentally, there are four basic concepts:

-- Carbon is found in "stocks" in tree stems or soils.

-- Carbon "flows" into or out of such stocks by growth, cutting, or death and decay.

-- The "pathways" linking the stocks are highly complex.

-- Foresters and scientists often estimate the "flows" by comparing changes in "stocks" over time.

Some of the terms employed are fairly clear (inventory = stock = pool = reservoir) (Box).

Chapter Outline

A. Forest Tree Biomass

B. Herbaceous Biomass

C. Forest Floor and Belowground Biomass

D. The Missing Carbon Sink

E. Forest Carbon Assimilation and Decomposition

F. Implications of Carbon Storage in Forest Systems

G. References

But terms like "storage" or sequestration may refer to very general processes or to stocks or flows, depending on context.

Carbon Cycle Terminology

Terms Used Synonymously:

Inventory	Net Growth
Stock	Flow
Pool	Flux
Reservoir	

Terms Depending on Context

Accumulation	}	
Storage	}	May refer to either stocks or flows
Sequestration	}	

A. FOREST TREE BIOMASS

In evaluating the carbon storage of standing woody biomass, i.e., the above-ground portion of the tree and the coarse roots (<2 mm), productivity should be considered at both the individual tree and the stand level. It is the interaction of biological, soil, and climatic factors on individual tree growth across stands that determines the amount of carbon stored in standing woody biomass of forest ecosystems. Units of measure for biomass vary in the literature; see conversion factors (Box).

In physiological terms, trees must exhibit a positive surplus of photosynthesis over respiration (net positive photosynthesis) in order to sequester carbon. Anthropogenic and natural disturbances, climate fluctuations, succession, and developmental stage may influence net photosynthesis in forest stands. Increased stand temperatures resulting from disturbances may lower net photosynthesis and carbon sequestration through less complete capture of incident sunlight and higher rates of respiration. Conversely, the atmospheric carbon dioxide necessary

for photosynthesis may be substantially lower in actively growing closed canopy stands (due to high rates of CO_2 uptake and low air circulation) than in open regenerating stands.

Conversion Factors for Carbon and Biomass

1 Megagram (Mg) = 10^6g = 1 tonne (metric)

1 Gigagram (Gg) = 10^9g — 1 ha = 2.471 A

1 Teragram (Tg) = 10^{12}g — 1 m^3 = 35.3147 ft^3

$$\frac{m^2/ha}{.2296} = ft^2/ac$$

Organic matter (kg/ha) x 0.58 x 0.892 = Carbon (lbs/A)

Merchantable volume (ft^3) x Ratio = Total volume (ft^3)

Merchantable volume/Total volume ratios:
- Softwood = 2.193
- Hardwood = 2.140

Total volume (ft^3) x Factor = Total tree carbon (lbs)

Conversion Factors	Softwoods	Hardwoods
Pine type	12.29	16.87
Spruce-Fir type	12.00	16.31
Hardwood type	12.48	18.65
Oak/Pine type	12.29	14.58

Resulting in potential reductions in net photosynthesis. The highest net photosynthesis occurs in young actively growing stands when the leaf area is at its maximum, near the time of canopy closure (Marland, 1988; Waring and Schlesinger, 1985). Therefore, older overstocked stands, which contain large stores of carbon, tend to be less efficient in sequestering additional carbon in biomass than young vigorous stands.

Estimates suggest that forests in the northeast will continue to sequester additional carbon until 2040 (Birdsey, et al., 1993). Forest clearing for agriculture in the U.S. reached its peak in the late 19th and early 20th century, and during this period large amounts of carbon dioxide were released to the atmosphere. However, recovery and regrowth are now accumulating atmospheric carbon into forest systems (Houghton, et al., 1983). By the late 1980's and early 1990's, U.S. forests represented a net carbon sink of 79-106 Tg/yr (teragrams/year) (Birdsey, 1992; Turner, et al., 1995). Net annual forest growth accounted for more than 300 Tg C/yr, but much of this was offset by losses due to timber harvesting. Birdsey, et al. (1993) estimate that stored carbon in U.S. forests has increased 38% since 1952. The largest net carbon sink (31 Tg/yr) appears to be in the Northeast where much of the forest is comprised of hardwoods (Turner, et al., 1995). The Northeast region accumulated about 60-68 Tg C/yr due to tree growth before reductions for timber harvesting.

Whittaker, et al. (1974) reported 191.5 to 182.6 t/ha of biomass for 75- to 100-year-old northern hardwoods in New England. Cooper (1983) computed estimates from data in several published reports and estimated that mature forests contain 200-400 t/ha biomass. The "typical forest does not exist. Many factors will determine the amount of carbon storage in forest systems," he concluded.

The amount of carbon stored in standing biomass varies with **forest cover type**. Understanding the tree carbon storage potential of different forest types is necessary to accurately account for forest carbon sinks and to assess the influence of management practices that alter tree species composition. Birdsey (1992) used U.S. Forest Service Inventory and Assessment data from 1987 to calculate the average carbon storage in live trees for different forest types in the Northeast and Mid-Atlantic States (Table 2.1). Forest types with a large hardwood component comprised the greatest area and contained the highest average carbon storage in trees, 50,000 to 56,000 lbs/A. Spruce-fir and pine forest types stored carbon in live trees at 42,000 to 47,000 lbs/A. Aspen-birch types showed the lowest potential for carbon storage at about 30,000 lbs/A. Early successional forest types comprised of aspen and birch

contained substantially lower levels of carbon storage in living trees than other forest types in the region due in large part to low per acre tree volumes.

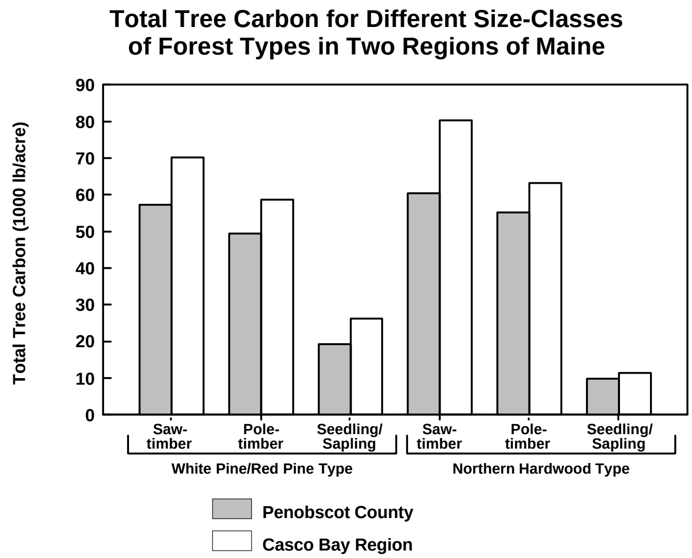
Table 2.1
Acreage, Total Volume, and Average Carbon Storage in Live Trees on Timberlands in the Northeast and Mid-Atlantic States by Forest Type (1987).

Forest Type	Acres 1000 A.	Softwood MMcf	Hardwood MMcf	Ave. C Stored lbs/A in trees
Oak-Hickory	36,730	1,591	47,795	55,943
Oak-Pine	3,539	2,022	2,668	53,510
Maple-Beech-Birch	29,145	4,861	34,129	50,971
White, red, jack pine	8,067	9,480	3,631	47,122
Spruce-Fir	10,007	12,310	2,407	41,829
Loblolly/Shortleaf	2,704	1,827	660	35,153
Aspen-Birch	3,240	471	2,589	29,814

Source: Birdsey, 1992.

In addition to forest type, **size-classes** within the forest influence the amount of carbon stored in trees. Older stands have had more time to accumulate timber biomass, woody debris and detritus, and soil carbon than younger stands. Stand age is especially important when evaluating the carbon storage potential of forests under differing intensities of forest management. Fig. 2.2 presents total volumes and carbon for forest types of three age-classes in two regions of Maine. The data are derived from the 1995 U.S. Forest Service Inventory (Griffith and Alerich, 1996) for growing stock using conversion factors developed by Birdsey (1992). Estimates assume pure stands for each forest type listed, i.e., spruce-fir stands were comprised of all spruce-fir trees. Results show a progressive increase in total volume and carbon with increased age- or size-class for all forest types. The magnitude of this increase varies with forest type and geographic region. The Casco Bay District exhibits higher total volumes and carbon storage than the Penobscot District in part from the high productivity of its soils.

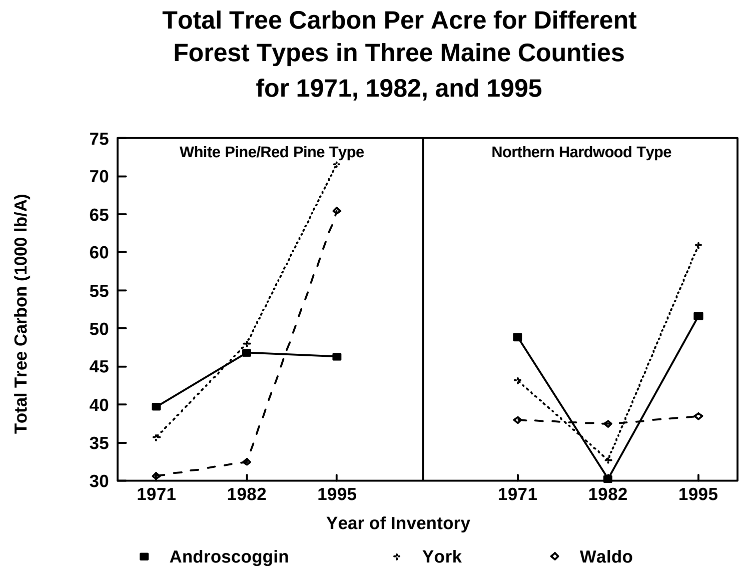
Figure 2.2



Source: Appendix Table A.1.

The amount of tree carbon stored in forest stands will vary with geographic region based upon site productivity and whether the species is approaching its range limits for natural distribution. Estimates for total tree carbon by forest type for three Maine counties were developed from U.S. Forest Service inventory data for 1971 (Ferguson and Kingsley, 1972); 1982 (Powell and Dickson, 1984); and 1995 (Griffith and Alerich, 1996) using conversion factors developed by Birdsey (1992) (Fig. 2.3). Estimates of total carbon vary over time because of harvesting and management activities, land use change, natural variability, and sampling errors. Larger differences may be expected for the same forest types separated by larger geographic distances within the Northeast region.

Figure 2.3



Source: Appendix Table A.2.

In York and Androscoggin Counties there has been a general trend of decreasing acreage in all forest types except northern hardwoods, which have increased dramatically over the 25 years. Results for Waldo County are variable but generally lower than for the other three counties. The lower values for Waldo County may be partially explained by the thinner soils along the rocky coastline and islands. In all counties, the total volume and tree carbon has increased for pine while the total acreage in this forest type has declined. In the Casco Bay and the Penobscot Districts, the acreage of sawtimber stands for all forest types is three times or more than pole-size and seedling/sapling-size stands combined (Fig. 2.2). The large proportion of older pine stands may in part explain the large increases per acre volume and carbon storage that have occurred over time (Fig. 2.3). Per acre total tree volume and carbon for northern hardwoods maintained relatively consistent levels through all three inventory periods for the three counties examined.

Combining specific forest types into more general forest type classifications may overlook differences in total tree volume and carbon. For example, northern hardwoods in the U.S. Forest Service inventories in Maine include the specific forest types sugar maple/beech/yellow birch, red maple/northern hardwoods, and mixed northern hardwoods. In the Capitol District in Maine, for example, we see similar volumes for sugar maple/beech/yellow birch and mixed hardwood forest types, but the per acre volume and total carbon for sawtimber red maple/northern hardwoods is much lower (nearly half) than the other two forest types (Table 2.2). The level of detail required depends upon the use to which the data will be put, as well as practical considerations.

Table 2.2
Acreage, Total Tree Volume, and Total Tree Carbon for Different Size-Classes of Specific Forest Types Classified as Northern Hardwood in the Capitol District, Maine for 1995

Species	Size-Class	Acreage (1000 A)	Total Tree Vol. (cu ft/A)	Total Tree Carbon (lb/A)
		Capitol District, Maine 1995		
Northern Hardwoods				
Sugar Maple/	Sawtimber	20.8	4,229	78,863
Beech/	Poletimber	76.7	2,282	42,565
Y. Birch	Seedling/Sapling	23.6	299	5,580
Red Maple/	Sawtimber	45.0	2,406	44,876
Northern	Poletimber	101.2	2,474	46,142
Hdwds	Seedling/Sapling	43.0	478	8,913
Mixed	Sawtimber	25.3	4,313	80,913
Northern	Poletimber	39.5	2,313	43,143
Hdwds	Seedling/Sapling	40.9	393	7,320

Source: Griffith and Alerich, 1996.

The potential for trees to store carbon also varies somewhat with **site productivity**. Trees on more highly productive sites in the Northeast and Mid-Atlantic States store greater amounts of carbon in live trees (Table 2.3) (Birdsey, 1992). Trees on site classes of 85 or greater stored 18% more carbon than the lowest site classes between 20 and 50. Forest types with the site classes of 85+ comprise about one quarter of all the forest lands in this region and represent 27% of the carbon stored in forests in the region. Sites in the middle and low productivity classes represent 46 and 27% of the total forest carbon stored in the region, respectively.

Table 2.3
Area, Volume, and Average Carbon Storage in Live Trees for Different Site Productivity Classes in the Northeast and Mid-Atlantic States (1987)

Site Class[1]	Acres (1000 A)	Softwood (MMcf)	Hardwood (MMcf)	Ave. C Stored (lbs/A in trees)
85+	24,028	7,766	27,074	54,477
50 - 85	44,744	15,995	44,517	49,857
20 - 50	30,381	9,065	26,880	44,824

[1]Capable of growing 85+, 50-84, or 20-49 cu ft/A/yr. based upon the mean annual increment of the most productive 20% of measured plots in each site class.

Source: Birdsey, 1992.

B. HERBACEOUS BIOMASS

The herbaceous or forest understory biomass is closely linked to the development stage of forests. On cleared or harvested land, understory biomass reaches a peak shortly after the onset of reforestation (Birdsey, 1996). However, as tree growth begins to cause competition for light, water, and nutrients, understory biomass begins to steadily decline until the forest is old enough for gaps to begin to occur in the overstory. At this point, understory biomass begins to increase at a slow rate.

Understory vegetation comprises a small percentage of all forest carbon components. Birdsey (1996) assumed that understory carbon levels at age 0 were nonexistent and peaked at about age 5 years followed by a decline to a reference level attained at age 55 years in the Northeast. The reference level was assumed to be about 2% of the total overstory carbon.

C. FOREST FLOOR AND BELOWGROUND BIOMASS

There are a number of different approaches to address forest floor and belowground biomass in forest ecosystems. In this review, forest floor biomass includes all dead organic matter above the mineral soil horizons except standing dead trees, which are included in the tree biomass. This includes litter, humus, and coarse woody debris that has fallen to the forest floor. The belowground biomass includes all soil carbon to a depth of one meter and fine roots (<2 mm in diameter). All larger roots are considered part of the tree biomass.

Belowground Biomass

Whether soils act as a source or a sink for carbon makes a large difference in the carbon sequestering potential of forests. Detrital inputs of carbon to the soil from forest ecosystems are estimated at about 60 x 10^{15} g/yr, while decomposition is at 50-60 x 10^{15} g/yr (Harrington, 1987, Post, et al., 1990). Johnson (1992) suggests that even a small imbalance (~10%) between detrital production and decomposition would either equal or offset estimated carbon emissions from fossil fuels (5.3 x 10^{15} g/yr), depending whether it was a negative or positive imbalance.

Soil carbon originates from the turnover and decomposition of roots, microorganisms, and forest litter. The rate at which the forest floor carbon accumulates and decomposes has a significant influence on soil carbon. In the Northeast and Mid-Atlantic states, estimates of organic matter and carbon on the forest floor (excluding standing dead trees) were higher for pine and spruce-fir stands than hardwood stands (Table 2.4) (Birdsey, 1992). Softwood stands tend to accumulate deep layers of duff due in part to dense, year-round shade from canopy cover,

acidified soils that favor fungal decomposers over bacteria, litter composition that is less readily decomposed, and resulting cooler temperatures that lower decomposition rates.

Table 2.4
Estimates of Organic Matter and Carbon Above the Mineral Soil Horizon (Including Litter, Humus, and Other Woody Debris) for Different Forest Types in the Northeast and Mid-Atlantic States

Forest Type	Organic Matter (kg/ha)	Carbon (lbs/A)
Pines	44,574	23,061
Spruce-Fir	44,693	23,122
Hardwoods	32,207	16,663

Carbon (lbs/A) = organic matter (kg/ha) x 0.58 (percent carbon) x 0.892

Source: Birdsey, 1992.

More than twice as much carbon is stored in soils than in above-ground portions of forests (Trexler, 1991). According to Zinke, et al. (1984), soil carbon storage in worldwide forests ranges from 10 to 20 kg/m^2. The amount of soil carbon storage in terrestrial systems is strongly influenced by temperature, precipitation and soil texture (Burke, et al., 1989). The majority of soil carbon results from the mortality and decomposition of fine roots that may "turnover" several times during a single growing season (Vogt, et al., 1986). Grier, et al. (1981) reported fine root turnover rates of 3 to 11 tons/ha/yr in old growth Douglas-fir stands. On an annual basis, 7-76% of the total net primary production in forests is allocated to fine root production (Gower, et al., 1995; Vogt, 1991) and appears correlated with annual litterfall amounts (Raich and Nadelhoffer, 1989). According to Nadelhoffer and Raich (1992), carbon allocation to fine root production could be about one-third of the total annual carbon allocation to the roots. Further, more carbon is allocated to support fine root respiration (maintenance) than to the production of fine root tissue. Coupled with fine roots is the vast symbiotic mycorrhizal fungal network that permeates all forest soils and depends directly and entirely upon growing

trees for carbon. A large proportion of energy expended to maintain fine roots actually supports these fungal symbionts.

Gower, et al. (1996) and Nadelhoffer and Raich (1992) examined studies on carbon allocation in forest systems worldwide and found a high degree of variation in net primary production allocated to fine roots and litterfall amounts. The results for forest types common to the Northeast are found in Table 2.5.

Table 2.5
Litterfall Amounts and Carbon Allocation to Fine Roots for Forest Types Common to the Northeast

Species	Location	Age (yr)	Litterfall (g C/m2/yr)	Fine Roots (g C/m2/yr)
Sugar Maple	Wisconsin	35-55	197	53, 193
		35-55	182	51, 312
Birch spp.	Wisconsin	35-55	195	156
White spruce	Wisconsin	35-55	184	77
White Pine	Wisconsin	35-55	197	44, 116
		mature	149	140, 162
White Oak	Wisconsin	125	248	127
		mature	144	154
Red Oak	Wisconsin	125	286	138
		mature	171	116
Oak/Maple/ Birch	Maine	80	138	333
Red Pine	Mass.			726
				420, 1,090, 410
	Wisconsin		360	198, 69
			243	253, 120
Hardwood	Mass.		489	400, 1,140, 540

* Numbers in each row represent estimates from different studies.

Source: Gower, 1996; Nadelhoffer and Raich, 1992; Raich and Nadelhoffer, 1989; and Vogt, et al., 1986.

Climate has a profound effect on soil carbon. Vogt, et al. (1986) analyzed soil carbon data from 90 forested sites worldwide and grouped them according to climatic zone (boreal, temperate, and tropical). Soil carbon levels were greatest in temperate forests (117 Mg C/ha) and lowest in boreal forests (62 Mg C/ha). When the data were grouped according to dominant tree species present, soil carbon levels were highest for forests dominated by hardwood species. In the worldwide boreal biome, soil carbon levels in deciduous forests represented 64% of the total forest ecosystem carbon compared to 17% in coniferous forests. In contrast, approximately 50% of the total ecosystem carbon was in the soil component for both deciduous and coniferous forests in the warmer temperate forest biomes. Mixed stands contained higher levels of soil carbon than those dominated by either deciduous or hardwood trees. Regression analysis of the data showed that mean air temperatures alone did not explain the observed differences in soil carbon levels.

The general influence of **temperature** and **precipitation** on soil carbon levels is demonstrated by examining soil carbon in selected life zones (Table 2.6) (Post, et al., 1982). Soil carbon density generally increases with increasing precipitation. Soil carbon density increases with decreasing temperature for any particular level of precipitation.

Table 2.6
Summary of Mean Soil Carbon Density for Selected Life Zones Found in the Northeast Region

Life Zone	Mean Soil Carbon Density (kg/m^2)
Boreal moist forest	11.6
Boreal wet forest	13.1
Cool temperate moist forest	12.1
Cool temperate wet forest	13.9
Warm temperate moist forest	6.0

Source: Vogt, 1986.

Temperature and precipitation effects on soil and forest floor carbon storage are the major determinants in the estimates developed by Birdsey (1992) from U.S Forest Service inventory data for the Northeastern states (Table 2.7). States in northern New England with cooler-wetter climates had higher levels of both soil and forest floor carbon compared to states in the southern portion of the region. Additionally, the states with extensive areas of conifer forest types (e.g., spruce-fir), such as Maine, New Hampshire, Vermont and New York, tend to have the highest average forest floor carbon on a per acre basis.

Table 2.7
Average and Total Soil and Forest Floor Carbon for the 11 Northeastern States (1987)

	Soils		Forest Floor	
State	Avg. (lbs/A)	Total (T)	Avg. (lbs/A)	Total (T)
Maine	136,455	1,096,346	17,208	138,258
N. Hampshire	112,586	256,413	16,544	37,679
Vermont	113,995	231,598	15,594	31,681
Massachusetts	108,637	152,611	16,079	22,587
Connecticut	103,769	85,430	14,699	12,101
Rhode Island	100,638	18,168	14,815	2,675
New York	97,309	828,706	15,102	128,612
Pennsylvania	86,950	670,321	10,931	84,270
New Jersey	82,229	74,037	13,961	12,570
Delaware	83,007	14,985	13,051	2,356
Maryland	79,769	95,233	12,551	14,984

Source: Birdsey, 1992.

D. THE MISSING CARBON SINK

Past estimates suggested that the temperate forest is approximately in balance or a small carbon source; however, using these estimates it has proven difficult to balance the global carbon budget (Sedjo, 1992). Estimates of global carbon fluxes among major components of the carbon cycle reveal that 1.2×10^{15} g/yr carbon (Detwiler and Hall, 1988) to $2.0\text{-}3.4 \times 10^{15}$ g/yr carbon

(Tans, et al., 1990) have not been accounted for in annual sinks. It has been suggested that an unidentified large Northern Hemisphere sink exists that contains terrestrial and oceanic components (IPCC, 1992).

According to Birdsey, et al. (1993), the forests of the U.S. have been assimilating carbon at 12-21% of the unexplained flux since 1952. Kauppi, et al. (1992) found that European forests have contributed 5-9% of the unexplained flux during the period of 1971-1990. Forests in the U.S. have accumulated 2.5 times as much carbon as European forests for the period 1970-1987 (Birdsey, et al., 1993). These studies indicate that a large proportion of the missing carbon sink can be explained by biomass accumulation in the temperate forests. Birdsey, et al. (1993) point out that this also does not include the additional carbon stored in wood products and landfills, which accounts for 14% of the net annual accumulation in U.S. forests between 1952 and 1987.

Sedjo (1992) suggests that since northern forests have been expanding in decades, they are largely responsible for the missing carbon sink. As a result of significant expansion in forest cover in Europe (15% between 1954 and 1984) and increased growing stock, expansion of forest cover in the U.S. and timber stocks, and reforestation in the former USSR and Canada, more carbon is being accumulated here.

Schimel, et al. (1995) has suggested that the carbon imbalance is a result of enhanced forest growth due to carbon dioxide fertilization, increased nitrogen deposition, and a positive response to climatic anomalies. Brown (1997) responds that any increased growth due to these factors would be included and accounted for in the repeated forest inventories used to generate estimates (not all investigators agree). She suggests that since tropical forest carbon estimates are based upon model simulations, not based upon repeated forest inventory measurements, the missing carbon sink may well be occurring in estimates of tropical forests. Furthermore, the model simulations do not include the effects of atmospheric carbon dioxide and nitrogen fertilization effects discussed by Schimel, et al. (1995).

E. FOREST CARBON ASSIMILIATION AND DECOMPOSITION

Assimilation and decomposition of carbon in forest ecosystems is determined primarily by two factors, climatic conditions and natural or human disturbance. The soil carbon content in surface mineral soil is also believed to be a major determinant of site productivity within many forest ecosystems due to its effect on soil microbiology and structure, as well as nutrient and water availability (Powers, et al., 1990).

Climate influences forest carbon assimilation and decomposition in a number of ways. Species composition and metabolic rates (e.g., photosynthesis and respiration) are largely a function of climate. It not only determines natural range and local distribution of species, but climate also determines the length of growing season and net primary productivity in forest stands. For example, in the Northeast, pine will exhibit one growth flush each year, while pine in the Southeast will have three or more growth flushes per growing season.

As longer growing seasons and warmer temperatures enhance tree growth, they also speed decomposition of organic matter. Litter and woody debris decompose quickly in warmer climates. A case in point is the vast amount of organic soil amendments that nursery managers must apply to beds simply to maintain soil organic matter levels above 10% in southeastern forest tree nurseries. Conversely, spruce-fir stands of the northern New England region accumulate thick mats of forest duff over several decades. In some older stands, the cooler climate, thin soils, and low decomposition rates may result in duff layers nearly one foot in depth. If foliage is easily decomposed by soil organisms (i.e., rich in calcium and other nutrients and not excessively woody), soil is warm, well-watered, and well aerated, organic matter is returned rapidly to the soil and litter does not accumulate. Such conditions characterize well-drained soils in temperate zones in deciduous forest in the eastern U.S.

The influence of disturbance on forest carbon levels depends upon their intensity and frequency. With the exception of pine barrens, fire-associated pine stands (e.g., jack pine), and insect epidemics, most natural disturbances in the Northeast are gap or patch openings in forests caused by the frequent fall of one to several large trees. Runkle (1985) estimated that these gaps

occur in mesophytic hardwood forests over 0.4 to 2.0% of the forest annually and could cause nearly complete canopy turnover in 150 years.

Forest stand replacement disturbances from fire, intense windstorms, and insect infestation occur relatively infrequently. Lorimer (1977) studied the Acadian forest of Maine and found evidence of stand replacement disturbance events occurring every 700 to 2000 years. Similar work in the Lake States indicated that these infrequent stand replacement disturbances have larger average and maximum patch sizes than those created by timber harvesting, but occur at intervals of hundreds to thousands of years (Canham and Loucks, 1984; Frelich and Lorimer, 1991). The spruce budworm, and to some extent gypsy moth, has caused massive stand replacement disturbances over the past 100-150 years. The budworm outbreaks have been more frequent, intense, and widespread over the past century causing stand replacement, especially in mature balsam fir-dominated forests (Blais, 1983).

Natural disturbances may cause some direct conversion of organic carbon to carbon dioxide as in wildfires, but the indirect effects of opening the forest canopy also influences decomposition and assimilation. Openings in the forest cause increased soil temperature, which in turn speeds decomposition. At the same time, full sunlight and increased mobilization of nutrients increases plant growth and assimilation. Since most natural disturbances in the Northeast are “gap” disruptions, the effect on forest stands is minimal. In the case of stand replacement disturbances, the effect can be large; equivalent to a heavy timber harvest without some of the impacts of machinery. On very “hot” fires, there is also the potential for sheet and gully erosional loss of carbon, in addition to combustion losses.

Human disturbances to forest systems are primarily from land clearing and timber harvesting, and may differ considerably from natural disturbances in intensity, frequency, and size. Timber harvests in the Northeast run the entire spectrum from frequent small partial cuts and thinnings to very large clearcuts covering 100 or more acres occurring every 100+ years. Organic matter accumulation and decomposition will vary substantially among these different disturbance events.

Leak, et al. (1994) studied standing and down deadwood in the White Mountain National Forest under different forest management regimes. Managed even-aged northern hardwood stands contained less deadwood than unmanaged stands over the 120-year rotation due to thinning at year 60-80 (Table 2.8). The deadwood carbon present at 0-20 years was primarily small diameter logging slash from the regeneration harvest that established the stand. Among the managed stands, the whole-tree harvesting regime contained less deadwood since tops and limbs were removed during harvest and thinning. Longer-lived, larger diameter deadwood (>11 inches) was completely absent under even-aged management until after year 60. Uneven-aged stands were harvested on a 20-year interval and contained less overall carbon stored in deadwood, but a large proportion was always stored in large diameter material. Old growth stands had nearly twice the carbon stored in deadwood as the even- and uneven-aged stands.

Table 2.8
Standing and Down Deadwood by Stem Size and Forest Management Regime for Northern Hardwood Stands in the White Mountain National Forest

	-- Forest Management Regime --		
Age (yr)	Conventional	Whole-Tree	Unmanaged
	-- 1,000 Pounds of Carbon/A --		
Even-aged			
0-20	10.8	4.2	11.4
20-40	3.5	3.5	3.5
40-60	7.6	7.6	7.6
60-80	3.0	1.7	7.1
80-100	4.1	4.1	4.6
100-120	4.4	4.4	5.9
Mean	5.6	4.2	6.7
Uneven-aged	4.8	3.2	
Old Growth			7.8

Note: Conventional and whole-tree even-aged management includes one thinning at 60-80 years and a clearcut at 120 years while unmanaged is merely clearcut at age 120 (data from Leak, et al., 1994).

Leak, et al. (1994) also considered the amount of deadwood present in spruce-fir stands in the White Mountain National Forest over a 20-year cutting cycle and in old growth stands. Old growth stands had nearly three times more and larger diameter deadwood carbon (9,600 lb/A) than either conventional (3,800 lb/A) or whole tree harvested stands (2,000 lb/A).

At least 15-18% of the wood fiber in a typical harvest remains on-site as broken or defective material (Bernow, et al., 1992; Pong and Hanely, 1984). In New England, dead balsam fir decomposition is about 3% complete after one year and 26% after 10 years (Lambert, et al., 1980). Aber, et al. (1978) estimate that a 30% increase in the forest floor decomposition rate immediately follows harvest of a northern hardwood stand resulting from increased water, temperature, and nutrient availability. Decomposition returned to its original value after 38 years. Similar results were reported for old growth Douglas fir-western hemlock, where a 50% increase in forest floor decomposition following harvest returned to it original value after 100 years (Harmon, et al., 1990).

Birdsey (1996) developed decomposition rates based on Turner, et al. (1993) for forest types common to the Northeast. Conifer stands had lower decomposition rates than hardwood stands. Estimates for decomposition in red and white pine stands and spruce-fir stands were 0.042% per year. Oak-hickory and maple-beech-birch stand decomposition estimates were 0.075 and 0.062% per year, respectively.

F. IMPLICATIONS OF CARBON STORAGE IN FOREST SYSTEMS

Forests of the United States contain about 60 billion tons of carbon (Birdsey and Heath, 1995), or nearly 40 times the amount of the nation's annual carbon emissions (Marland, et al., 1994). Consequently, the productivity and use of these systems can have a large influence on the global carbon cycle. The majority of the forest carbon occurs in soils, more than 60%, while trees and forest floor debris account for 29 and 10%, respectively. Forests of the North make up about 25% of the total carbon stored in U.S. forests (Hair, et al., 1996).

The forests of different geographic regions in the U.S. are enormously different in their ability to store carbon in different forest components. These differences arise from climate, especially precipitation and temperature that influence carbon accumulation and decomposition, soil and physiographic factors, tree species composition, and forest management practices. Although more subtle, these differences are also apparent at the regional- and subregional-level.

The Northeast is among the most heavily forested regions of the U.S. with a very high level of plant and tree species richness. A wide variety of forest types commingle across the region, from spruce-fir flats and northern hardwood ridges in the far north to temperate hardwoods and pine forests in the most southerly portion. Variation is also noted within states. The northern states in this region, Vermont, New Hampshire, and Maine, occupy the transitional "Acadian" forest with characteristics of both the temperate forest to the south and the boreal forest to the north.

As policymakers begin to consider the role that forests can play in sequestering carbon as part of mitigation plans, they must understand the inherent variation in the ability of different forests to accumulate and store carbon. The natural processes operating in these forests are essentially the same; however, the resulting carbon storage will vary with forest characteristics from one forest type to the next. Even within one specific forest type, differences in age and past management practices will influence growth and carbon storage.

The next two chapters will build on these basic relationships to review what is known about the impacts of managing existing stands and planting new stands.

G. REFERENCES

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III. FOREST MANAGEMENT SYSTEMS AND CARBON STORAGE IN FORESTS: EXISTING STANDS

Forest ecosystems are the major terrestrial carbon reservoirs and will be a critical factor in plans to mitigate the impacts of elevated atmospheric carbon levels. Measures taken today to convert marginal pasture and crop land to forest, increase timberland growth, replace fossil fuels with biofuels, and increase wood recycling and substitution will result in higher rates of carbon sequestration. This chapter examines the influence of different management regimes on the various pools of carbon in the forest ecosystem.

Forest management can affect the forest slowly, because only a small area of land is harvested, thinned, or planted each year. The USDA Forest Service estimates that about 2% of the region's forest area is harvested each year. This is an implicit 50-year cutting cycle. This number includes clearcuts and partial cuts, and probably includes an estimated 35,000 acres per year of timber stand improvement. This chapter discusses stand-level effects in some detail based on current literature. Estimates of potential landscape-level effects would have to be based on more detailed state or regional assessments.

Chapter Outline

A. Introduction
B. Uneven-Age Systems and Partial Harvests
C. Even-Age Systems
D. Thinnings and Intermediate Harvests
E. Forest Preserves
F. Forest Management and Carbon at the Landscape Level
G. Implications of Forest Management for Carbon Storage
H. References

A. INTRODUCTION

Forest management systems can have a major influence on carbon storage in forest ecosystems. At one end of the management spectrum, intensive forest management systems that involve clearcutting, site preparation, plantation establishment, and subsequent herbicide treatment may cause short-term carbon losses, but may result in long-term gains in carbon storage due to increased growth rates. At the other end,

elimination or reduction of timber harvests may increase current carbon storage in the forest ecosystem, but potential long-term gains will be reduced. One thing is certain, however, if forests are harvested periodically, the amount of carbon retained in the ecosystem is much less (when averaged over the entire rotation) than the maximum amount the area can support (Cooper, 1983).

Helms (1996) identifies two basic principles of forest management that should be recognized with any forest management system. First, soil erosion must be minimized since surface mineral soil contains the bulk of soil carbon. Second, any forest management treatment, including harvesting, site preparation, and thinning, will increase soil temperature and water content, at least for a time. These changes directly increase the rate of decomposition of soil organic matter and respiration of soil microorganisms.

The carbon balance between managed forests and the atmosphere depends upon the lifetime of wood products utilized (see Chapter VI), as well as the frequency and intensity of harvest (Dewar, 1991). This chapter will examine the influence of forest management systems on the major carbon pools of forest ecosystems: standing woody biomass; herbaceous biomass, soil carbon and litter/woody debris.

B. UNEVEN-AGE SYSTEMS AND PARTIAL HARVESTS

As a result of past harvesting practices, there are relatively few truly uneven-aged stands in the northeast , i.e, stands with three or more distinct age-classes. Most "uneven-aged" stands in the region are actually two-aged stands with a few scattered individual trees of other ages. High-grading and heavy reliance on diameter-limit cuts have yielded what would be technically defined as even-aged stands, even though the harvesting methods have been partial cuts. Harvesting usually occurred when sufficient sawtimber had accumulated to make it economical to cut. Even treatments dubbed “selection” or “selective” by some foresters or landowners may not be implemented in ways that create multiple-age stands.

Uneven-aged systems are well suited to growing a variety of types of timber, especially sawtimber, which requires relatively long periods of time to mature. Hardwood sawtimber stands with relatively high aboveground biomass (172-175 Mg/ha) in the eastern U.S. tend to accumulate the greatest biomass in the 20- to 40-cm diameter classes with few very large trees (>100 cm DBH) (Brown, et al., 1997). Brown, et al. (1997) examined two mature forests in Indiana that had been partially harvested 90 and 55 years before the study. Although the aboveground biomass density was ~200 Mg/ha with about 15% of the biomass in trees >70 cm DBH, biomass was concentrated in trees of the 40- to 60-cm diameter class with no trees >75 cm DBH. The impacts of past logging on carbon storage could be detectable in aboveground biomass of older stands for at least 60 years. By contrast, old growth stands, which have almost twice the total biomass, have the most biomass in 60- to 80-cm diameter classes with the greatest biomass quantities skewed to the largest diameter classes (i.e., > 100 cm DBH). The data suggests that hardwood sawtimber stands are typically harvested well before they reach their maximum carbon storage potential, and that there may be merit in retaining very large trees in harvested stands to sequester additional carbon.

The influence of harvesting intensity on carbon storage is illustrated in partial cuts for a northern hardwood ecosystem in northeastern Wisconsin (Strong, 1997). Results would likely be similar in the northeast. The forest was comprised of 40% sugar maple and 30% white ash, basswood, yellow birch, and ironwood. Five intensities of partial harvesting were examined over a 40-year period: 1) control; 2) 8-inch diameter-limit cut (23 ft^2/A residual basal area); 3) heavy selection cut (62 ft^2/A); 4) medium selection cut (77 ft^2/A); and 5) light selection cut (88 ft^2/A). The control remained uncut, the diameter-limited harvest was cut once at the beginning of the experiment, and the selection harvests were made at four 10-year intervals. (Under the Maine Forest Practices Law the diameter-limit cut would be considered a clearcut, i.e., less than 30 ft^2/A basal area remained in the residual stand.)

The amount of carbon in dead and harvested trees and in the ecosystem after 40 years is shown in Table 3.1 (Strong, 1997). Carbon in dead trees was greater in the control than in the

four harvest treatments, but did not differ significantly among harvest treatments. Among the harvest treatments, harvested carbon was significantly lower in the diameter-limit cut than all selection harvests that had multiple harvest entries. The heavier the selection harvests in the three 10-year cutting cycles, the more carbon was harvested over the 40-year period. At the end of the 40-year period, the control had significantly more carbon stored in overstory trees than all harvest treatments. There was no significant difference in overstory carbon between the diameter-limit cut and the light selection harvest. Heavy and medium selection harvests had the least amount of carbon in the overstory after 40 years of treatments. The frequent entries and moderate overstory removals associated with heavy and medium selection harvests resulted in significantly more sapling carbon than the other treatments.

Table 3.1
Mean Aboveground Carbon (lbs/A.) by Harvest Treatment for Dead and Harvested Overstory Trees for the 40-year Period, and Live Overstory Trees, Saplings, and Ground Vegetation at Year 40 in a Northern Hardwood Ecosystem

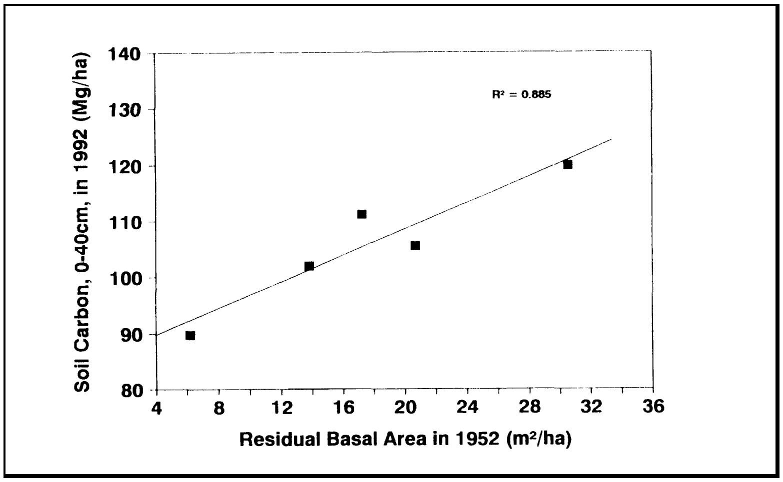
	40-year means		Means after 40-year period			
Treatment	Dead	Harvested	Overstory	Saplings	Ground Vegetation	Total
			-- 1,000 Pounds of Carbon/A --			
Control	29.9	0	103.9	1.4	0.19	135.3
Light	8.4	58.3	79.1	3.4	0.10	149.3
Medium	10.3	65.7	66.4	5.6	0.09	148.0
Heavy	4.0	74.7	57.6	5.4	0.10	141.9
Diameter-limit	10.2	41.8	88.1	1.9	0.18	142.1

Source: Strong, 1997.

Carbon in ground vegetation was significantly less in all selection harvests versus the control and diameter-limit treatments because, although more light penetrated the canopy, it was intercepted by the sapling layer. Although only one significant difference in soil carbon

occurred among harvest treatments (less soil carbon for the diameter-limit cut at 3-10 cm depth), a significant correlation of decreasing soil carbon after 40 years with increasing harvest intensity occurred (Figure 3.1). A similar response was reported by Rollinger and Strong (1995) for red pine.

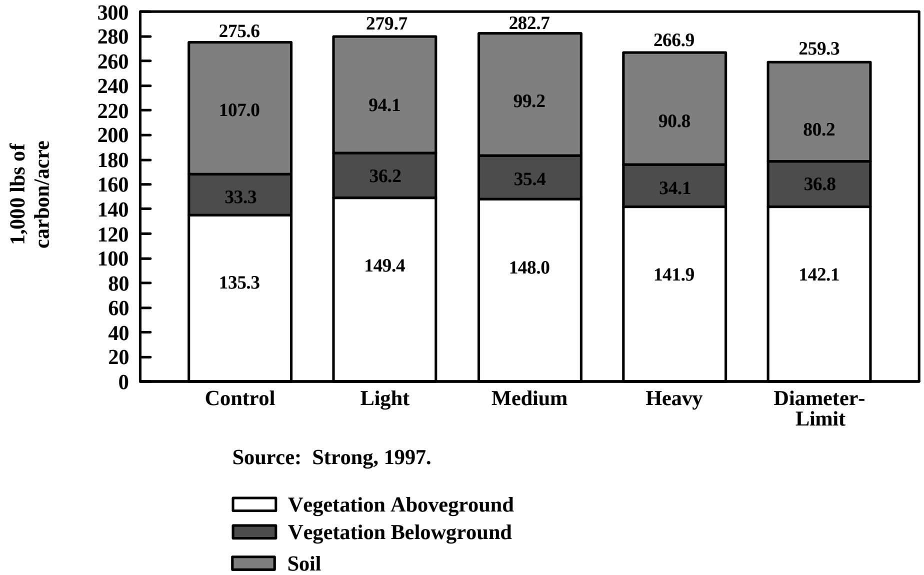
Figure 3.1
The Relationship Between Soil Carbon in 1992 (Mg/ha)
and Residual Basal Area (m^2/ha) in 1952



After 40 years of treatments, the total ecosystem carbon did not differ significantly by harvest intensity in a northern hardwood ecosystem for components measured (Table 3.2) (Strong, 1997). However, the trend of decreased carbon levels with increased harvest intensity observed for soil carbon was also present for total ecosystem carbon. Although small and not statistically significant, this trend could have implications on carbon sequestration and site productivity over multiple cutting cycles. For example, the diameter-limit harvest treatment had 16.3 lb/A (or nearly 10%) less total ecosystem carbon stored (including soil carbon) than controls. If extrapolated to the 29 million acres of northern hardwoods in the Northeast and Mid-Atlantic States, it would represent a difference of 236 million tons of carbon. Light and moderate selection harvests actually had more total ecosystem carbon than controls after 40 years.

Figure 3.2

Ecosystem Carbon for a Northern Hardwood by Harvest Intensity for Aboveground and Belowground Vegetation, Soil (to 16" Depth) and Total



Source: Strong, 1997.

Strong (1997) concludes that light to moderate harvesting in northern hardwood ecosystems does not appreciably alter carbon cycling. He cautions that heavier cutting may result in carbon loss, possibly from the increased soil respiration rates associated with opening the canopy. More research is needed to determine whether magnitude of the trend in other regions and the possible impacts on carbon sequestration and the sustainability of current forest practices.

C. EVEN-AGE SYSTEMS

Even-aged stands are comprised of one or two age-classes of trees, usually a dense overstory that may or may not have seedling or sapling regeneration below. These stands originate from abandoned fields, stand-replacement level natural disturbances, and harvesting that removes essentially the entire stand, e.g., clearcutting. Consequently, one size class of trees grows to maturity at one time. An even-aged stand can often be converted to an uneven-aged

stand, depending upon species composition, over many decades by opening the stand periodically enough to establish new age-classes of trees, thereby establishing three or more distinct age classes.

Shelterwood Systems

The shelterwood system is a regeneration method, and thus involves the end of one rotation of trees and the beginning of another rotation with several years of overlap. Typically one or two partial harvests are performed before a final harvest removes the last of the mature trees. The final harvest occurs 10-20 years following the initial partial cut at which time regeneration has become established and has attained a height of about 5-10 ft depending on the tree species involved. An even-aged stand of advance regeneration results. A variation of the system is termed an irregular shelterwood (or shelterwood with reserves) in which a number of the best trees are retained in the regenerated stand to accrue additional growth and provide vertical diversity for wildlife habitat.

Frank (1986) examined the shelterwood system on four central Maine spruce-fir sites comprised of 40% red spruce, white spruce and balsam fir, 45% hemlock, white pine, and northern white cedar, and 15% hardwoods. Two sites were harvested and regenerated using a 2-stage and two using a 3-stage shelterwood. The regeneration was at least one or two feet tall at the time of final harvest and fully stocked (at least 40% of the plots). The amount of carbon removed during harvests in both systems is shown in Table 3.2. The positive influence of the initial harvest entries on the growth of residual trees for both the 2- and 3-stage shelterwood systems is evident in the total amount of carbon present at the final harvest. The 2-stage system increased carbon by 17% and the 3-stage by 27% over 11 and 17 years, respectively. As a result pulpwood-size trees and additional portions of sawtimber-size trees likely grew into sawtimber classes, which represent longer-lived end-products. These gains in carbon are in addition to carbon assimilated by the resulting fully-stocked regeneration that was released or established during treatment. If an even-aged stand were regenerated using clearcutting, carbon would have

been assimilated only by the natural or planted regeneration, and only the initial volume of wood would have been removed.

Table 3.2
Tree Carbon Estimates for Successive Timber Removals During Harvesting of Mature Spruce-Fir Stands in Central Maine Using 2-Stage and 3-Stage Uniform Shelterwood Systems

Time and Species	-- 2-Stage Shelterwood -- Total Tree carbon	Harvested Total Tree carbon	-- 3-Stage Shelterwood -- Total Tree carbon	Harvested Total Tree carbon
	-- 1,000 pounds of Carbon/A --			
At First Harvest	*1957*		*1955, 57*	
Balsam Fir	11.1	5.1	7.9	3.4
Spruce	13.9	1.3	13.2	1.2
All Species	61.6	27.7	55.9	20.1
At Second Harvest			*1966, 68*	
Balsam Fir	*(not applicable)*		4.7	4.2
Spruce			17.6	3.0
All Species			50.8	33.0
At Final Harvest	*1967*		*1973, 74*	
Balsam Fir	7.2	6.0	1.3	1.3
Spruce	17.9	17.7	16.3	16.3
All Species	46.7	42.0	23.0	23.0
Total	4.7	69.7	0	76.1

Source: Frank, 1986.

In the northeast, especially in northern and eastern Maine, old clearcut or heavily harvested softwood stands and budworm-damaged stands have developed into aspen overstories following harvest. Consequently, nature developed a "shelterwood" system with mature aspen overtopping sapling-size spruce-fir. Large areas of this forest mix have been treated with overstory removal of the mature aspen, releasing nearly pure stands of spruce-fir. On adjacent

stands in Minnesota, aspen showed no difference in forest floor biomass compared to white spruce, red pine, and jack pine stands, however; the softwood stands contained 10-40% more soil carbon. Results suggest that conversion of intolerant aspen stands to softwoods may increase soil carbon sequestration. Other work in the Lake States (Alban and Perala, 1992), indicated no changes in soil carbon levels associated with aspen succession to tolerant hardwood tree species.

The shelterwood provides a silvicultural system for managing even-aged stands that may have greater benefits to carbon sequestration than clearcutting. Soil carbon may be conserved since less erosion potential occurs, the soil is partially shaded at all times, thus reducing decomposition rates, and litter and slash inputs from harvesting are spread over a longer period of time. Since special care is taken to protect regeneration, both standing woody biomass and herbaceous cover are present on the sites in relatively high amounts. Finally, additional carbon storage occurs on the best trees in the stand that are left until the final harvest to accumulate additional biomass.

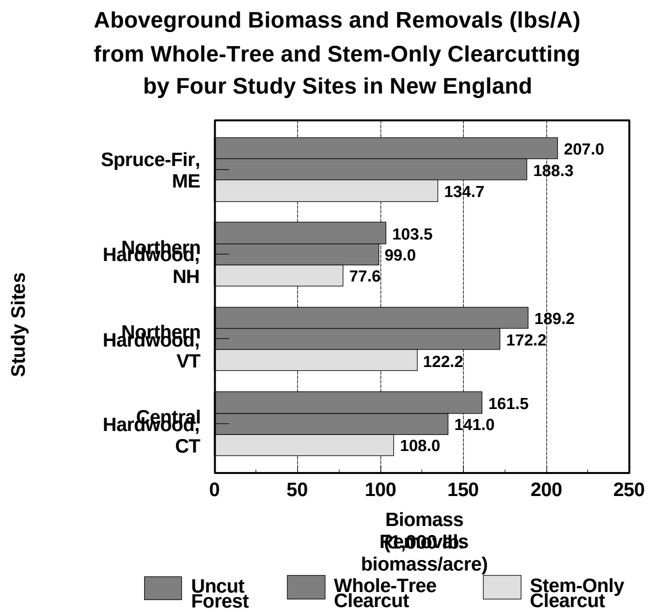
Clearcutting Systems

Clearcutting encompasses a variety of harvesting methods that are applied to regenerate forest stands. Commercial clearcutting removes all merchantable trees and usually includes only sawtimber and pulpwood. The residual stock is comprise saplings < 5 inches DBH. Silvicultural clearcutting involves the removal of all trees from the site and typically involves chipping or felling small trees, tops, and limbs (whole-tree clearcutting). Both of these clearcut harvesting methods may involve either limbing and topping trees at the stump or hauling the entire stem and branches to the landing where they are delimbed and processed. The manner in which clearcutting is performed may have a substantial impact on carbon storage in the new stand.

Pierce, et al. (1993) examined the impact of mechanical whole-tree clearcutting on the productivity of three forest types in New England: 1) spruce-fir in central Maine; 2) northern hardwoods (sugar maple-beech-yellow birch) in northern New Hampshire; and 3) central hardwoods (mixed oak) in south-central Connecticut. Estimates from biomass equations indicate

that whole tree clearcutting removed 90-96% of the forest stand while stem-only clearcutting removed 65-75% of the original standing biomass (Figure 3.3). Whole-tree clearcutting results in removal of significant quantities of slash that would otherwise decompose adding carbon to the soil component and atmosphere. Coupled with increased decomposition rates from warmer soil temperatures and mechanical mixing of surface soil by machinery, biomass removals reduced soil organic matter content in the surface soil horizons.

Figure 3.3



Source: Pierce et al., 1993.

According to Helms (1996), clearcutting adversely effects soil carbon storage by increasing root mortality, increasing soil temperature, and creating conditions that have the potential for high soil erosion. Trexler (1991) cites studies from the literature suggesting forest soils may loose 40% of their carbon 10-25 years after clearing before the soil once again begins to act as a sink.

Clearcutting reached its peak in Maine in the late 1980's when about 150,000 acres of approximately 17 million acres of timberland were clearcut annually. That level has declined to

about 55,000-60,000 acres annually in recent years. With the closing of many biomass facilities in the region, demand for fuelchips has declined. Consequently, whole-tree clearcutting has also decreased; however, it is still common practices to yard whole-trees and delimb them roadside in logging yards. This practice effectively eliminates the return of tops and limbs to the forest site. Some landowners will leave white pine within clearcut areas creating a "seed tree" effect that enhances "green retention" and may add somewhat to stored carbon. However, the aim is to return for these trees in several decades after additional volume has accumulated.

Studies of forest types common to the Northeast provide contrasting results for the fate of soil carbon following clearcutting or whole-tree harvesting (Table 3.3). The majority of studies reviewed by Johnson (1992) indicated little or no change in soil carbon (+/- 10%) associated with harvesting and regeneration. This agrees with Cooper (1983), who suggested that if forest vegetation is reestablished soon after harvest, loss of soil organic carbon is small.

According to Aber, et al. (1978), forest floor biomass in northern hardwoods appears to be affected more by the rotation period than the intensity of harvest, with short-rotation, complete-forest harvesting causing the greatest reductions in biomass. Forest floor organic matter in northern hardwoods underwent an initial period of decline after harvesting, followed by a period of recovery toward pre-harvest levels (Aber, et al., 1978). In aspen stands, litter fall returned to pre-harvest levels five years after harvesting (Alban and Perala, 1992). The authors suggest that logging slash and severed roots in the soil help maintain constant levels of soil carbon in harvested aspen stands.

Other work suggests a substantial effect of harvest intensity on forest floor carbon. Mroz, et al. (1985) examined whole-tree harvesting of hardwoods on sites of varying quality in Upper Michigan and reported losses of forest floor carbon ranging from 40-70%. Covington (1981) contrasted forest floor biomass in 13 conventionally clearcut northern hardwood stands (ages 3 to 57 years) in New England with an uncut stand. Forest floor biomass declined to about 45% of its original value after 15 years, after which it slowly accumulated to 95% of the precut value by age 50 years. Work by Pastor and Post (1986) noted a 20% decrease in soil carbon following

harvest and regeneration to pin cherry and northern hardwoods with slowing regaining of carbon after 20 years. In a study of a spruce swamp in Upper Michigan, McLaughlin, et al. (1990) found that whole tree harvesting and site preparation reduced forest floor carbon but had complex effects on soil carbon reserves. Certainly the diversity of results in this literature to date suggests caution in making extrapolations or generalizations.

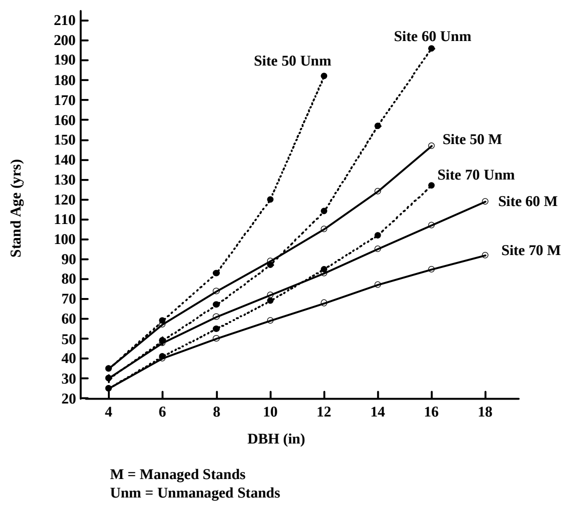
Table 3.3
Summary of Research Results for the Effect of Timber Harvesting on Soil Carbon

Forest Type/ Location	Treatment	Percent Change in Soil Carbon	Reference
Mixed Conifer/ Hardwood (Ontario)	Whole-Tree Harvest	+14%	Hendrickson, *et al.*, 1989
N. Hardwood (NH)	Whole-Tree Harvest	1%	Johnson, *et al.*, 1991
N. Hardwood (NH)	Whole-Tree Harvest	0%	Huntington and Ryan 1990
Aspen (MN)	Whole-Tree & Stem Only Harvests	0%	Alban and Perala 1990
N. Hardwood (ME) (well-drained)	Biomass Harvest	0%	Fernandez, *et al.*, 1989
N. Hardwood (ME) (poorly-drained)	Biomass Harvest	- 39%	Fernandez, *et al.*, 1989
N. Hardwood (MI)	Whole-Tree Harvest	40 to 70%	Mroz, *et al.*, 1985
N. Hardwoods (N.E.) (13 stands)	Clearcut	- 45%	Covington 1981
Mixed Oak (TN)	Clearcut & Sawlog Harvest	+	Johnson and Todd 1997
N. Hardwood	Light, Medium, Heavy, & Diameter Limit	0%	Strong 1997

While initial soil carbon recovery is occurring on clearcut sites, an even-aged forest stand will become established. The amount of tree carbon accumulated over time depends on a variety of factors including site index and the intensity of forest management practiced, including precommercial and commercial thinning. The speed with which stands attain different average DBH-classes increases with increasing site index and intensity of forest management (Figure 3.4) (data from Hornbeck and Leak, 1992; Leak, et al., 1987). The DBH in unmanaged northern hardwood stands begins to level off after age 100 years for all site indices while the DBH of intensively managed stands continues to increase.

Figure 3.4

Average DBH for Unmanaged and Intensively Managed Northern Hardwood Stand in New England Over Time for Three Different Site Indices

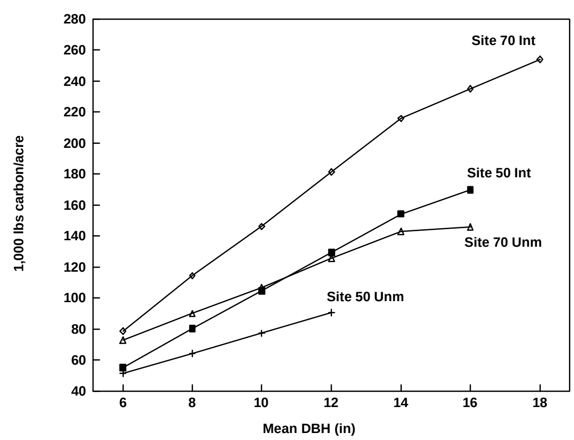


Growing stock volumes for different size-classes of even-aged northern hardwoods in New England were presented for intensively managed (data from Leak, et al., 1987) and unmanaged stands (data from Hornbeck and Leak, 1992). Using conversion factors developed by Birdsey (1992), volumes were converted to total tree carbon (Fig. 3.5). Tree carbon for

intensively managed hardwood stands includes carbon from thinnings and standing trees. Intensive management increased carbon yield on all site indices through biomass harvested in thinnings and by reducing the time for trees to reach a merchantable size. A comparison of Figure 3.4 with Figure 3.5 reveals that unmanaged stands not only produce less biomass for any particular size-class, but they also take substantially more time to attain that size class than intensively managed stands. This comparison considers tree carbon only.

Figure 3.5

Total Tree Carbon for Different Age-Classes of Unmanaged (unm) and Intensively Managed (inm) Even-Aged Northern Hardwoods in New England on Sites with Different Productivity (Site Indices)



Source: See Appendix Table A.3.

D. THINNINGS AND INTERMEDIATE HARVESTS

Many thinnings are performed in poletimber or small sawtimber stands. The U.S. Forest inventory data used by Brown, et al. (1997) indicates that these stands contain 100-125 Mg/ha of aboveground biomass with the highest amounts concentrated in the 20- to 25-cm size-class.

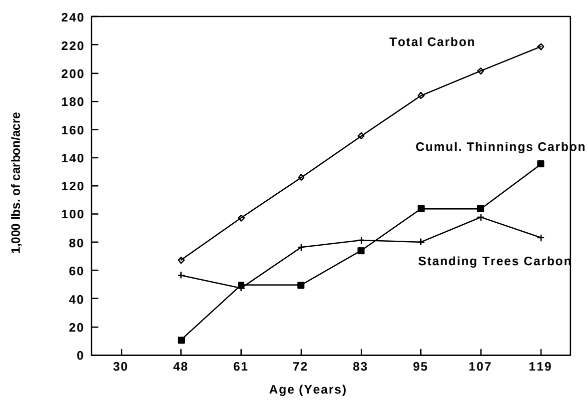
Thinnings and intermediate harvests are intended to anticipate natural mortality. Mortality should be minimal in intensively managed stands (Cooper, 1983). Following thinning, stand growth increases until canopy density reaches full light utilization, and then remains

constant until decreasing rapidly at the highest stocking levels. Cooper (1983) estimates that standing biomass is reduced by a third to a half during thinnings, depending on the interval between entries. However, trees released by thinning tend to grow faster, and total merchantable wood production over time in properly thinned stands often equals or exceeds that in unthinned stands depending on site conditions (Waring, et al., 1981).

The influence of thinning on total tree carbon in an even-aged northern hardwood stand on an average site index (60) is shown in Figure 3.6 (data from Leak, et al., 1987). Growing stock volumes were converted to carbon using methods of Birdsey (1992). Once carbon levels in the developing even-aged stand reached ~80,000 lb/A at about year 75, they were maintained within a range of 80-100,000 lb/A (2,000-2,600 ft^3/A) through periodic thinning. Unmanaged stands reached this level at about 110 years, and they begin to reach their total tree carbon asymptote near 125,000 lb/A about age 150 years (Hornbeck and Leak, 1992). Thinned northern hardwood stands produced twice the amount of total tree carbon over time as comparable-aged unmanaged stands. The benefit to carbon sequestration depends largely on the fate of the carbon harvested during thinnings.

Figure 3.6

Tree Carbon from Thinnings and in Residual Standing Trees for Even-Aged Northern Hardwoods in New England on an Average Site (SI = 60).



Source: See Appendix Table A.4.

In precommercial thinnings and some timber stand improvement (TSI) operations, the submerchantable trees are felled or killed and left on site. In commercial thinnings and most TSI operations, slash and tops may be left behind, especially where pulpwood markets are weak (which is much of the Northeast region). Much of this biomass will be incorporated into soil carbon pools, but a substantial portion will be released to the atmosphere through decomposition processes.

Vasievich and Alig (1996) quantified the biological and economic opportunities to increase net annual timber growth on U.S. timberlands and the associated impacts on carbon storage. Results indicate that 52% of the 390 million acres of timberland outside national forests could increase net annual growth through regeneration and stocking control treatments. More than four-fifths of the area with biological opportunities was in the eastern U.S. -- 43% in the North and 40% in the South (Table 3.4). Although most of the timberland is owned privately (71%), the proportion of each ownership type with biological opportunities is roughly the same for private (53%) and industrial (49%) timberlands.

Table 3.4
Biological and Economic Opportunities for Increasing Net Annual Growth on Timberlands in the Northeast/Mid-Atlantic States Region ((1989)

		---------BIOLOGICAL---------		----------------------ECONOMIC----------------------		
Treatment	Area	Treatment Opportunity Area	Net Annual Growth Increment	Treatment Opportunity Area	Cost	Net Annual Growth Increment
	-- Million Acres --		*Billion ft^3*	*Million Acres*	*Billion $*	*Billion ft^3*
Regeneration		38.3	1.3	5.9	0.7	0.3
Stocking Control		9.1	0.3	6.2	0.3	0.2
Total	89.3	47.9	1.6	12.1	1.0	0.5

Source: Vagievich and Alig, 1996.

If all the biological opportunity were captured, net timber growth would be increased by 8.2 billion cubic feet annually, fairly evenly distributed over the entire area (Vasievich and Alig, 1996). However, only 99 million acres are estimated to have economic opportunities (i.e., yielding 4% or more net of inflation or deflation) yielding an increase in net annual timber growth of 5.8 billion cubic feet. At least several decades would be required to realize substantial increases in current growth, in addition to large investments in regeneration and stocking control measures. Significant changes in growth and carbon storage would begin to show up in two to three decades. The full potential would not be realized until near the end of the 21st century. If all biological opportunities were implemented, carbon storage could be increased by 210 million tons/yr, enough to offset 14% of current carbon emissions. Economic opportunities would account for 10% of the annual carbon emissions.

Natural Regeneration

Seedling and sapling size-class units from the U.S. Forest Service inventory data have aboveground biomass densities of 20-50 Mg/ha (Brown, et al., 1997). Most of these stands, although dominated by small trees, had large trees (>70 cm DBH) scattered throughout (<1 per ha) accounting for about 2 Mg/ha of aboveground biomass.

E. BIOMASS HARVESTING IN CONVENTIONAL FORESTRY

Harvesting of trees for biofuel has the potential to displace large amounts of fossil fuel with a net beneficial influence on the carbon cycle budget (Schlamadinger and Marland, 1996). However, the direct effect on carbon storage in the forest ecosystem will be negative initially following harvest. The manner in which biofuels are harvested and the forest managed will determine the overall influence on carbon storage in the forest ecosystem.

In the literature, much attention has been given to short-rotation "energy" plantations of willow and poplar species on abandoned agricultural land (Schlamadinger and Marland, 1996; J. Peterson and E. White, pers. comm.). Although results suggest that these plantations can

produce biomass for fuel rapidly and effectively displace fossil fuel, it is also true that biomass removed for biofuel during conventional forestry operations can also accomplish similar fossil fuel displacement.

Biomass harvesting involves the removal of low grade wood from stands that is unsuitable for pulp or pallet grades. The trees are typically removed as whole trees (i.e., including tops and branches) and chipped to be later burned in wood-fired energy systems. Biomass harvesting is used in both partial harvests and clearcut operations, but the impact on forest ecosystem carbon may be very different for the two types of harvests.

Since nearly 70% of all nutrients in trees are found in the leaves and smaller branches, biomass removals have the potential to lower the nutrient content of soils (Hewett, 1985). Nutrient depletion can lower site productivity, and consequently carbon assimilation rates in emerging forest stands. Nutrient depletion may be a serious problem on sites that are clearcut in combination with biomass removals since essentially very little slash and debris is left on-site and decomposition rates are accelerated. For this reason, short-rotation plantations may also deplete nutrient reserves rapidly and require supplemental fertilization.

Partial harvests that incorporate biomass removals may not generate as much biomass as short-rotation plantations or clearcuts, but they leave trees behind to replenish soil nutrient reserves and shade that maintains lower rates of decomposition. In addition, the sheer size of the forested region of the northeast provides an enormous supply of biomass-grade material for biofuel. Coupled with existing conventional timber harvests, biomass provides tremendous potential for displacing fossil fuels.

F. FOREST PRESERVES

There are a number of reasons for considering forest preserves in mitigation plans for sequestering carbon in forests. Social, economic, cultural, and environmental concerns ensure that large areas of forest land will be set aside from active forest management. In addition, forest preserves provide the benchmark for assessing the impact of various management scenarios on carbon storage potential. While forest protection can result in significant net carbon storage, a point of equilibrium eventually is attained beyond which no further sequestration occurs over time (Schlamadinger and Marland, 1996). This section will discuss the potential carbon storage that can be expected on lands set aside from active forest management.

The primary advantages of forest preserves to carbon sequestration is the large amount of carbon that can be stored in old growth forests and the long-term nature of the storage. The average carbon storage in managed forests can be 30% less for living trees and 70% less for soils when compared to old growth forests (Covington, 1981; Cooper, 1983). Numerous factors, such as forest type, site productivity, fire and disturbance regime, and climate, will affect the carbon storage potential of old growth forests eventually produced in forest preserves. Of the various carbon storage pools in old growth forests, standing biomass carbon, soil carbon, and forest floor carbon would be at their maximum levels. The understory carbon pool would remain at about two percent of the standing biomass carbon level (Birdsey and Heath, 1993).

Several forest types in the Northeast that may produce old growth forests include birch-beech-maple, oak-hickory, pine-oak, pine, hemlock, spruce-fir, and mixedwood. Brown, et al. (1997) examined the aboveground biomass produced in hardwood stands in the eastern U.S. In stands examined, they found that old growth hardwood forests had nearly twice the above ground biomass density of sawtimber hardwood forests and often five times greater proportion of biomass in large trees (i.e., >70 cm diameter at breast height (DBH)). The aboveground biomass density was estimated to range from 220-260 Mg/ha, with one stand greater than 300 Mg/ha. Up to 30% of the total aboveground biomass density was in trees greater than 70 cm DBH. Whittaker (1966) reported aboveground biomass density of 500-600 Mg/ha for undisturbed cove

forests in the Smoky Mountains, but these represent optimal growing conditions and would not reflect broad-based growing conditions of typical forest stands. Work by Martin (1977) on a large tract of maple-beech-birch in New Hampshire estimated 262 Mg/ha of aboveground biomass, which is in line with estimates of Brown, et al. (1997). Estimates for aboveground biomass for several old growth forests are shown in Table 3.5.

Table 3.5
Estimates of Aboveground Biomass for Old Growth Forests in the Eastern U.S.

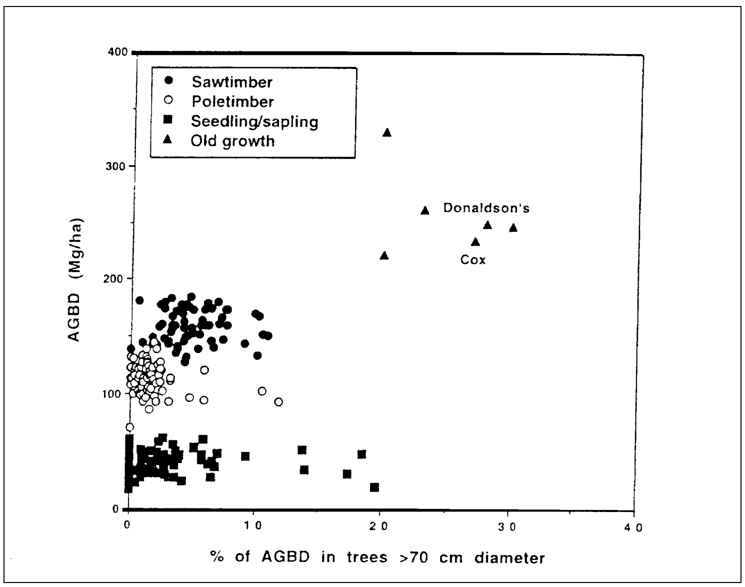
Forest Type	Location	Aboveground Biomass (Mg/ha)	% Biomass in Large Trees	Source
Hardwood	KY	330	20	Muller, 1982
Hardwood	IL	262	23	Weaver and Ashby, 1971
Hardwood	ID	250	28	Schmelz and Lindsey, 1965
Hardwood	ID	247	30	Schmelz and Lindsey, 1965
Hardwood	ID	235	27	Schmelz and Lindsey, 1965
Hardwood	ID	222	20	Schmelz and Lindsey, 1965
Oak-Hickory	Smoky Mts.	370	~30	Whittaker, 1966
Maple-Beech Birch	NH	262		Martin, 1977
Hardwood	NH	~350		Whittaker, et al., 1974
Hardwood	MI	284		Mroz, et al., 1985
Hardwood	MI	325		Mroz, et al., 1985
Hemlock-Pine	WI	280		Crow, 1978

Brown, et al. (1997) also examined oak-hickory and maple-beech-birch from the U.S. Forest Service inventory plots to estimate aboveground biomass density and to relate results to old growth biomass estimates and the percentage of large trees present. No significant

differences in the two forest types were detected, and maximum values were 175-185 Mg/ha. The authors suggested from the inventory data that a progression exists from low biomass in regenerating forests with few large trees, to young secondary forests with more biomass but with <5% of the biomass in large trees, to advanced-recovery forests with the highest biomass and up to 10% of the biomass in large trees (Figure 3.7). The trend is similar to that reported for mature

tropical forests with aboveground biomass densities near 350 Mg/ha and 30-40% of the biomass contained in large trees (Brown, 1996).

Figure 3.7
Stages of Development and Recovery of Aboveground Biomass Density of Eastern Hardwood Forests in Comparison to Old Growth Forests



The eastern hardwood forests represented in the forest inventory data had much lower aboveground biomass density than the old growth forests. Consequently, hardwood forests in the East have the biological potential to accumulate significant quantities of additional carbon if left unharvested (Brown, et al., 1997). Many existing sawtimber stands could at least double

their aboveground biomass before reaching maturity. It would require 100-200 years for such stands to reach carbon levels comparable to old growth stands. Presently, about five million acres of the Northeast is in wilderness, watershed, game preserve, etc. where long rotation or preserve prescriptions will be implemented.

G. FOREST MANAGEMENT AND CARBON AT THE LANDSCAPE LEVEL

Discussion of the influence of forest management on carbon sequestration thus far has concentrated primarily on the stand level. Measures at the stand level will only be effective as they are implemented at the larger landscape level. The initial step must be an assessment of the current carbon stocks and fluxes associated with the region and the likely impacts of management practices (Price, et al., 1997). The U.S. is fortunate to have over 40 years of U.S. Forest Service inventory data upon which to make this assessment. Several models, including the FORCARB model (Birdsey, 1993), have used this information to estimate both carbon stocks and fluxes and are discussed in a later chapter. Case studies at the landscape level using other methods include Price, et al., 1997 -- the foothills area in western Canada; and Hoen and Solberg -- a large area in Norway.

In the Northeast, assessment information suggests that forest ecosystems are acting as net carbon sinks, absorbing more carbon via photosynthesis than is being released through respiration. This trend is partially a result of the cooler climate that favors carbon retention, relatively less frequent disturbances, and aging stands (in particular hardwoods), and it is expected to continue through 2040 (Birdsey, 1993). Although forests across the Northeast are now net accumulators of carbon, forest management could add significantly to carbon sequestration in the region.

In northern New England and portions of New York and Pennsylvania, vast tracts of timberland are managed by large corporate or private landowners; 30% of the entire Northeast region is in ownerships larger than 1000 acres. Whether held for investment purposes or to furnish mills, these lands are harvested regularly and do not attain carbon storage levels

equivalent to old, mature forests. These lands may hold the greatest potential for increasing carbon sequestration rates through forest management. The Northern Forest region of Maine, New Hampshire, Vermont, and New York is characterized by expansive spruce-fir forests, northern hardwood ridges, and mixedwoods largely managed by industry and private interests. The level of management could be characterized as low to moderate. Heavy reliance on clearcutting and diameter-limit harvesting, as well as a recent severe budworm infestation has left this region with few very old, mature softwood stands and millions of acres of younger stands of spruce-fir and intolerant successional hardwoods. Implementing forest management practices that increase carbon sequestration in this region could add significantly to carbon storage.

While large corporate ownerships characterize the northern part of the region, there are also large ownerships further south as well. Many of these ownerships manage high-value pine and hardwood species, often employing much different types and levels of forest management. Tolerant hardwood species, such as sugar maple and yellow birch, are often managed using selection systems with frequent harvest entries, but always maintaining a productive residual stand. Pine and moderately-tolerant hardwoods, such as oak and hickory, are frequently managed using shelterwood systems. Since both of these silvicultural systems maintain intact growing stock at all times, the carbon storage capacity of the site (minus timber removals) remains relatively high.

Sixty-five percent of the Northeast forest land is owned in tracts of 100 acres or less. It is much more difficult to generalize about the type and intensity of forest management practiced on these lands. However, it is clear that timber production is not the major reason that forest land is held by this group (see Sec. I). It would safe to speculate that forest management on these small private ownerships as a whole is low.

Even with the most aggressive forest management efforts to increase carbon storage in forest ecosystems, growing stock levels would eventually reach a peak. The forest has a finite capacity to store carbon within the limits of soil and climatic factors. The challenge then lies in

applying the best management practices, efficiently harvesting and processing and recycling wood products, displacing fossil fuel with biofuels when feasible, and substituting wood products for more energy-demanding products, and shifting harvested volume from pulp into longer-lasting solid wood products.

H. IMPLICATIONS OF FOREST MANAGEMENT FOR CARBON STORAGE

Forest management activities encompass a wide variety of cultural practices associated with growing and tending stands of forest trees. These practices may include establishment of stands on harvested or cleared land through plantation establishment or natural regeneration, commercial or precommercial thinning, and timber harvests that range from selection to clearcut harvests. Also included are supplemental measures, such as herbicide and pesticide treatment, fertilization, and site preparation, that may protect or enhance growth of forest stands. Unharvested forest reserves also require a certain level of management. The practices applied depend upon the objectives of the forest landowner.

The practices involved in forest management are essentially those of managing forest carbon; therefore, they directly affect carbon sequestration. A superficial examination might lead to a conclusion that removing major stores of carbon through timber harvesting and converting it to a variety of products would lead to an overall loss in carbon storage. However, the impacts of such activities depend upon the manner in which trees are harvested, the future use to which these products and the land is put, and period of time over which the activities are viewed. Well-designed timber harvests that minimize erosion and site disturbance can lead to increased levels of carbon fixation over time through enhanced growth rates in forest stands. In addition, products that have long life-spans, e.g., dimensional lumber, furniture stock, and wood panels, or displaced fossil fuel consumption may actually augment carbon sequestration. Finally, the potential benefits of forest management to carbon sequestration may only become apparent when considered over the life-span of trees and forest stands.

Although the greatest amount of carbon is stored in old, mature, fully-stocked stands, the actual net carbon assimilation rate in these stands may be near zero. In contrast, young, rapidly growing forest stands exhibit the highest rates of net carbon assimilation but have small carbon pools. Therefore, maintaining high annual rates of carbon storage in managed forest stands will require removal of trees that have become inefficient in carbon assimilation (Hair, et al., 1996). In general, highest levels of carbon uptake occur in fast-growing, well-stocked stands of mixed species with large trees and multiple canopy layers. However, promising opportunities for carbon sequestration also exist for intensive short-rotation plantations used to produce fossil fuel-replacing biofuels.

Considering that only 2% of the region's forest is treated each year, and that the forest is already gaining volume and carbon storage, it would take a long time for forest management practices to make a large difference in the region's forest carbon pool. This does not mean the opportunities need not be pursued, only that it will take time to make a difference. In time, the impacts of forest treatments will reach a maximum, and will need to be maintained. This is why analysts speak of forest management as a "buying time" strategy. Useful essays for historic context include Houghton (1998), and ch. 4 of the same volume.

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IV. PLANTATIONS FOR CARBON STORAGE

Plantations may play a variety of roles in carbon storage planning (Box). The opportunities vary widely within the northeast. In this assessment, we will give no further consideration to urban situations or to restoration. Some work has been done on the urban opportunities (Sampson, Moll, and Kielbaso, 1992; Ning and Abdollabi, 1997). Shelterbelts have also been examined, though the primary opportunities lie in other regions (Brandle, Wardle, and Bratton, 1992). Considering the potential area involved and potential for carbon storage impacts, we will confine ourselves to traditional forest plantings and to biomass energy plantations. Useful recent reviews are Sedjo and Botkin (1997); Sedjo, et al. (1994); a global overview is provided by Nilsson and

Potential Roles for Forest/Tree Plantings

Additional Tree Plantings/Tree Retention in Urban Areas

Restoration: e.g. Coalmine Reclamation

Dedicated Energy Feedstock Systems (SRIC)

Traditional Forest Plantations for timber

Shelterbelts and Agroforestry

Wastewater/Ash Disposal

Converting marginal cropland to forest

Replacement of degraded or overstocked stands

Chapter Outline

A. Background

B. Conventional Forest Plantations

C. Potential for Biomass Plantations

D. Some Win-Win Opportunities

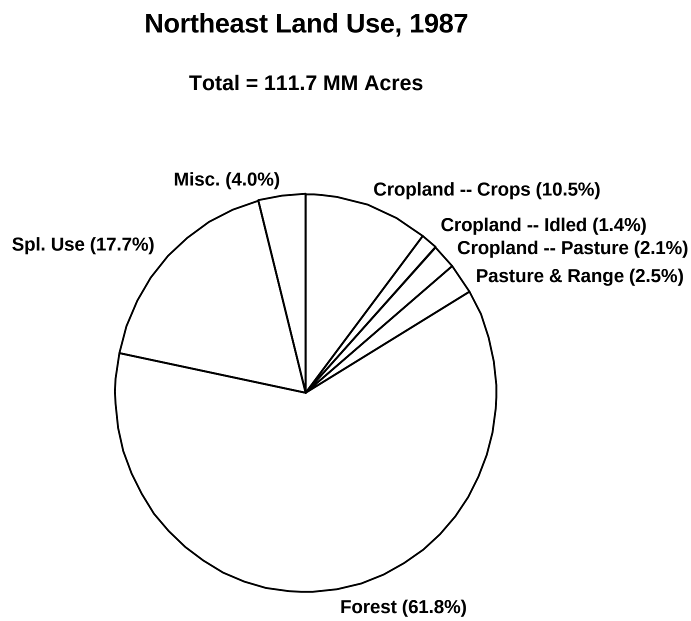
E. References

Schopffhauser (1995); Parks, et al. (1997) concentrate on methodological issues. Assessments of C storage potential from plantations suggest that on a national basis the potential is very large. Yet, many local factors need to be considered in evaluating the opportunities at a state level.

A. BACKGROUND

In the Northeast, forest already dominates the landscape; cropland area is less than urban and developed land (Fig. 4.1).

Figure 4.1



Source: USDA.

Currently, the annual amount of tree planting in the region is modest (Table 4.1). There are a variety of reasons for this, including the low near-term returns from planting, the continuing increases in timber inventories in most states, and the low funding level of USDA programs that have traditionally assisted tree planting. Abundant natural regeneration and the limited development of genetically improved stock help account for this. The level of planting

on industry land in the region, in fact, is so low that nursery capacity has been significantly cut back in recent years.

Table 4.1
Tree Planting, Including Seeding and Timber Stand Improvement (October 1, 1995 to September 30, 1996)

	TOTAL ACREAGE	
	Tree Planting	Timber Stand Improvement
Maine	8,000	5,545
New Hampshire	142	1,060
Vermont	84	1,982
No. New England	8,226	8,587
Connecticut	169	436
Massachusetts	401	790
Rhode Island	35	23
So. New England	605	1,249
Delaware	1,282	1,198
Maryland	7,314	9,137
W. Virginia	5,166	6,057
Border States	13,762	16,392
New Jersey	751	2,613
New York	739	4,327
Pennsylvania	13,554	1,021
Mid-Atlantic	15,044	7,961
Region	37,637	34,189
Total U.S.	2,406,700	2,633,075
Region as % of Total U.S.	1.56%	1.30%

Source: Moulton and Snellgrove, 1997. Tree planting in the U.S., 1996. pp. 14, 15.

* MFS Silvicultural Activities Report, 1996. The Moulton and Snellgrove report is in error for Maine for this year.

B. CONVENTIONAL FOREST PLANTATIONS

An early assessment of potential for forest plantations was done by Parks, Hardie, and co-workers. They considered both softwoods and hardwoods and presented state by state detail for much of their data (Parks, Brame, and Mitchell, 1992). They did not consider specialized short rotation energy plantations. They viewed the forestry opportunities as occurring on marginal crop and pasture land. In their assessment, they found 14 million acres of marginal land in the region of interest for this study (PB&M, p. 106). This assumes that essentially all of the region's farmland (16 million A.) is marginal and available for other uses, which may not be true. Not surprisingly, Pennsylvania and New York showed the largest amounts of land. The amounts were about evenly divided between current pasture and cropland (Table 4.2).

Table 4.2
Area of Marginal Crop and Pasture Land in Private Ownership Physiographically Suited for Conversion to Softwood and Hardwood Forests in the Contiguous U.S., by Region and State, 1987

	Total	Cropland	Pasture Land
Maine	632.9	360.7	272.2
New Hampshire	182.5	87.3	95.2
Vermont	662.2	379.5	282.7
No. New England	1,477.6	827.5	650.1
Connecticut	128.8	76.8	52.0
Massachusetts	170.3	99.0	71.3
Rhode Island	19.4	2.1	17.3
So. New England	318.5	177.9	140.6
Delaware	96.7	88.9	7.8
Maryland	863.2	592.8	270.4
West Virginia	2,091.6	521.6	1,570.0
Border States	3,051.5	1,203.3	1,848.2
New Jersey	210.4	121.6	88.8
New York	4,505.5	2,182.8	2,322.7
Pennsylvania	4,508.4	2,919.1	1,589.3
Mid-Atlantic	9,224.3	5,223.5	4,000.8
Total Northeast	14,071.9	7,432.2	6,639.7

Source: Parks, Brame, and Mitchell, 1992, p. 106.

Calculations were given showing expected costs of establishing forest on these areas and the resulting incremental growth produced. Conversions to carbon were not shown. Parks, et al. (1992) considered in a general way how to use the existing Conservation Reserve Program structure as a means of implementing a tree planting program. Current CRP planting in the region is nominal (Table 4.3). Several authors have considered the effects on agriculture of converting farmlands to forest uses (e.g., EPA, 1995, p. 26 ff; Callaway and McCarl, 1994). These reports examined various implementation scenarios, and calculated various measures of economic welfare impacts. They do not present state by state or regional data. Plantinga (n.d.)

has studied costs of plantings and landowner responsiveness to CRP programs using econometric methods applied to a portion of Wisconsin. None of the sources present cost estimates for northeastern conditions.

Table 4.3
Conservation Reserve Acres and Tree Planting Through June 1992 (12 signups)

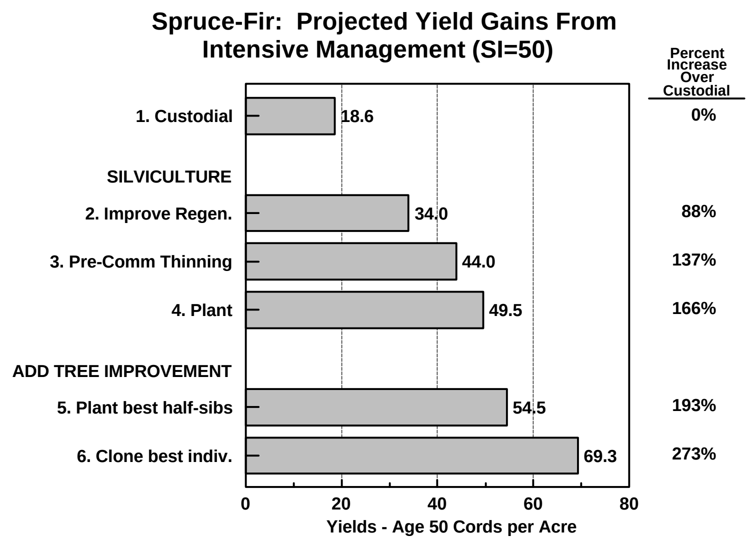
	Total CRP	Acres With Trees
	(thousand acres)	
Maine	38.5	2.5
New Hampshire	0.0	0.0
Vermont	0.2	0.0
Massachusetts	-	-
Rhode Island	0.0	0.0
Connecticut	-	-
New York	64.5	3.6
New Jersey	0.7	-
Pennsylvania	101.1	2.2
TOTAL	205.0	8.4 *

*... out of 2.5 mm acres with trees nationally.
Source: USDA, ERS, 1996

Conventional forest planting programs can rely on existing planting and harvesting capabilities. Also, they are adaptable to lower value and more rugged lands where biomass plantings are not. Further, they rely on existing wood markets which are likely to strengthen in the future. As a result, a new social infrastructure to support harvest and delivery to energy customers is not needed. Conventional plantings will yield multiple products over a long span of time, so analyzing their carbon storage effects is very complex. Foresters and forest scientists believe that the yield potential for such plantations is far higher than is being achieved in current practice (e.g., Greenwood, Seymour, and Blumenstock, 1988). Intensively managed timber

plantations can play a role in carbon storage, and existing and planned management activities should be assessed for their impacts.

Figure 4.2



Source: Greenwood, Seymour, and Blumenstock, Maine Agr. Exp. Sta. Misc. Rept. 328, 1988, p.4.

C. POTENTIAL FOR BIOMASS PLANTATIONS

Biomass energy researchers have done considerable feasibility study and pilot testing on so-called “Dedicated Feedstock Supply Systems” (DFSS). These systems involve planting of selected clones or genetic lines of trees in plantations designed for maximum yields on short rotations. Rotations as short as 6-10 years are possible. Such plantations have often been termed “Short Rotation Intensive Culture” (SRIC) plantings as well. A considerable line of research argues that achieving carbon storage by such means is cost-effective by comparison with other measures that have been suggested for carbon mitigation (see, e.g., VanKooten, Arthur, and Wilson, 1992).

Research has shown that there is potential for contributing to carbon storage in tree plantations grown to produce biomass energy. The energy thus produced can then replace fossil fuels, producing an additional gain for the carbon cycle. It is thought likely that such plantations,

under some conditions, will store still more carbon in soils as forest floors develop under the canopies. It turns out, though, that for the best yield performance, it is necessary to use productive land that is easily cultivated by mechanized planting and harvesting systems. Intensively managed plantations in the North can yield 5 tons (dry) of wood/A/yr., with highest experimental yields exceeding 10 tons/A/yr. Since a ton of dry wood is about 50% carbon, the growth would be 2.5 tons/A/yr. of carbon.

The System

These plantations are to be planted on a fairly large scale to achieve scale economies in planting and harvesting. The trees are often established by cuttings rather than seedlings, and the concept is to regenerate them by resprouting from the rootstocks (“coppicing”) after they are clearcut. The trees are then whole-tree chipped for shipment to energy plants. Ability to reproduce from root sprouts and to achieve high growth rates is the reason why hardwoods have been emphasized in these programs. According to Wright (1994), the species considered most promising for the northeast include black locust, hybrid poplars, silver maple, and willows. A Salix Consortium is actively planting and developing this system in New York (Neuhauser, et al., 1997).

Experience with such systems in Sweden, based on willows, has shown that significant reductions in delivered costs of chips can be achieved by achieving scale economics and by designing the system as a whole for efficiency. The intensive cultivation required means higher energy consumption for growing these stands.

Several assessments have been done of the likely environmental impacts of such plantations if applied on large scale. The results suggest that, while many questions are unanswered, the impacts overall are probably no more significant than if the same lands were in traditional row crops (Ranney and Mann, 1994; U.S. Congress, OTA, 1993).

The difference in annual yields between the South and the North is not very large, except for extreme northern Maine and New York. This is because the longer growing season in the

South is offset by low soil fertility and by summertime periods of drought. The Northeast is not expected to be a leading region if plantations of biomass crops become important. There are several reasons. First, the region does not have large amounts of unused and suitable, productive farmland. Second, abundant quantities of topwood and slash are available from logging jobs and land clearing. Third, the region's wood processing industries and urban sources provide large supplies of low-cost wood fiber sources. It will be very difficult to compete with such sources by growing wood in plantations. Also, estimated costs per ton in the northeast are high. Still, in long-term planning for the role of forests in carbon storage, it would be useful for states to consider what role such plantations may play.

There should be potential for reducing the costs of the energy component of the harvest by managing the plantations in a way that retains some stems to grow to larger sizes for sawlog uses. If this can be done, there could be additional environmental benefits. This would resemble a traditional European silvicultural system known as “coppice with standards” in which intensively managed stands, often of natural origins, are managed for multiple products.

At the present moment, demand for wood fiber for energy is declining in the Northeast, not increasing. While there are local exceptions to this generalization, the current process of utility restructuring creates major uncertainties. These affect existing plants as well as potential new investments. Until a clearer future is seen for existing plants, there is little likelihood of new investment in electricity generation capacity using wood. Assessment of this option, then, would be for long-term assessment of opportunities and contingency planning. As uncertainties become clearer in local areas, it will be possible to move forward.

Land Availability

Graham (1994) has screened the database on cropland quality and use maintained by the Natural Resources Conservation Service (NRCS). The database is based on the agency's Natural Resources Inventory, which uses about 800,000 sampled field points nationwide. It is used for assessments of the condition of U.S. farmland resources, conducted every five years. Using a

number of screening criteria, Graham sifted out the number of acres likely to be suited to and potentially available for biomass plantations. Identifying 10 million hectares or 27 million acres in the northeast (at fig. 3, p. 184). The Northeastern region, however, was defined in that study to include Ohio, which is not included in our assessment. A separate table, perhaps using different regional boundaries, he shows 7.3 million hectares or somewhat less than 20 million acres. *This is essentially the entire area of cropland and pasture in the region, so it is not a very useful figure for planners*. For lands meeting the minimum productivity level, the average yield found for the Northeast for biomass plantations was 13.2 Mg./ha/yr. (p. 185).

ORNL has developed a county-by-county database (ORECCL) showing potentially available cropland that could be converted to energy plantations. This database should be useful to planners conducting state by state feasibility analyses. Additional information is available in USDA Agricultural Resources and Environmental Indicators, published annually and available on the Web. The database can be used to initially screen farmland and pasture totals. Examples are shown in Table 4.4 and Figs. 4.3, 4.4, and 4.5.

Table 4.4
State Summary: Oak Ridge Energy Crop County Level Database, December 20, 1996

State	Crop92 (acres)	CRP (acres)	Suited for SRWC_gd Cropland (acres)	Suited for SRWC_gdp Pasture (acres)	ERS Cropland Rental Rate $/A/yr
Connecticut	192,756	10	145,017	51,628	$50.60
Delaware	495,156	996	446,024	15,140	$57.90
Maine	559,424	38,490	469,741	102,594	$43.80
Maryland	1,663,907	20,392	1,453,526	262,423	$55.40
Massachusetts	232,677	32	164,393	69,677	$36.80
New Hampshire	135,437	0	101,867	36,165	$41.25
New Jersey	623,466	723	477,295	99,283	$50.60
New York	4,875,517	64,499	3,916,278	1,262,699	$34.90
Pennsylvania	5,019,867	101,085	4,180,191	1,143,632	$44.10
Rhode Island	24,411	0	18,727	5,418	$50.60
Vermont	658,765	193	493,465	243,592	$38.70
Regional Totals	14,481,383	226,420	11,866,524	3,292,251	n/a

Source: ORNL, ORECCLL Database.
CRP = Conservation Reserve Program.
SRWC = Short rotation woody crops.

Figure 4.3

Counties With Less Than 1000 Acres of CRP Land

(CRP = Conservation Reserve Program)

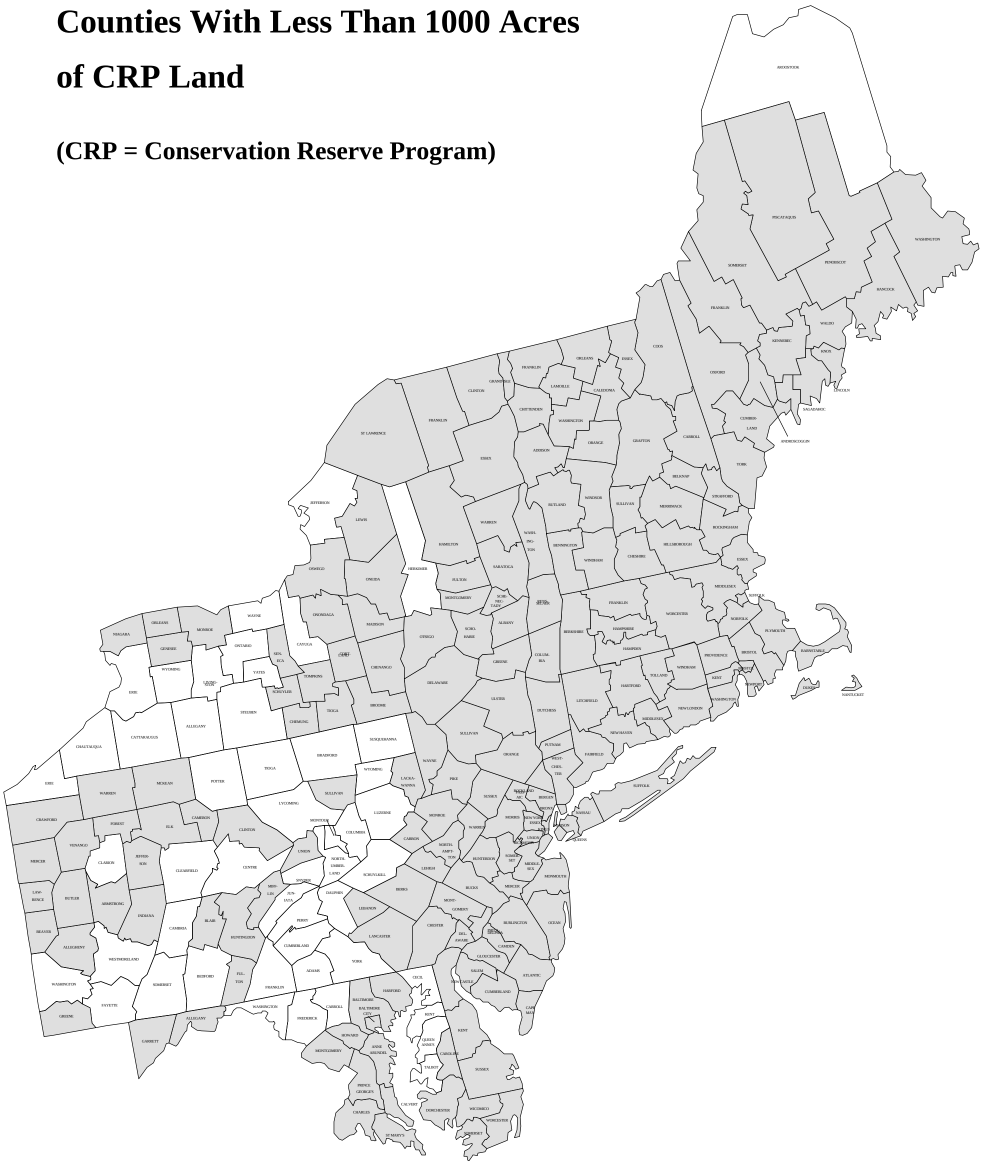


Figure 4.4

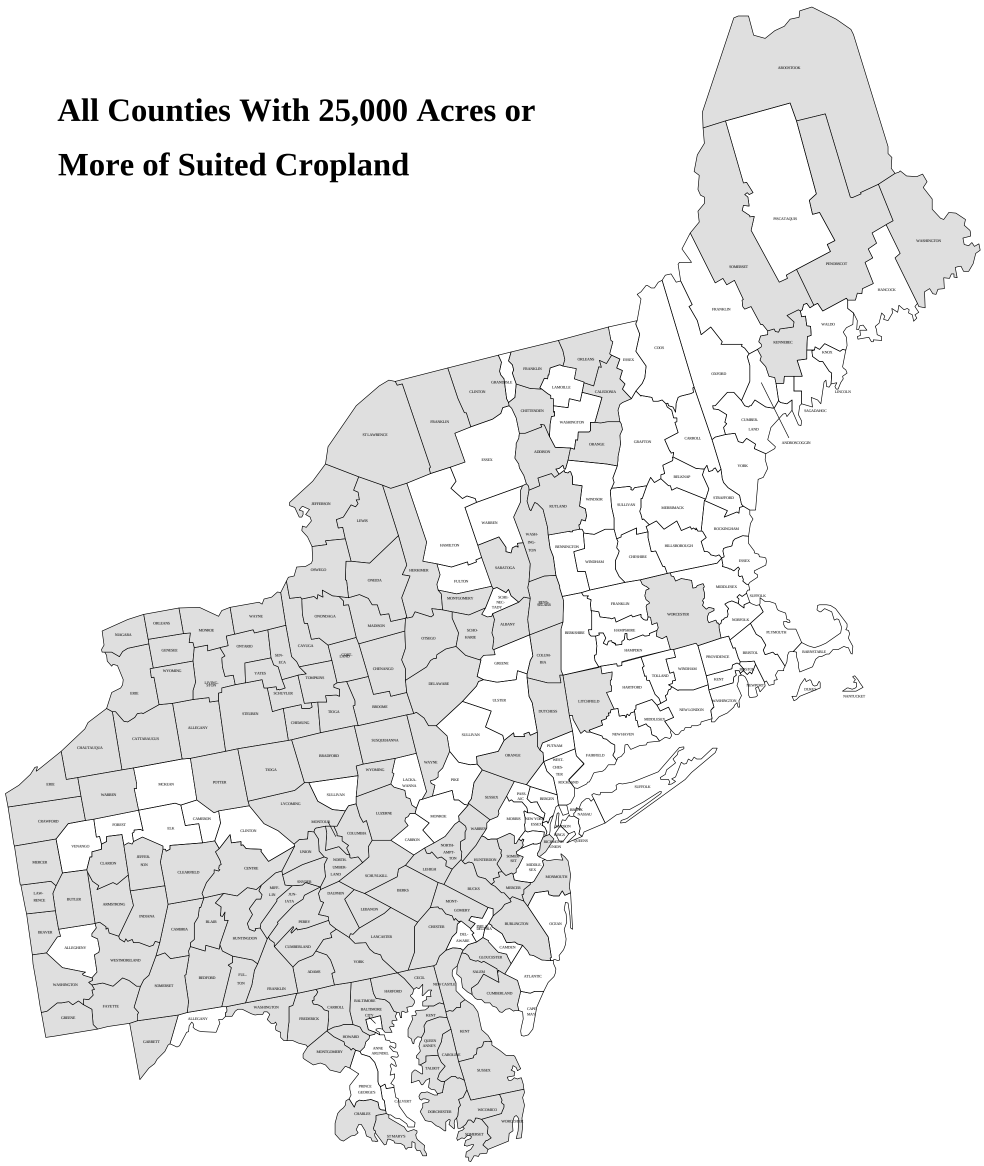
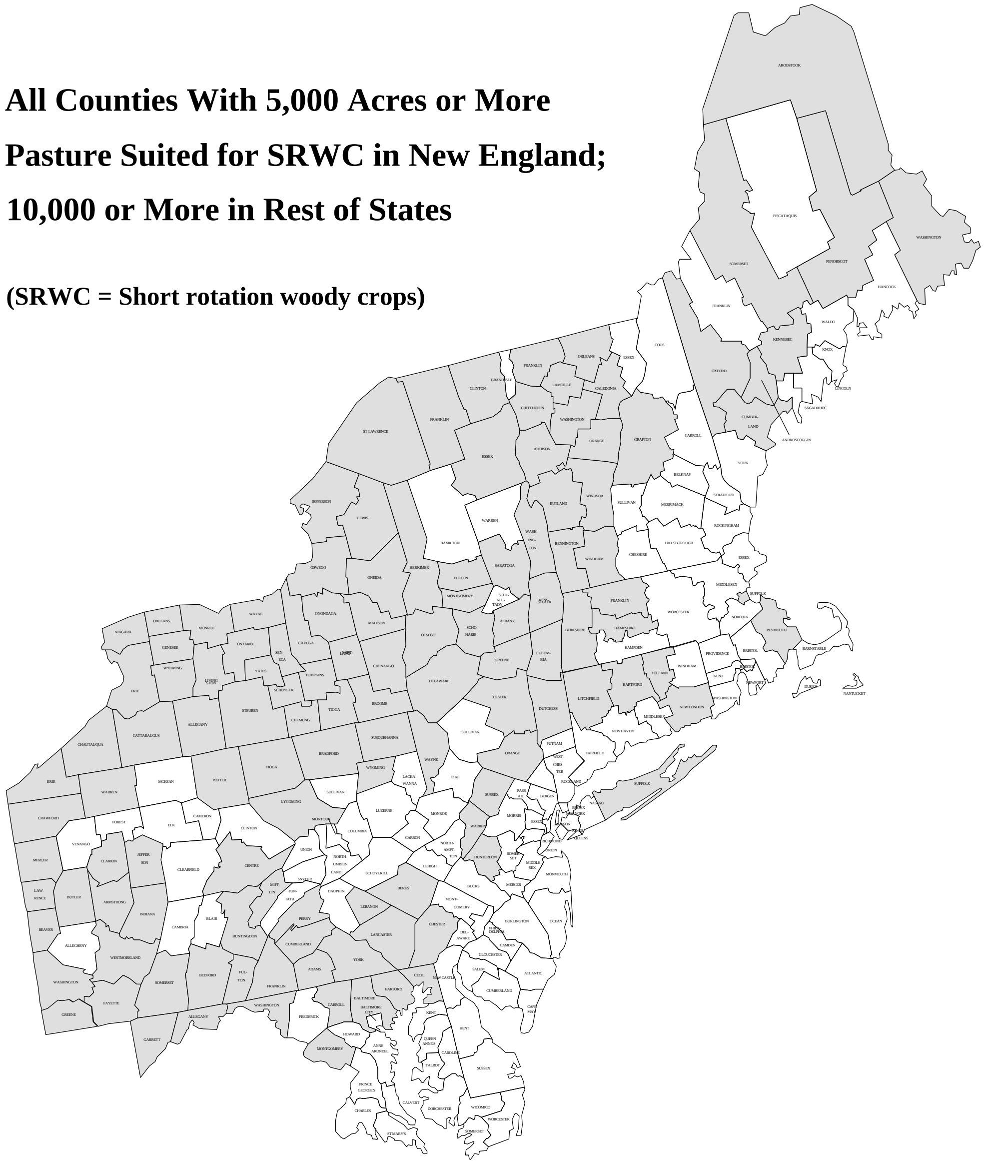


Figure 4.5


All Counties With 5,000 Acres or More
Pasture Suited for SRWC in New England;
10,000 or More in Rest of States
(SRWC = Short rotation woody crops)

Screening for Feasibility

The analysis reported above rely on national datasets that are several years old. Further, they represent estimates of what may be technically feasible and have not employed site-specific market and economic information. They were intended as first-cut national assessments. The competitive position of northeastern row crop agriculture suggests that additional acres could become available for other uses in the future, in farming regions where suburbanization is not the likely alternative land use.

Further, the potential acreages were not screened for size, location, environmental and social factors, changes in ownership and land use patterns, or other factors that would limit land use for plantations. The cumulative effect of these limitations is likely to be very large, and would significantly reduce estimated acreages available for tree planting.

Challenge: Gaining Long-Term Commitments

An area which needs additional development is the “social infrastructure” for operating and managing the plantations and the resulting flows of products. For land to be committed to such plantations, it will be necessary to solve a host of problems, including:

-- rental arrangements, if any, for the land;

-- availability of specialized equipment for planting and harvesting;

-- contractual arrangements for purchasing the biomass fuel and determining fair prices for it; and

-- methods of ensuring that the plantations remain in place for long periods in order to serve their carbon storage purposes.

Costs of Plantations

The costs of a C-sequestration plantation program will depend on many variables:

-- quality and cost of land used;

-- biomass of conventional approach;

-- local markets for wood;

-- whether least-cost schedules and practices can be implemented in practice or not. Cost analysis for proposed programs will have to make assumptions on these matters and develop locally specific data. Initial work on these points has been carried out at SUNY-CESF under the Willow program; in other states, experts in planting would have to be consulted.

Multiple-Product Nature of Plantations

Placing the total cost of plantation wood on the energy yield may be inappropriate. Considering other potential benefits of such plantations, and sources of revenue to pay for those benefits would need to be identified. The future of the CRP program would be a consideration.

D. SOME WIN-WIN OPPORTUNITIES

There may be some potent win-win games to be developed in the Northeast. We have relatively high energy costs, a farm economy that is struggling financially in many rural areas, and a heavy dependence on fossil fuels. In many areas, an infrastructure for forest products harvesting and hauling is in place. Skills and plants needed for converting woodfiber to electricity are in place and functioning in some local areas, or readily available.

By bringing together farm programs for cropland retirement, existing incentive programs for tree planting, and interested biomass fuel users, it should be possible to craft planting strategies for producing multiple products on farmland that would generate multiple social benefits including carbon storage and fossil fuel displacement. An excellent base of experience is being developed to support such an approach, but extensive further research and field testing will be required to validate site-specific approaches and “social infrastructure” to make such systems work. Restoration planting such as local mine revegetation may offer further win-win situations. An excellent example is the commitment of the 3 Chesapeake Basin States to establish 2,100 miles of new forest streamside buffers to protect water quality. Theses will yield many important benefits in addition to carbon storage.

The next chapter reviews models for analyzing forest carbon stocks at national and regional levels.

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V. FOREST CARBON MODELING CONSIDERATIONS

A. INTRODUCTION

The potential adverse impacts of elevated levels of carbon dioxide in the atmosphere and associated global climate change have generated interest in strategies to store additional carbon in forests and other terrestrial carbon sinks. These strategies involve complex interrelationships among numerous carbon pools within these natural systems and the products harvested from them. Modeling can be an effective tool in analyzing the influence of various resource management and land-use strategies on net carbon storage and fluxes.

Three examples of models that have been applied to forest carbon are FORCARB, the Forest and Agriculture Sector Optimization Model (FASOM), and the Graz/Oak Ridge Carbon Accounting Model (GORCAM). Each of these models may provide important information to researchers and policymakers involved with the formulation of strategies designed to mitigate rising levels of carbon emissions to the atmosphere. They enable the empirical evaluation of various strategies or policies for their respective influence on forest carbon storage in different forest situations. In this way, policies can be tested to determine their effectiveness in modifying carbon sequestration in forests.

The FORCARB and FASOM models project future changes in forest carbon nationally and regionally for different management and utilization scenarios based upon extensive forest sampling and estimates for carbon storage in forest systems. The GORCAM model evaluates the influence of different management and land-use practices on forest carbon storage and biomass

Chapter Outline

A. Introduction

B. Problems of Carbon Modeling

C. Description of the FORCARD Model

D. FASOM: The Forest and Agricultural Sector Optimization Model

E. GORCAM: The Graz/Oak Ridge Carbon Accounting Model

F. Comparison of the Models

G. Predicted Opportunities for Enhancing Forest Carbon Sequestration

H. Opportunities for Improvement of Forest Carbon Models

I. References

utilization at the forest stand level.

The following will offer a description of each model, the various parameters and assumptions incorporated, the modeling results, and their strengths and limitations.

B. PROBLEMS OF CARBON MODELING

Forests are dynamic systems comprised of inter-related processes. One of the major controlling factors is the cycling of carbon in forest ecosystems. Tracking the flow of carbon into and out of these systems requires simultaneous consideration of numerous sources and sinks that are constantly exchanging carbon over time. Without a model to describe these changes, the task of making predictions about carbon storage and fluxes in forest ecosystems becomes an extremely arduous and uncertain task.

Complicating the task of tracking carbon under the biophysical activities of the forest ecosystem, is the harvest and use of biomass products. The hydrocarbon-based fuels used to harvest and process materials, the lifetime of harvested materials, the fossil fuels displaced when wood is substituted for other materials used in everyday life, and the displaced fossil fuel when bioenergy is used all affect the global carbon budget. It is also important to consider market forces that influence land-use decisions that can either increase of decrease the total area of forest land. Further, the type of management that is applied will influence its carbon storage and flux activities.

Forests are slow growing systems in human terms, and the impacts of policy decisions on them take many decades to be realized. Therefore, a reliable method for forecasting anticipated results is needed before policies are implemented. The three models discussed in this chapter are examples of methods that can help sort-out the ramifications of policies. All contain assumptions and estimates that involve a certain amount of uncertainty, but models will be essential tools for policymakers and planners charged with developing mitigation plans for optimizing carbon sequestration in forest ecosystems.

C. DESCRIPTION OF THE FORCARB MODEL

Background

Interest in offsetting carbon dioxide emissions to the atmosphere through forestry activities on U.S. timberlands prompted the development of the FORCARB model. A method was needed to analyze the influence of increased tree planting, increased recycling, changes in harvesting, and combinations of options on carbon sequestration, all within the context of the economic, demographic, and political assumptions that underpin the management and use of the nation's forests. In response to this need, the U.S. Forest Service developed FORCARB, a carbon accounting model that is linked with a socioeconomic model of the forest sector for national assessments of forest resources.

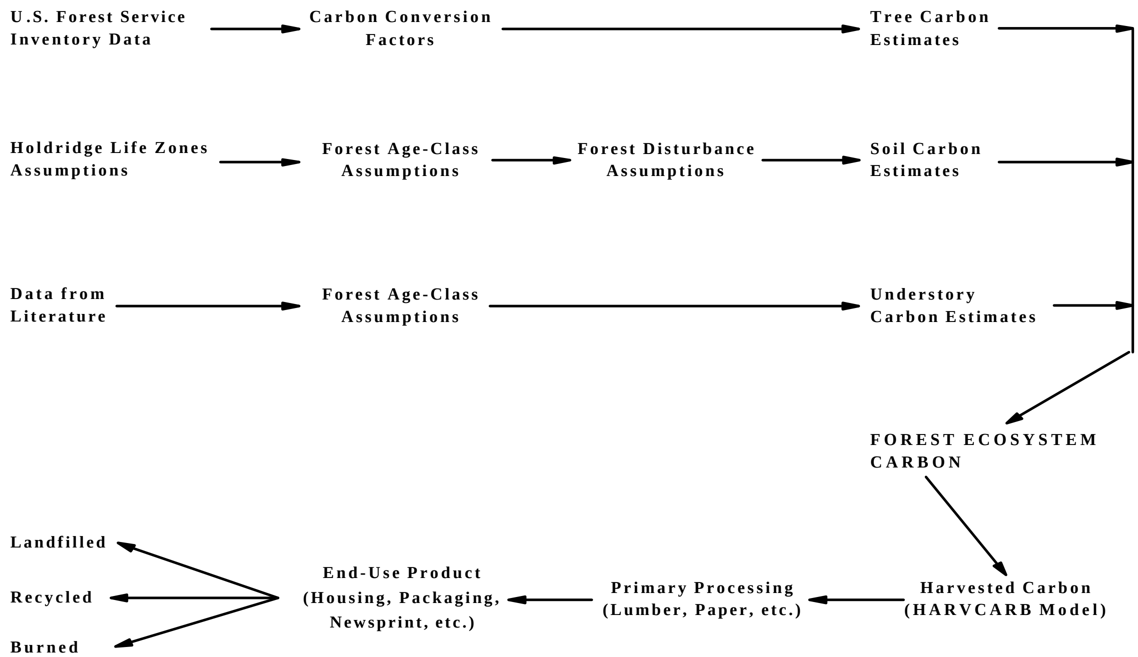
The FORCARB model relies heavily upon the data collected from the periodic assessments of the nation's forests conducted by the USDA Forest Service under the Federal Resources Planning Act (RPA) and the Forest Sector Model, which is used to analyze that information. The Forest Sector Model uses the assessment data to project changes in forest resources under the basic assumption of market equilibrium (demand equals supply) for wood products. The Forest Sector Model incorporates the Timber Assessment Market Model (TAMM) (Adams and Haynes, 1980; Haynes and Adams, 1985) to project U.S. demand for wood products, including the demand for stumpage from private timberlands. The information from TAMM is used with the Aggregate Timberland Assessment System (ATLAS) (Mills and Kincaid, 1991) to determine changes in the U.S. private timberland inventory. ATLAS uses assumptions about silvicultural treatments and harvesting methods to project inventory changes. Timber growth estimates are from U.S. Forest Service permanent plot inventories, and land-use trends are projected with regional models (Alig, 1985).

FORCARB Model Parameters

FORCARB is designed to include all carbon storage pools in the forest ecosystem, as well as the fate of carbon in materials extracted and processed into wood and paper products

(Table 5.1). The following describes each pool and discusses the manner in which each is estimated.

Table 5.1
Overview of Major Parameters of the FORCARB Model for Forest Ecosystem Carbon and Fate of Harvested Carbon



<u>*Estimates of Forest Carbon Storage*</u>

Tree carbon storage *i*s derived from estimates of growing stock volume in two stages. First, the growing stock volume is converted to total tree volume by multiplying the value by a ratio that accounts for the additional volume not represented in growing stock volume, i.e., tops, branches, foliage, rough and rotten trees, small trees (<5.0 inches DBH), standing dead trees, stump sections, roots, and bark. The ratios are derived from a nationwide biomass study prepared by the U.S. Forest Service containing estimates of above-ground biomass by tree

component (Cost, et al., 1990), and a report by Koch (1989) containing estimates of the proportion of below-ground tree volume. Separate ratios were developed for hardwoods and softwoods, as well as for different regions of the U.S. to account for differences in tree form and to be consistent with data used to develop merchantable yield tables.

The second stage is the conversion of the calculated total tree volume (cu ft) to total carbon content (lbs). Separate conversion factors were developed for major forest types, for softwoods and hardwoods within each forest type, and for broad geographic regions. The volume-to-carbon conversion factor was calculated in two steps. First, the volume was converted to total biomass dry weight using the specific gravity of the three predominant softwood or hardwood species in each forest type. The second step was to multiply the total biomass dry weight by a factor to account for the average carbon content of the tree. Past estimates of carbon content in trees range from 45 to 52% (Houghton, et al., 1985; Koch, 1989).

Carbon storage tables were developed using a modification of the model of Moore, et al. (1981). Carbon storage tables are identical in concept to traditional timber volume tables. Carbon storage tables include accumulation of all live and dead organic matter above or belowground in the forest ecosystem. Tables were developed for 5-year age-classes through 80 years in the South and for 10-year age-classes through 155 years elsewhere.

Expected volume yields are available from a large database of sample plot data collected across the U.S. during U.S. Forest Service Inventory and Analysis inventories over the past 15 years. Estimated yields (from growing stock) were used for nonindustrial private timberland planted with regular planting stock or regenerated naturally, except for the South and Pacific Northwest where genetically improved stock is available. Expected future thinning was not included in the yields. These expected merchantable volume yields represent the most likely yields for the average timber stand within each selected classification. A set of 92 carbon yield tables were generated for reforestation and a supplemental 50 tables were developed for afforestation. Afforestation tables used a higher timber volume production equal to the estimates

reported in Moulton and Richards (1990) and were for pure stands rather than partial mixtures of species.

Growing stock inventories by age and area were obtained from the ATLAS model and grouped into 248 management units defined by region, owner, species, and site quality. The growing stock inventories were then converted to reflect tree, soil, forest floor, and understory carbon. The model only simulated changes in carbon stored in merchantable portions of trees. The soil, forest floor, and understory carbon were derived from the growing stock inventories using separate equations.

Total tree carbon was estimated from growing stock volume using conversion factors to account for additional volume in non-merchantable portions of the tree (Birdsey, 1992). Changes in tree carbon inventory result from tree growth and timber removals. In the general model, tree carbon increases rapidly in early years, but as the tree productivity declines, the rate of increase also declines. Declines in the tree carbon inventory were estimated from growing stock removals. Following a harvest, the non-merchantable portion of the tree was assumed to be converted to emissions instantaneously. The harvested wood is handled separately.

Soil carbon storage accounts for more than half of the carbon present in U.S. forests; however, the literature shows wide variation (Houghton, et al., 1985). For the most part, published estimates for soil carbon are from non-statistical samples and compilation of results of many different studies of specific ecosystems. Multiple regression work by Burke, et al. (1989) on cropland and pasture in Central Plains grassland and adjacent areas showed that mean annual temperature, mean annual precipitation, and soil texture were the best predictors of soil carbon.

Data from Post, et al. (1982) were used in a similar model to estimate regression coefficients for forest lands in FORCARB. Post, et al. (1982) was able to estimate mean soil carbon density for all of the life zone groups of the Holdridge life zone system (Holdridge, 1967) using data from published reports. Regression coefficients for forest land were obtained by relating mean soil densities to average precipitation and mean annual temperature for each life zone group. Temperature and precipitation averages for each state were estimated from

published weather records (Ruffner and Bair, 1987). State level estimates were then aggregated to the regional level by weighting the individual state estimates by the area of timberlands. The resulting estimates are for soil carbon in relatively undisturbed, secondary forests.

Estimates for soil carbon in forests with different age-classes required certain assumptions about when the forest reached the level of development represented in the data by Post, et al. (1982). It was assumed that these levels would be reached at age 50 years in the South and 55 years elsewhere. The average per-acre estimate of soil carbon for a state or region was adjusted to reflect the actual age structure of the forest present by determining the average age distribution by age-class. This value was then converted to percent and a weighting factor was computed by comparing the age distribution with a model of soil carbon changes over time. On average, eastern forests are younger than the reference age of 50-55, and western forests older. The weighting factor was multiplied by the initial estimate for a state or region to obtain a final estimate.

Since the resulting estimates are for soil carbon in relatively undisturbed, secondary forests, it was necessary to make assumptions about when this level of forest development would be reached after harvest or abandonment of agriculture land to develop soil carbon yields. According to Houghton, et al. (1983, 1985), soil carbon will reach "natural" levels on reforested cropland or pasture after about 50 years. On cutover forest land, about 20% of the soil carbon will be lost to oxidation after 10-20 years, with natural levels reached at about age 50 years. In the FORCARB model, 20% of the soil carbon is assumed lost by age 10 years in the South and by age 15 years elsewhere. Natural levels would be reattained at age 50 years in the South and 55 years elsewhere. For replanted pasture, soil carbon at age 0 was the level estimated by Burke (1989), and natural levels were attained at age 50 in the South and 55 elsewhere. Using figures from Burke, replanted cropland attained natural levels at age 60 in the South and 65 elsewhere. The rate of accumulation of soil carbon was assumed to taper off after natural levels were attained as the forest matured.

Carbon storage estimates for the forest floor, including coarse woody debris, are available for a very broad array of forest classifications and for very specific ecosystems (Schlesinger, 1977; Vogt, et al., 1986). FORCARB uses estimates from these sources for forest floor carbon in key age-classes of the forest, and to derive estimates for other age-classes. Estimates by Vogt, et al. (1986) for broad ecosystems were used for regional carbon yields by applying them to the broad forest types common in each region in the U.S.

A weight factor was calculated to account for general composition and relative age structure of state and regional forests in a similar fashion as for soil. Area estimates were developed for hardwood, softwood, reserved, and other forest land in each state. Estimates from Vogt, et al. (1986) were applied to timberlands, and other sources for other forest land. A weighted average for all forest land was then computed for each state and multiplied by a factor to account for the actual age distribution of forests within the state. The factor was derived in the same manner as for soil carbon.

When cropland or pasture was reforested, no carbon was assumed to be present on the forest floor at age 0, and the reference level of carbon was reached at age 50 in the South and 55 elsewhere. Because of the extensive use of site preparation in the South, no forest floor carbon is assumed at age 0 on regenerated stands. Elsewhere it was assumed that forest floor carbon was equal to 33% of the reference estimate after harvest. After reaching the reference level at age 50 or 55, organic matter on the forest floor accumulated at a decreasing rate.

Understory carbon storage comprises such a small percentage of the total carbon in the forest ecosystem that it is often ignored or combined with estimates of all live vegetation. Estimates are generally from ecological studies of specific forest ecosystem (Messina, et al., 1983; Ohmann, 1984; Switzer and Nelson, 1972; Turner and Long, 1975).

Model estimates assume no understory carbon at age 0 and a peak in understory biomass at age 5 years for all regions and forest types. Understory carbon storage was assumed to decline to a reference level by age 50 years in the South and 55 years elsewhere. Reference levels were defined as 2% of the carbon in the overstory, except for Douglas-fir and red pine, which were

1%. The distribution of estimates by age-class was compared with actual age-class distributions of forest land by forest type to obtain a weighted average value for carbon in the understory in each state.

Harvesting of growing stock and disposition was followed using the HARVCARB model (Row and Phelps, 1991) (HARVCARB will be discussed in more detail in later chapter). HARVCARB was used to trace removals through three transformation phases. In the first, logs are processed into primary products such as lumber, plywood, paper, and paperboard. In the second phase, primary products are processed into end-use products such as housing, packaging, and newsprint. The first two phases generate byproducts, much of which are used for cogeneration. The third phase describes the disposal of end-products based upon their time in service and final disposition patterns. Products that are recycled or landfilled are fixed as carbon with allowances for landfill emissions. Products not recycled or landfilled are burned with or without energy generation or left to decompose.

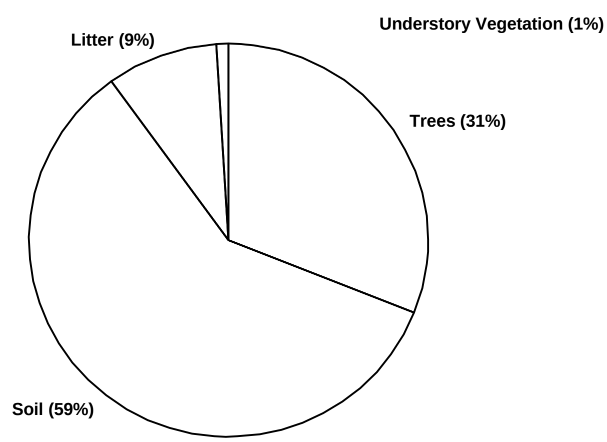
Disposition patterns for different types of harvests were calculated for three broad regions. Harvest types reflected differences in the diameter of logs and end-use products. Pulpwood harvests are small diameter trees used to make paper. Because paper products are short-lived, the percentage of carbon fixed in these products declines sharply between years 1 and 10, much of it being emitted through burning and decomposition during the first year. Sawtimber harvests are larger diameter trees used to make lumber and plywood. Lumber and plywood are generally long-lived, so a greater amount remains fixed in wood products and landfills compared to pulpwood. Large sawtimber harvests refer to old growth harvests in the West. Disposition patterns for old growth harvests are similar to sawtimber harvests except that less carbon is initially stored in products due to greater breakage during harvests and more defects.

Results from the FORCARB Model

United States forest ecosystems contain about 52.5 petagrams of carbon, which is about four percent of all carbon stored in world forests (Ajtay, et al., 1979). The forested area of the U.S. is about 296 million hectares, or about five percent of the world forests. Base year estimates for carbon storage in the U.S. were generate using the FORCARB model for 1987 and 1992. On average, U.S. forests contain 17.7 kg/m^2 of carbon with 31% in trees, 59% in soil, 9% in litter, and 1% in understory vegetation (Fig. 5.2). If tree roots are added to the soil carbon levels, nearly 64% of the total carbon found in forest ecosystems is found in the belowground portion. Estimates of past carbon storage in U.S. forests were derived from the U.S Forest Service periodic assessments for 1958, 1965, 1974, and 1982. Generalized conversion factors were derived from estimates for the base year (1987) and applied retroactively to previous estimates of growing stock volume by region and forest type for specified years.

Figure 5.2

Carbon in U.S. Forests



Source: USFS.

Carbon Storage by Region

Carbon storage in forest ecosystems varies considerably between regions of the U.S. About 39% of the of the total carbon in U.S. forests is found in the Pacific Northwest, 15% each in the Northeast and Rocky Mountains, and about 10% each in the Southeast, South Central and North Central regions.

Soil carbon levels ranged from a high of 64% in the Pacific Northwest to 49% in the Rocky Mountain region and were closely related to temperature and precipitation. Cooler temperatures slow the oxidation of soil carbon, while higher rainfall produces greater growth of vegetation, fine roots, and litter, which are the major sources of soil carbon.

Forest carbon levels increased from southern to northern states due primarily to climate and average age of forests. The cooler, wetter climates favor higher carbon retention on the forest floor and in soils. In addition, the northern forests tend to be older and less frequently disturbed then southern forests.

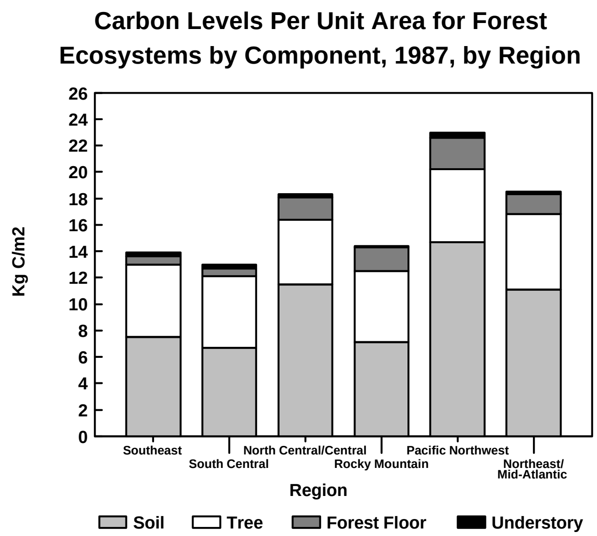
Figs. 5.3 and 5.4 shows the carbon storage for each forest ecosystem component in different regions of the U.S. generated by the FORCARB model. The amount of carbon stored in the soil component is the primary factor contributing to the overall higher levels found in the Pacific Northwest, the Northeast/Mid-Atlantic, and North Central regions. In the Northeast/Mid-Atlantic region, the south-north continuum for increasing soil carbon levels in the forest shows Maine, New Hampshire, Vermont, Massachusetts, and Connecticut with relatively high soil carbon levels. Delaware and Maryland exhibit substantially higher levels of carbon stored in trees, but much lower levels of soil carbon.

Carbon Storage by Forest Type

Across the U.S., there are large differences in carbon storage associated with forest type. Douglas-fir stands of the Pacific Northwest contain large quantities of carbon stored in trees while pinyon-juniper stands show small amounts due to the dry climate and sparse vegetation density. Loblolly pine plantations, which tend to be younger, store relatively low levels of carbon in trees and have low soil carbon levels due to the warmer climate of the South.

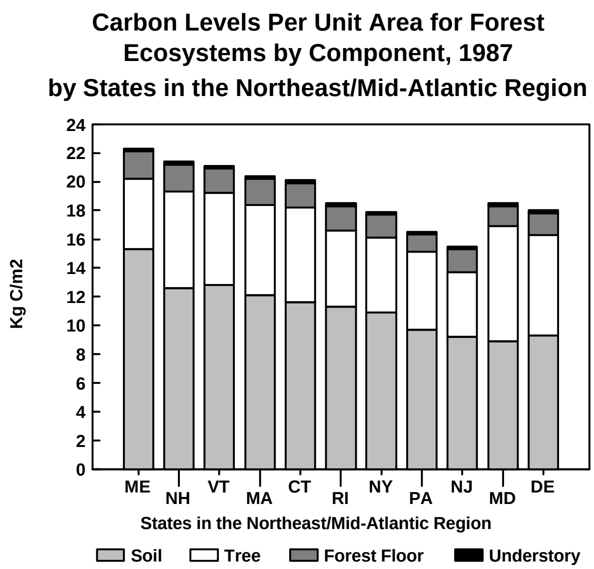
Spruce/fir stands of the Northeast have high carbon content by virtue of the high levels stored in the soil.

Figure 5.3



Source: Appendix Table A.5.

Figure 5.4



Source: Appendix Table A.5.

Carbon storage and accumulation rates for the major forest types and land areas for the Northeast/Mid-Atlantic states are shown in Table 5.2. Forests of northern New England contain more total carbon than forests of southern states in the northeast, and these higher levels are primarily associated with increased soil carbon. The dominant forest types of this region include maple/beech/birch, oak/hickory, spruce/fir, and white/red/jack pine. Oak/hickory and maple/beech/birch forest types account for the vast majority of annual carbon accumulation and storage in this region. Spruce/fir and white/red/jack pine forest types have intermediate levels of total carbon storage, but relatively low levels of annual accumulations.

Table 5.2
Annual Carbon Accumulation and Total Carbon Storage for Different Forest Types in the Northeast/Mid-Atlantic States (1987).

		Annual Accumulation		Total Storage	
Forest Type	Area (1000 A)	Ave C/yr in Trees (kg/m^2)	Annual C Total (1000 T)	Ave C in Trees (kg/m^2)	Stored C Total (1000 T)
White/Red/Jack Pine	8,067	0.12	4	5.3	172,426
Spruce/fir	10,007	0.11	4	4.7	189,875
Loblolly/Shortleaf Pine	2,704	0.20	2	3.9	43,117
Oak/pine	3,539	0.21	3	6.0	85,898
Oak hickory	10,560	0.19	28	5.7	244,166
Elm/ash/cottonwood	4,879	0.12	2	3.6	72,059
Maple/beech/birch	29,145	0.16	18	5.7	673,836
Aspen/birch	3,240	0.12	1	3.3	43,810

Source: Birdsey, 1992.

Changes in Carbon Storage

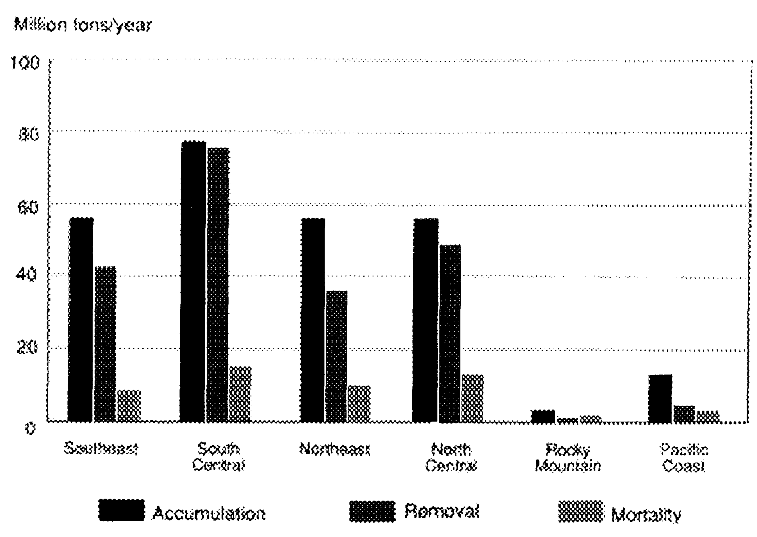
Changes in carbon storage in forest ecosystems are primarily a function of the carbon storage in live trees. Carbon accumulation rates in live trees are greatest in regions with the most rapid volume growth, e.g., the Southeast and Pacific Northwest. The U.S. average for carbon

accumulation in live trees is about 0.14 kg/m^2, which is a rate of increase of 2.7% of the amount stored in live trees.

The accumulation of carbon in live trees is 461 teragrams per year, while the total removals from timber harvesting, landclearing, and fuelwood account for about 355 teragrams. Comparison of accumulation and removals indicates that U.S. forests are storing additional carbon at a rate of 106 teragrams per year. This is equivalent to about 9% of the annual U.S. emissions of carbon to the atmosphere per year (Boden, et al., 1990). Annual mortality accounts for about 75 teragrams of carbon annually; however, this amount was not included in the comparison of accumulation and removal since much of the carbon remains in the forest ecosystem as standing dead trees, coarse woody debris, and eventually soil organic matter.

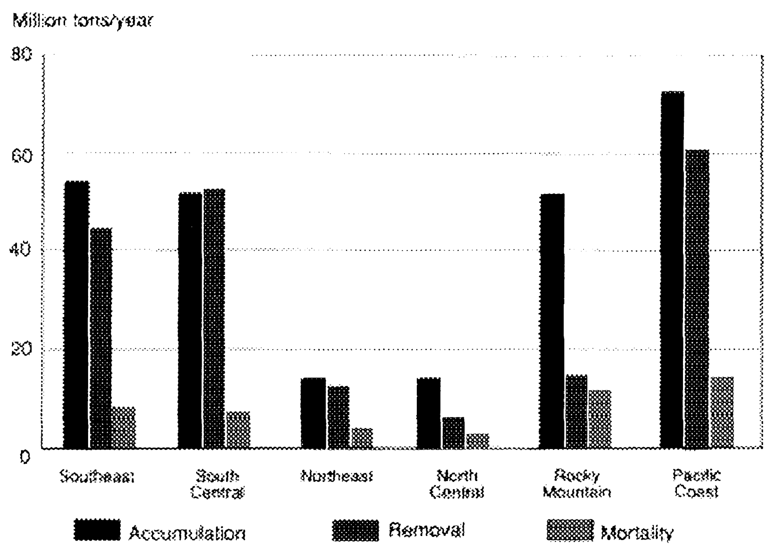
Total estimates of relative and total carbon accumulation, removal, and mortality differ with regions in the U.S. The Northeast has the largest excess of hardwood carbon accumulation over removal (Figure 5.5). Comparison of softwood removals and mortality with accumulation in the Northeast shows a net carbon deficit (Figure 5.6).

Figure 5.5
Annual Changes in Carbon Storage in Live Hardwood Trees on All Forest Land by Region



Source: Birdsey, 1992.

Figure 5.6
Annual Changes in Carbon Storage in Live Softwood Trees on All Forest Land by Region



Source: Birdsey, 1992.

By the end of the 19th century, nearly all the northern forest had been cleared for agriculture or heavily logged for timber products, with the exception of extreme northern parts of Maine and the Great Lakes States. Beginning in the mid-19th century and accelerating in the 20th century, marginal agricultural land has reverted to forest and produced a dense stocking of trees with much of the area of timberland distributed in the 25- to 65-year age-classes. These forest lands of mixed species are in the middle of a period of rapid growth that can be sustained for several more decades before reaching a period of declining net growth (Gansner, et al., 1991). In the future, harvesting is not expected to increase enough to offset continued accretion of biomass (Haynes, 1990).

Recent and Projected Trends in Carbon Storage and Flux

Between 1952 and 1987, carbon storage on U.S. timberlands has increased an estimated 8.8 petagrams, or enough to offset 21% of the U.S. carbon emissions for that period (Boden, et al., 1990). Increases in carbon storage in the northern and southern regions offset declines in the western regions. However, projections through 2040 show an additional increase of only 3.9 petagrams of carbon storage. The lower value reflects: 1) a slowdown in accumulation in northern forests as the average growth rate of these forests slow with increased age and less increase in soil carbon as fewer lands reverted to forest; 2) an increase in intensive forest management in the South such that tree carbon declines (although soil carbon continues to build); and 3) reduced harvest of old growth in the West and more younger, more vigorous, intensively managed forests.

Since 1952, carbon flux has averaged about 250 teragrams per year, but that value drops to about 75 teragrams per year in projections through 2040. Nearly 2/3 of the flux is carbon buildup in the soil; however, this relationship changes in the projections so that all of the increase is in the soil component by the period 2020-2030. The divergence between the relationships may in part be the result of different modeling techniques and lack of detailed information about past age-class distributions.

Projected changes in forest carbon storage was significantly affected by ownership. Model results showed that other public owners (all except National Forest) maintain a constant high positive carbon flux (net increase in carbon storage). National Forest lands shift from a source to a sink for carbon. Forest industry lands maintain stability at near zero flux, while other private lands decline from a positive to a near zero flux.

Forest Management Scenarios Examined with FORCARB

The FORCARB model allows for the examination of the influence of different forest management scenarios on forest carbon storage. Haynes, et al. (1994) used FORCARB to assess

the impact of lower timber harvests on National Forest lands, recycling levels, tree planting programs, and export levels on total forest carbon storage. The different scenarios examined are:

1. **Current Base -** 1987 RPA with lower National Forest Service (NFS)
2. **1987 RPA** - Base scenario used in 1989 RPA Assessment
3. **Reduced NFS Harvest** - Timber harvest reduced further on NFS lands to represent possible resolution on ongoing debates
4. **Low Recycling** - Recycling scenario that increases wastepaper use to 41 percent of total fiber by 1995
5. **High Recycling** - Recycling scenario that increases wastepaper use to 45 percent of total fiber by 1995
6. **Reforestation M/R 60** - Tree planting scenario based on Moulton and Richards' enrollment schedule and funding of $60 million/yr for 10 yrs
7. **Reforestation M/R 110** - Scenario #6 at $110 million/yr for 10 yrs
8. **Reforestation M/R 220** - Scenario #6 at $220 million/yr for 10 yrs
9. **Reforestation P/H 110** - Tree planting scenario based on Parks and Hardie's enrollment schedule and funding of $110 million/yr for 10 yrs
10. **Reforestation P/H 220** - Scenario #9 at $220 million/yr for 10 yrs
11. **Combination 1** - Combines "reduced NFS harvest" and "low recycling"
12. **Combination 2** - "Combination 1" plus double export levels relative to the 1989 RPA
13. **Combination 3 -** Combines "combination 2" and "reforestation M/R 110"

Although all scenarios result in positive carbon storage, little difference in total carbon storage over the projection period is shown among the various scenarios. The amount of carbon stored in the U.S timberlands is so large that it takes considerable time for the limited actions implied in the various scenarios to have any effect on the inventory of carbon. The three scenarios with the greatest effect by the end of the projection period are "fast recycling," "reforestation M/R 220," and "combination 3."

In general, *the recycling scenarios have greater short-term impact*, while it takes longer for the reforestation scenarios to have an influence. The analysis remains incomplete until better simulation can be performed on the fate of carbon from harvested timber. The magnitude of harvested carbon fluxes is enough to significantly alter the results.

A straight comparison between scenarios and the current base (1987) shows differences in flux estimates of no more than 21 teragrams in any single period, and the greatest positive

change from 1990 to 2040 is only 11 teragrams for the fast recycling scenarios. Although these differences are real, it is unlikely that they represent a significant contribution to overall sequestration.

D. FASOM: THE FOREST AND AGRICULTURAL SECTOR OPTIMIZATION MODEL

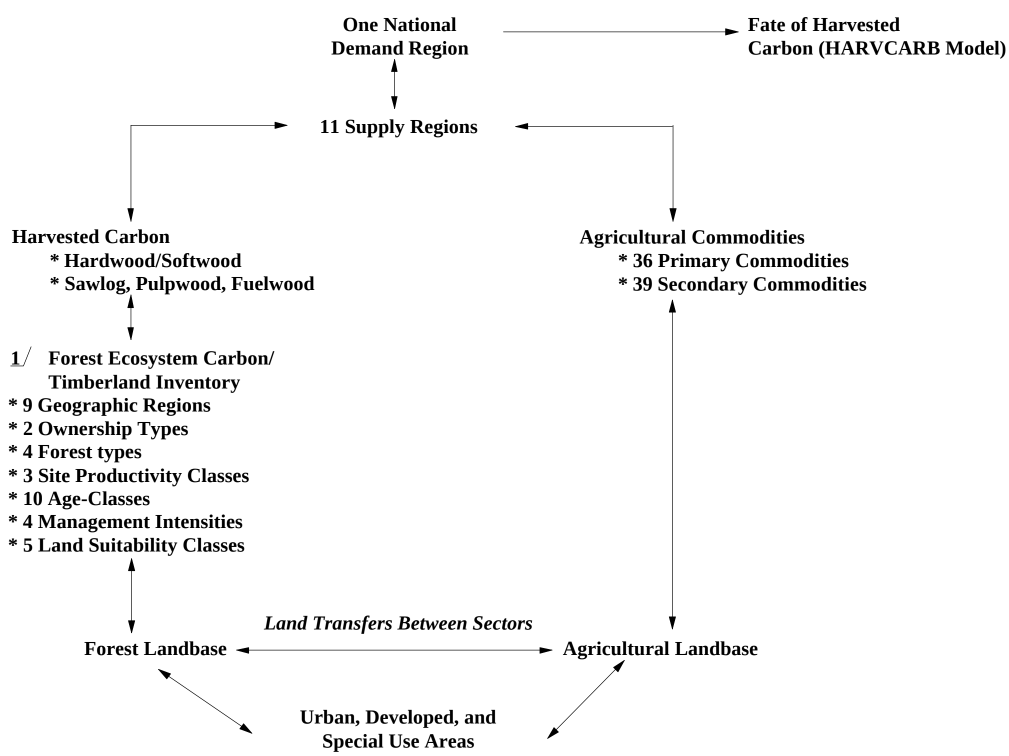
The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear, programming model that depicts the allocation of land over time for competing uses in agriculture and forestry. It was originally developed to evaluate welfare and market impacts of policies for sequestering carbon in trees, but it has been applied to a wider range of forest and agriculture policy scenarios. FASOM provides information about the effects of a range of potential policies on carbon sequestration, market prices, land allocation, as well as consumer and producer welfare under different supply and demand conditions and producer eligibility-participation constraints.

The concept for FASOM is an outgrowth of two previous studies. The first (Adams, et al., 1993) modified an existing, price-endogenous Agricultural Sector Model (ASM) (McCarl, et al., in press) to consider tree planting and harvesting on agriculture land to sequester carbon. Adams et al. work provides estimates of the cost of sequestering carbon when agricultural crops are displaced by trees (including rising agricultural prices) and the impacts of different size programs on both the total and distribution of the consumers' and producers' welfare. The second study (Haynes, et al., 1994), used the Timber Assessment Market Model (TAMM) and a linked inventory model (Aggregate Timberland Assessment System, ATLAS). Results of this work enabled the spreading out of the harvest of trees planted to sequester carbon, which was a limitation of the modified ASM model of Adams, et al. (1993). It is unlikely that all trees planted in a single year will be harvested at the same time.

The previous two models do not allow for the examination of the effects of future price expectations on the decisions of existing private timberland owners and the likely impacts of

these decisions on the total carbon sequestered. A major purpose for FASOM was the need to model the optimal behavior of the economic factors through time that would be affected by carbon sequestration policies (Table 5.3). For example, harvest in reforestation decisions by private timberland owners are likely to be influenced by farmers planting millions of acres of potentially harvestable timber. FASOM links the forest and agricultural sectors in a dynamic framework so that producers in both sectors can foresee the future consequences of different tree planting policies and adjust their decisions and actions to accommodate the future effects. In essence, they have "perfect foresight." FASOM allows for transfers of land between sectors based upon the land's marginal profitability in all alternative forest and agriculture uses across the time horizon of the model.

Table 5.3
Summary of the Parameters Used in the FASOM Model



1/ Forest ecosystem carbon storage components and pool sizes similar to FORCARB estimates.

There are 11 supply regions and a single national demand region in FASOM, excluding Alaska and Hawaii. Land use and exchanges of land between forestry and agricultural sectors are constrained for empirical or practical reasons, e.g., climate or environmental conditions in certain areas may preclude significant amounts of commercial forestry or cost effective carbon sequestration.

Forest Sector Parameters

Forest sector parameters for FASOM fall within three basic categories: 1) demand functions for forest products; 2) timberland area, inventory, and dynamics; and 3) production technology and costs.

Product Demand Functions

FASOM uses a single national demand region for forest products that treats only the log market portion of the forest sector. Although there is little interregional shipment of logs in the U.S., competitive price relations among regions at the log and stumpage market levels are maintained through extensive trade and competition at the secondary wood product level (lumber, plywood, pulp, etc.). Log demands in FASOM are aggregated into six categories: sawlogs, pulpwood, and fuelwood for both softwoods and hardwoods. Only the growing stock portion of trees delivered to processing facilities are considered for the log demand function. Log demand curves are developed from solutions of TAMM (for sawlogs) and North American Pulp and Paper (Ince, 1994) (for pulpwood) models. Fuelwood demand, which is not price sensitive in TAMM, is represented by a fixed minimum demand quantity and a fixed price. Demand curves shift from decade to decade reflecting changes in the secondary product demand environment, secondary processing technology, and secondary product capacity adjustment across regions. Export trade occurs at the supply region level and includes both hardwood and softwood sawlogs and pulpwood. Fuelwood is not traded.

Inventory Structure

Timberlands are characterized by nine geographic regions, two classes of ownership, four forest types, three site productivities, four management intensities, five land classes for suitability of land transfer, and ten 10-year age-classes. Each stratum is associated with the number of acres and the growing stock volume per unit area (cu ft/A) that it contains. Inventory estimates for private timberlands are similar to those for FORCARB, from Powell, et al. (1993) and Haynes, et al. (1995). Public timberlands are not explicitly modeled and public timber harvests are taken as exogenous due to the same data limitations encountered with FORCARB.

In any selected stratum, 0 to 100% of the area can be harvested at a time. The harvested acres flow to a pool from which they can be allocated to new timber stands by using one of several regeneration methods, or they can be shifted to agricultural use. Different levels of management intensity can be applied to newly regenerated stands. In FASOM, the growth of existing and regenerated stands is simulated using timber yield tables that provide net wood volume for the selected strata by age-class. Timber yields for plantations on agricultural lands were based on work by Moulton and Richards (1990) and Birdsey (1992).

Production Technology, Costs, and Capacity Adjustment

In FASOM, when an acre of timberland is harvested, the volume is translated into hardwood and softwood products (sawlogs, pulpwood, and fuelwood) in fixed proportions. The mix of products differs across sites and other land strata, over time as the stand becomes older, and between rotations if the management intensity changes. Downward substitution (sawlogs for pulpwood and pulpwood for fuelwood) is allowed when the price spread between pairs of products is eliminated. This substitution is technically realistic and prevents the price of pulpwood from rising above sawlogs and fuelwood above pulpwood.

The strata in the forest inventory have associated management costs (tending and planting) that differ with inventory characteristics and management intensity. The cost estimates are from Moulton and Richards (1990) and the 1989 RPA assessment (Alig, et al., 1992). Each

product has specific harvesting and hauling costs that were derived from the TAMM data base and cost estimates from the 1993 RPA timber assessment (Haynes, et al., 1995).

Available processing capacity restricts the consumption of sawlogs and pulpwood. Investment in additional capacity is made endogenously by allowing the purchase of capacity increments at externally specified prices, thereby increasing the current and future capacity bounds. It also reduces producers' surplus by the cost of the capacity acquisition. Over time, capacity declines by an externally specified depreciation rate.

Agricultural Sector Parameters

A version of the ASM model (Chang, et al., 1992) was incorporated into FASOM to model farmland uses. The major difference from the full ASM model is the delineation of the 11 FASOM supply regions instead of the 63 state-level regions in ASM.

Primary and Secondary Production Commodities

The ASM is a price-endogenous agricultural sector model that simulates the production of 36 primary crop and livestock commodities and 39 secondary or processed commodities. Crops compete regionally for land, labor, and irrigation water. Costs are included in the budgets for regional production variables for each decade modeled in FASOM. There are more than 200 production possibilities (budgets) for field crops, livestock, and tree production in each decade.

Numerous secondary commodities are produced by processing variables (e.g., soybean crushing, potato processing, dairy products, etc.). The processing cost for each variable is calculated as the difference between its price and the cost of the primary commodity used in its production. The ASM model prevents unrealistic combinations of crops from entering the optimal solution by requiring that the crop mix for a region fall within the mix of crops in the past 20-year cropping records. These crop mixes are required for the first two decades in FASOM, but are relaxed thereafter.

Primary and Secondary Demand

Primary and secondary commodities are sold to national markets. The demand functions represent total willingness to pay for agricultural products. The difference between total willingness to pay and production and processing costs is equal to the sum of producers' and consumers' surpluses. Demand and supply components are updated between decades by projecting growth rates in yield, processing efficiency, domestic demand, exports, and imports.

Land-Use Options

In FASOM, agriculture landowners and timberland owners make decisions about land-use each decade. Owners of agricultural land can decide: 1) whether to keep each acre in agricultural production or plant trees; 2) what crop-commodity mix to plant and harvest; and 3) what type of timber management to apply if land is converted to forest use. The same types of decisions apply to timberland owners. These decisions are based entirely on the relative profitability of land in its various competing uses over the life-span of the possible choices.

Carbon Sector Parameters

The carbon sector in FASOM meets four specific objectives:

1. accounts for quantitative changes in major carbon pools of private timberlands and cropland;

2. imposes policy constraints on either (or both) the carbon pool size at any given time or the rate of accumulation from year to year;

3. imposes policy constraints by region, owner, land class, etc.; and

4. values carbon in the objective function, instead of constraining it to meet a specific target, allowing for modeling carbon subsidies directly in FASOM.

FASOM accounts for five basic groupings of carbon related to terrestrial systems. These include: 1) carbon accumulation in forest ecosystems on existing stands in the existing private timberland inventory during the projection period; 2) carbon accumulation on reforested and

afforested stands during the projection period; 3) carbon losses from nonmerchantable pools in harvested stands from harvest to regeneration or conversion to agricultural land; 4) carbon "decay" over time for wood products; and 5) carbon on agricultural lands.

Carbon in the forest ecosystem is divided into two broad pools. The first is tree carbon, which includes the merchantable portion of the growing stock, as well as the unmerchantable portion (bark, roots, branches, foliage). The second is the ecosystem carbon pool, which includes soil carbon, understory carbon, and forest floor carbon. When an age-class of trees is harvested, the merchantable and unmerchantable portion of the tree carbon follow separate life cycles. The merchantable carbon goes to either wood products or landfills, is burned, or oxidizes to the atmosphere. Nonmerchantable carbon represents woody debris or residue that either survives in the ecosystem or is oxidized and lost to the atmosphere.

Preharvest Carbon Accumulation

On forested lands, carbon accumulates over time in four carbon pools: tree carbon, soil carbon, forest floor carbon, and understory carbon.

Tree Carbon - Tree carbon in FASOM is the same as for FORCARB (Birdsey, 1992). Preharvest carbon in a stand is the product of three factors: 1) merchantable volume; 2) ratio of total volume to merchantable volume in a stand; and 3) a carbon factor that translates tree volume into carbon. Merchantable volume, by age-class, on each representative stand is obtained from the growth and yield tables in the model.

Soil Carbon - Estimates for soil carbon are generally the same as for the FORCARB model. Soil carbon for reforested and afforested stands is fixed at a positive, initial level with the regeneration of a new stand. Reforested stands initially lose soil carbon and subsequently accumulate soil carbon until a critical stand age is reached. After the critical age is attained, soil carbon increases at a decreasing rate over time until harvest. Soil carbon estimates differ with region, land type, forest type, and age-class.

Forest Floor Carbon - Forest floor carbon closely follows that of FORCARB. As with soil carbon, forest floor carbon values are fixed at regeneration and then increase by a constant annual increment up to another fixed value at a critical age. After the critical age is attained, forest floor carbon increases at a declining rate over time until the stand is harvested. FASOM also includes a somewhat different approach to forest floor carbon accounting that takes into account the buildup and decay of woody debris in forest stands.

Understory Carbon - Since understory carbon is such a small fraction of the total carbon in forest ecosystems, and since it is dependent on tree carbon yield for only a portion of the life cycle of a tree, FASOM models understory carbon yield as independent of tree carbon yield. Estimates were the same as used in FORCARB.

Carbon at Harvest

The fate of carbon at harvest is followed in each of the four pools: tree carbon, soil carbon, forest floor carbon, and understory carbon.

Tree Carbon - Tree carbon is divided into two smaller pools, merchantable and nonmerchantable. Each of these pools is a fixed fraction of the tree carbon at the harvest age based on volume factors for different regions and species. When a harvest occurs, the merchantable carbon level is maintained, while the nonmerchantable portion is adjusted to reflect immediate harvest losses. The fraction of the tree carbon left on site immediately after harvest was determined by adjusting volume factors of Birdsey (1992) to agree with information about the magnitude of this fraction from Harmon (1993).

Soil, Forest Floor, and Understory Carbon - When a stand is harvested, it is assumed that carbon in each pool will return to an appropriate initial level by the end of the decade in which the harvesting occurred. The initial level will depend on the use to which the land is put.

Carbon Fate in Wood Products and Woody Debris

FASOM tracks the fate of carbon, after harvest, for both merchantable and nonmerchantable timber carbon pools.

Merchantable Carbon - In FASOM, timber harvested flow to three products: sawlogs, pulpwood, and fuelwood. The life cycle of each of these products can vary greatly depending on both short-term fluctuations in prices and long-term technological changes.

The HARVCARB model is used to simulate the fate of carbon in trees after harvest and conversion into wood and paper products, used in a variety of ways, and burned or disposed of in landfills. The fate of carbon for each product is determined by a set of coefficients showing the average fraction of merchantable carbon remaining after harvesting a specific age-class in each subsequent time period for four different uses. These are: 1) wood products in use; 2) wood products in landfills; 3) burned wood products; and 4) emission to the atmosphere. The carbon fate coefficients differ with the product, species, and length of time after harvest. The fate of carbon in burned wood is determined by fixed proportions in two categories, displaced fossil fuels and emissions to the atmosphere. The same general treatment is applied to fuelwood, except that it is assumed that fuelwood displaces conventional fossil fuels in a fixed proportion.

Nonmerchantable Carbon - Nonmerchantable carbon, or woody debris decays after harvest. The decay rates differ with region, species, and decade. Data for modeling these decay rates are from Harmon (1993). FASOM does not track stands by acreage after harvest, instead the land is harvested is thrown into a pool of acres from which new acres to be regenerated can be drawn. Consequently, there is a tendency for very large accumulations of carbon to develop in this pool. One way to deal with this problem is to shorten the number of periods over which the woody debris from a given age-class can accumulate. A truncation of 3-4 periods tends to produce a terminal woody debris pool similar to that of Turner, et al. (1993).

FASOM Outputs and Policy Applications

The purpose of FASOM is to maximize the present value of consumers' and producers' surpluses, which are measures of economic benefits. It assumes a multiperiod simulation of economic activity in competing sectors (forestry and agriculture) under perfect foresight of future prices. Land will shift into forestry from agriculture if the expected returns in forestry

exceed the returns in agriculture over the remaining decades. Decisions regarding the transfer of land from forestry to agriculture would involve the opposite considerations.

Consumers' and Producers' Welfare - The model produces information about the distribution and the present and future values of consumers' and producers' surpluses over both space and time.

Agricultural Production and Prices - FASOM provides region-level information about the market-clearing production and price levels for ASM commodities by decade. Regional production levels for crops can be further segregated into average yields and acreage harvested.

Forest Inventory Levels - For each 10-year age-class, FASOM reports regional inventory levels by owner, land use suitability, forest type, site class, management intensity, and age.

Harvest Levels and Prices - Harvest levels are provided at the same level of detail as other inventory statistics. Prices may be examined at either the national or regional levels.

Wood Product Output and Prices - Wood product output levels, by decade, are provided for each of the three products (sawlogs, pulpwood, and fuelwood) by region and forest type. Price levels for these products are endogenous.

Land and Forest Asset Values - Since FASOM simulates the competition between forest and agriculture for land, it produces information about marginal land and forest asset values over time.

Carbon Sequestration Amounts and Prices - FASOM produces regional and national information about the total carbon storage in each decade and the storage rate (i.e., change in storage) during each decade. If carbon is "forced" into the model, then FASOM will generate an estimate of the shadow price associated with the requirement provided the constraint is binding.

Land Transfers - FASOM was designed so that land transfers between sectors would occur endogenously as a result of intertemporal economic forces. Thus, an important output is the listing of land transfers in each decade, which are shown by region, land class, and sector for each decade.

Policy Applications

The initial impetus for FASOM was to develop a model that could evaluate different policies to sequester carbon in an economic framework, and not only account for the impacts of these policies on forest and agricultural sector markets, but also the reaction to these policies by consumers and producers in these markets. It is clear that the model can also be used to evaluate the consequences of a wide range of forest and agricultural policies, not just those to promote carbon sequestration. Several examples of FASOM's past applications are listed below.

Forest Carbon Sequestration Programs - FASOM can be used to estimate social welfare costs of different carbon sequestration policies, in terms of both specified carbon levels and timing of carbon sequestration. Alig, et al. (in press) specified carbon target levels for the U.S. by decade. No restrictions were placed on the manner in which decadal carbon flux or inventory targets could be met, and the resulting solutions can be considered least-cost allocations of land and investments to meet the targets. Results showed that land-use shifts to meet policy targets need not be permanent, implementation of land-use and management changes in a smooth fashion over time may not be optimal, and land-use changes account for the largest part of the adjustments to meet policy targets. Results also demonstrated that land-use changes promoted by forest carbon policies may generate compensating land-use transfers. In response to a proposed policy requiring afforestation of 12 million acres of pasture between 1990 and 1999, other forest land was converted to agriculture resulting in a net gain in forested acres significantly smaller than suggested in previous studies using static models (Moulton and Richards, 1990; Parks and Hardie, 1995).

Other efforts have assessed timber supply or the carbon sequestration potential of various proposed reforestation programs, e.g., the Stewardship Incentive Program and America the Beautiful (Alig, et al., 1992; Dutrow, et al., 1981; Haynes, 1990; Moulton and Richards, 1990). These studies identified a range of potentially profitable investments in forest management, but they did not model the effect of programmatic subsidy levels on investment enrollment. In FASOM, all investments in land compete with each other at the margin in the asset market for

land. Forest carbon policies or programs simulated in FASOM reflect the effects of programmatic subsidy levels on areas enrolled and countervailing land transfers to agriculture (Alig, et al., in press).

Changes in Farm Program Payments - FASOM can project the influence of inclusion (or exclusion) of provisions of the current Farm Bill or many other farm program alternatives. It can be used to examine the effects of reducing loan rates and target prices while increasing tree planting payments, as in the current Conservation Reserve Program. Alig, et al. (in preparation) simulated the elimination of farm programs in the first decade (1990's) of the projection which led to a reduction in the forest area converted to agricultural use. The impacts were concentrated in the eastern U.S. where most land exchanges between forestry and agriculture have occurred.

Changes in Harvest Levels on Public Timberland - With public policy for National Forests and other public timberland moving in the direction of more emphasis on non-timber uses, timber harvesting is being reduced on these lands. This will allow carbon stored in existing trees to accumulate further on public lands, but the rate of accumulation will be slower as trees age. At the same time, potential land on which to plant trees that can more rapidly sequester carbon will decline. The net impact of these two forces on total carbon sequestration is made uncertain by several factors, including the rate at which carbon in wood oxidizes after harvest. The current trends on public lands raise important and complex issues that can only be answered easily with a model like FASOM.

While FASOM currently does not have detailed data on public forest inventories, it does have information on harvests from these lands. Reductions in harvests from public lands were simulated by Adams, et al. (1996). They examined the impacts of these reductions on harvesting and management investment decisions in the private sector and found that the market was far more elastic to changes in public timber harvest levels than past studies had indicated. Shifts in private investments over time acted to dampen the price and aggregate harvest impacts of public harvest changes over time. Underlying the moderated timber market impacts were larger interregional shifts in harvest and private owner welfare than suggested in other studies.

Other Applications - FASOM has also been used to examine scenarios involving production of biomass energy that can displace conventional fossil fuel emissions, capital limitations affecting decisions by nonindustrial private landowners that pertain to management investments (Alig, et al., in preparation), and increases in paper recycling as an input in the production of paper in the U.S. (Adams et al., 1994).

E. GORCAM: THE GRAZ/OAK RIDGE CARBON ACCOUNTING MODEL

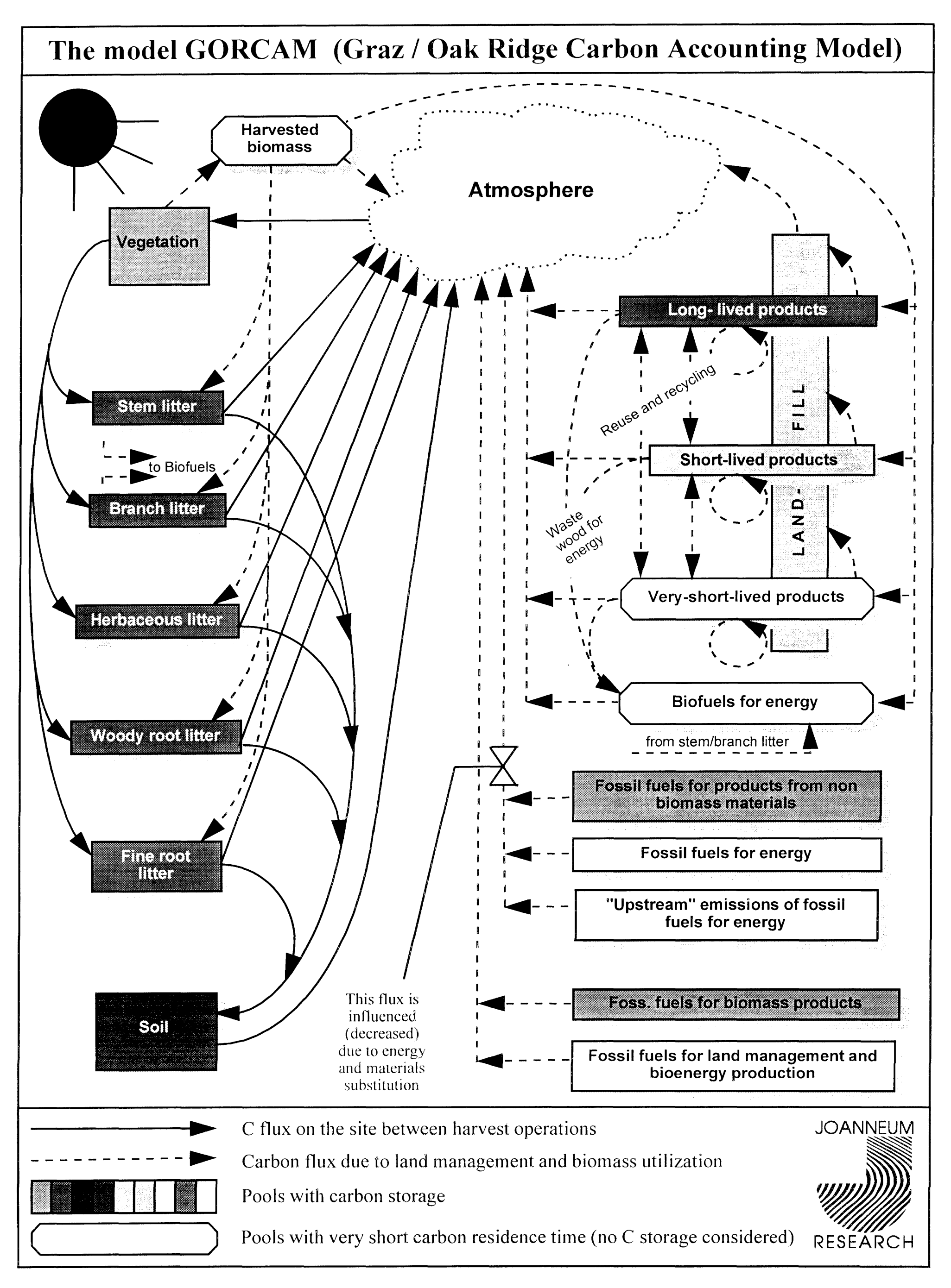
The Graz/Oak Ridge Carbon Accounting Model (GORCAM) is a spreadsheet model (based on Microsoft Excel 5.0) developed to calculate the net fluxes of carbon to and from the atmosphere over time associated with different land management and biomass utilization strategies. The model calculates carbon accumulation in plants, soils, long- and short-term wood products, fossil fuels not burned because biofuels are used instead, and fossil fuels not burned because of less energy-intensive alternative wood product substitutions. The model uses parameters to describe the allocation of carbon from forest harvest to various product and waste streams, the mean lifetime of wood products and soil and litter carbon, the efficiency with which wood products are used, and the energy required to the forest products system. Wood products can be recycled, placed in landfills, or used to generate energy at the end of their useful lives.

The GORCAM model differs from the FORCARB and FASOM models in that it assesses forest management practices at the stand level. GORCAM starts with a specified initial condition (e.g., old growth, regenerated stand, pasture, etc.) to which an initial harvest can be applied with a set of parameters that can be changed for subsequent harvests. Unlike the previous models discussed, parameters describing initial conditions are externally specified. The model then calculates the carbon balance in a unit of area.

The structure of the system of carbon pools and fluxes used in the GORCAM model are shown in Figure 5.7, which is very similar to the structure described by Apps and Price (1996). The land management portion of the model is shown on the left side and follows previous work (Dewar, 1991; Dewar and Cannell, 1992; Cooper, 1983). The biosphere of the model is divided

into a vegetation pool, five litter pools (stems, branches, foliage and herbaceous ground cover, woody roots, and fine roots), and a soil carbon pool. In determining the carbon balance for a forest ecosystem, all seven carbon pools are considered. The right portion of Figure 5.5 represents the biomass utilization part of the model. Solid arrows represent the natural carbon fluxes in the stand between harvests, and dotted arrows represent carbon fluxes associated with harvesting and biomass utilization.

Figure 5.7
Flow Diagram for Forest Carbon Used in GORCAM (from ORNL/Graz)



Source: Cushman, Marland, and Schlamadinger, 1997.

Initial Condition Parameters at First Harvest

An initial harvest is defined by a set of parameters that describe the condition of the forest stand (e.g., mature forest, regrown from previous forest, etc.). These input parameters include the following.

1. initially harvested carbon (if an initial harvest occurred);

2. shares of the initial harvest used for:
   * long-lived products,
   * short-lived products,
   * very short-lived products (do not store carbon at all),
   * biomass fuels;

3. carbon emissions from making products from wood versus other materials;

4. efficiency of bioenergy system versus substituted fossil fuel system;

5. carbon emission rate of substituted fossil fuel;

6. fossil fuel input for maintaining plantation and for harvesting;

7. additional fossil fuel input for processing biofuels and for conversion of bioenergy into
   heat and/or electricity;

8. similarly for the substituted fossil energy system.

These parameters can be changed for each subsequent harvest. The model calculates the carbon balance in a unit of area (1 ha). However, in order to have a constant output of products and raw materials over time, there must be a harvest every year. To accommodate this, the model allows for the consideration of a 100-ha stand that is divided into a number of harvestable parcels equal to the rotation length of the stand. That is, if the rotation length is 60 years, the parcel harvested at time 0 would again be harvested in year 60. Each harvest would be conducted on an area 1/60 of 100 ha.

Growth Parameters for Trees

GORCAM uses a simplified growth function for trees (Marland and Marland, 1992). The total above-ground biomass of standing stock is assumed to be a function of its original biomass, a growth rate, and a limiting value for biomass that can be supported on the site. Standing stock grows accordingly at a constant rate until it reaches a point half its maximum value, at which time growth becomes a constant fraction of the remaining distance to the maximum value. In work reported (Schlamadinger and Marland, 1996), a maximum supportable biomass of 160 Mg C/ha was assumed, and a constant growth rate was applied up to 80 Mg C/ha. The growth rate in plantations is defined by a combination of two additional parameters, rotation length and juvenile growth rate.

Two other growth functions are also available in the model. The first, follows an S-shaped course with time, with lower growth rates at the beginning, followed by higher growth rates, and eventually lower growth rates again as the stand's carrying capacity is approached (Cooper, 1983). The second alternative growth function describes the influence of selective logging in which only some trees are harvested so that the residual standing stock varies between and upper and lower limit. Any other growth function can be used in the model with minor changes.

Soil, Roots, Litter, and Product Decay Parameters

Dead plant material is transferred from the vegetation pool to one of the five litter pools, with woody litter production a function of the total vegetation pool size (Kindermann, et al., 1993). Decay of organic matter in litter pools produces carbon dioxide emitted to the atmosphere, and some carbon from litter pools is added to the soil carbon pool, which also emits carbon dioxide to the atmosphere.

Six parameters are required to describe soil, roots, litter, and product decay:

1. net soil carbon uptake (or loss) over time;
2. time interval over which net carbon uptake (or loss) occurs;

3. net roots and litter carbon uptake (or loss) over time;
4. time interval over which net roots and litter uptake (or loss) occurs;
5. average lifetime of long-lived products;
6. average lifetime of short-lived products.

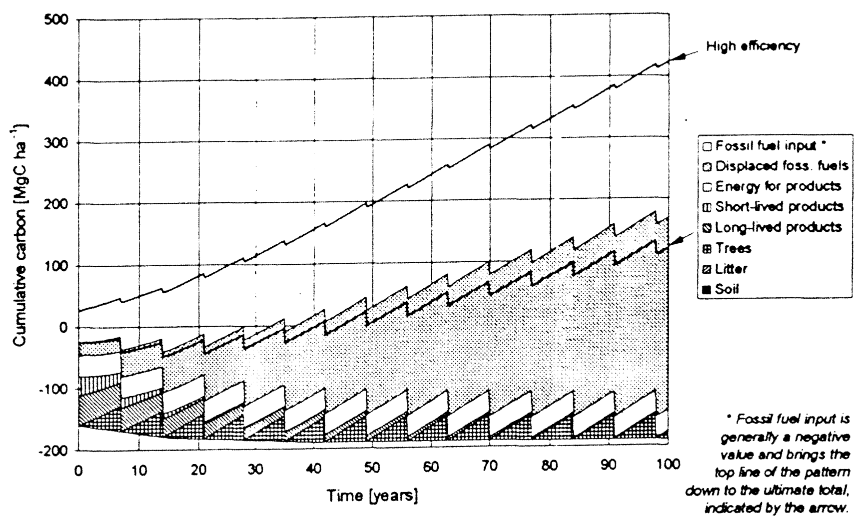
In a simplified version of the model, soil and litter carbon dynamics are not calculated but are prescribed by the user based upon expert knowledge of the past and future of land use at the site.

Harvested biomass can be used for bioenergy or for long-, short- or very short-lived products. Long- and short-lived products can store significant amounts of carbon, whereas the carbon in very short-lived products is neglected. Biomass waste can be either placed in landfills, recycled for other biomass products, or burned as biofuels. Burning of biomass waste or harvested biomass results in emissions to the atmosphere.

Results for the GORCAM Model

The GORCAM model output is presented in diagrams with time on the horizontal axis and net cumulative change in carbon storage on the vertical axis (Figure 5.8). The net changes in carbon storage is the sum of the individual carbon pools that are illustrated separately on each diagram. In some diagrams, the bottom line of the plot drops below zero to represent gross carbon loss due to initial harvest of standing biomass and/or net losses of soil or litter carbon. The regrowth of trees following initial harvest is then represented above the baseline as an increase in tree carbon. Each diagram shows net carbon uptake (or loss) in soils, litter, vegetation, long-lived products, short-lived products, landfills, retained in fossil fuels due to substitution of wood-based materials for more energy-intensive materials, and retained in fossil fuels displaced by biofuels.

Figure 5.8
Sample of Output from GORCAM Model



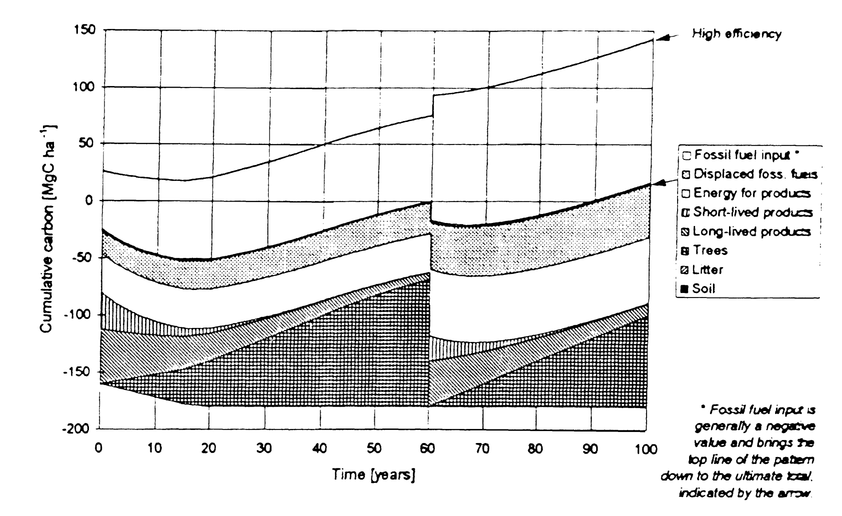
Source: Schlamadinger and Marland, 1996.

Net cumulative carbon sequestration from the atmosphere for short-rotation forestry when the plantation follows harvest of a mature forest of 160 Mg C/ha. The top lines shows the implications of high efficiency in product and fuel substitution.

Although the top line in each diagram represents the total carbon sequestered in either the forest ecosystem, wood products, or displaced fossil fuels, it does not represent the net savings in carbon emissions since an input of fossil fuels is required for land management, processing of biofuels and products, etc. The auxiliary fossil fuel input in the diagrams is represented by a solid black line, which represents the true savings.

Resulting diagrams can describe a single parcel of land with discontinuous carbon flows due to periodic harvest, or a larger tract with continuous flows of carbon due to regular harvesting of different portions of the tract. Figure 5.9 shows the results of a 1-ha parcel harvested at time 0. Figure 5.10 shows the results of a 100-ha tract with a rotation age of 60 years in which 1/60 of the area is harvested every year.

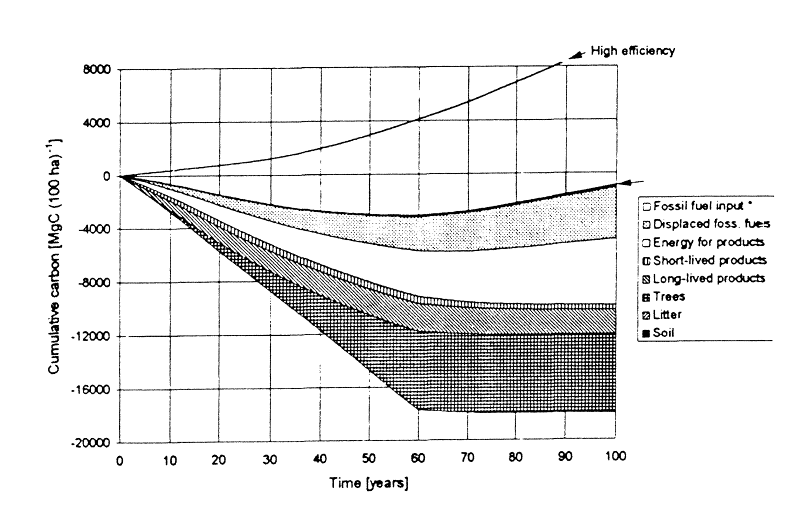
Figure 5.9
GORCAM Model



Net cumulative carbon sequestration from the atmosphere for conventional forestry (starting with a mature forest) producing long- and short-lived products and some biofuels on a 60-year rotation. Results are for 1 ha of forest that is harvested at time = 0 and again at 60 years. The top line shows the implications of high efficiency in product and fuel substitution.

Source: Schlamadinger and Marland, 1996.

Figure 5.10
GORCAM Model



Net cumulative carbon sequestration from the atmosphere for conventional forestry (starting with a mature forest) producing long- and short-lived products and some biofuels on a 60-year rotation. Results are for 100 ha of forest where the product flow is maintained uniform by harvesting 1/60 of the area each year. The top line shows the implications of high efficiency in product and fuel substitution.

Source: Schlamadinger and Marland, 1996.

Sixteen scenarios were simulated with GORCAM to assess the influence on carbon storage and fluxes. The scenarios are largely illustrative, and many parameters are highly variable depending on specific of geography, timing, land management, land-use history, and resource allocation.

1. agriculture energy crop (ethanol from corn)
2. conventional forest starting with mature forest and base case efficiency
3. scenario #2 with high efficiency of product use
4. short-rotation forestry on agriculture land and base case efficiency
5. scenario #4 with high efficiency of product use
6. short-rotation forestry starting with mature forest and base case efficiency
7. scenario #6 with high efficiency of product use
8. afforestation of agriculture land
9. afforestation of agriculture land for conventional forestry base case efficiency
10. scenario #9 with high efficiency of product use
11. continued conventional forestry and base case efficiency
12. scenario #11 with high efficiency of product use
13. conventional forestry on second-growth forest and base case efficiency
14. scenario #13 with high efficiency of product use
15. protection of forest under prior conventional forest management
16. protection of a uniform second-growth forest

Results obtained from model runs led to several observations regarding forest management strategies. In all scenarios, a dominant feature of carbon balance is the extent to which renewable biofuels displace fossil fuel use and wood products displace energy-intensive alternative materials. Although a significant net storage of carbon can occur in trees, soils, forest litter, and wood products, all of these carbon pools achieve some equilibrium at some level and provide no further sequestration over time. In all cases, the efficiency with which biofuels and

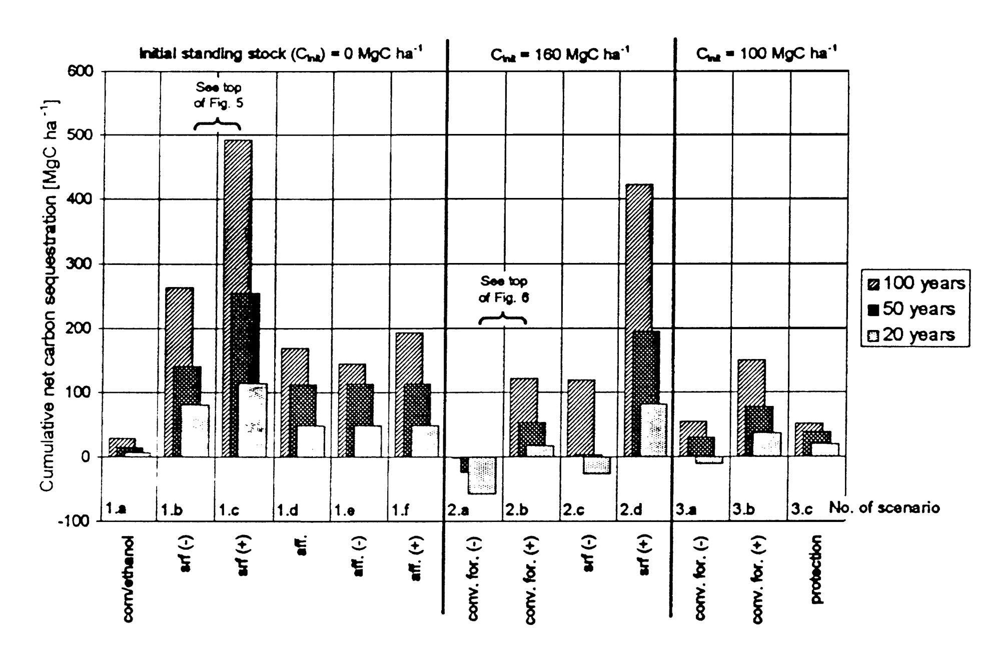
wood products are able to displace fossil fuels and the rate of forest productivity play major roles in the carbon balance. A summary diagram of results is shown in Figure 5.11.

The impact of conventional forestry on carbon sequestration is highly dependent upon the initial site conditions, the degree to which fossil fuels are displaced, and the efficiency with which biomass products are used. High product-use efficiencies always resulted in net positive carbon sequestration, regardless of initial site conditions. However, base case product-use efficiency levels often resulted in carbon losses from the system for much of the projected period of 100 years. On mature stands, base levels carbon storage was not retained until 100 years or more using conventional forestry methods on a 60-year rotation. If conventional forestry is applied to an immature, growing forest the net carbon balance is positive from the beginning, but more carbon would have been stored in the first 100 years if the forest would have been left to continue growing.

Short-rotation forestry involves mechanically harvesting trees on a cycle of seven years with regeneration from existing root stock. The growth rate was 6 Mg/ha/yr. On agriculture land conversions, the carbon sequestration is always positive and progressively increases with time. On mature forest land, the carbon sequestration does not become positive until about year 40. The large carbon benefits of short-rotation forestry arise because it capitalizes on very high biomass growth rates and thus can displace large amounts of fossil fuel. The net storage in the forest ecosystem is relatively low. Forest protection sequesters carbon only in the storage components of the forest ecosystem and does not displace fossil fuels for energy or from product substitution. Consequently, the net carbon balance is positive, but very low.

Some scenarios, particularly those implemented where there is a pre-existing forest, yield net carbon losses over short time horizons, but net carbon benefits over longer times. Consequently, short-term benefits can be much larger if implementation occurs in areas not already forested.

Figure 5.11
GORCAM Model



Summary of the results for 13 scenarios. For each scenario, three columns are shown representing the total net reduction of carbon emissions on 1 ha of land after 20, 50, and 100 years. Abbreviations: srf = short-rotation forestry; aff = afforestation; conv. for. = conventional forestry; (-) indicates base case efficiency of harvest utilization; (+) indicates highly efficient use of the harvest.

Source: Schlamadinger and Marland, 1996.

F. COMPARISON OF THE MODELS

Each of the three models offer specific strengths and limitations in their applications to forest carbon sequestration (Table 5.4). The FORCARB and FASOM models allow for the assessment of different management and policy scenarios over large regions and states based on sound forest inventory and scientifically based assumptions about carbon storage in forest components. The GORCAM model provides a means of simulating growth on individual forest stands or tracts with a variety of specific forest management prescriptions, and provides a detailed accounting of the impacts of those prescriptions on forest ecosystem carbon and displaced fossil fuels.

Table 5.4
Basic Functions of Three Forest Carbon Models

Model	Application	Forest Data	Land-Use Changes	Product Use	Model Type
FORCARB	Region or State-Level	U.S. Forest Inventory	-	+	Integrated Model
FASOM	Region or State-Level	U.S. Forest Inventory	+	+	Integrated Model
GORCAM	Stand-Level	User Assigned	-	+	Spreadsheet

A number of limitations are shared by these models:

-- lack of inventory data for public lands hinders analysis of public land issues;

-- harvest impacts are based on very general assumptions that would need adjustment for local applications, as would be true of any model;

-- in addition, the lack of data on soil and litter carbon for a wide variety of stand conditions requires generalized assumptions.

A major strength of the FORCARB model is its baseline information on carbon storage in specific forest ecosystem components across the U.S. Detailed information is available by region, state, ownership, forest type, and ecosystem component, and it is expressed in a variety of quantitative units. Since the data used in FORCARB is that of the U.S. Forest Service's periodic timber assessments for each state, there is sufficient data for statistically-sound examination of historical trends, as well as for projecting estimates into the future. Lack of detailed information about past age-class distribution prevents age-class effects from being considered in the past. FORCARB also has been shown to provide realistic simulations of carbon sequestration under different scenarios that considered lower harvest rates on federal lands, different recycling levels, different reforestation programs and export levels. Projections were simulated to the year 2040.

Some of the limitations of FORCARB include the handling of land-use changes, and unlimited data on the fate of carbon in harvested wood, and on energy inputs for the harvesting and processing of wood products.

The FASOM model overcomes some of the limitations of the FORCARB model, but retains much of its strengths by using the same inventory data base. FASOM tracks land-use changes between the forestry and agricultural sectors based upon simulated market-driven forces. It also uses many of the same estimates for forest ecosystem carbon that are employed in FORCARB. Using the ASM model, FASOM sets up competition between the two sectors based upon consumer and producer welfare. The fate of processed wood products is tracked using the HARCARB model (as does FORCARB), but the analysis has been developed further in FASOM. FASOM has been used to simulate a number of different agriculture and forestry policy recommendations.

Since many of the assumptions about forest ecosystem carbon are derived from the FORCARB model, the limitations on these are similar. One of the assumptions in FASOM is that outcome of timberland management investments are known with certainty, before investment. Consequently, investment adjustments are made instantaneously to any shift in imposed modeling conditions. Such rapid adjustment does not accurately characterize actual investment behavior in that investment decisions are slow to change and exhibit some inertia. For practical reasons, FASOM collapsed forest products into three categories for both softwood and hardwood species (sawlogs, pulpwood, and fuelwood). This prevents the tracing of specific wood products and their eventual disposition.

GORCAM provides an entirely different approach to modeling carbon storage and flux. To date it has been used as an illustrative model for demonstrating the impact of different forest management strategies on carbon sequestration at the forest stand or tract level. Unlike the other two models, GORCAM requires input parameters about the initial stand conditions and the products produced. Its strength is in its treatment of displaced fossil fuels resulting from bioenergy and wood product substitution. It is also possible to use this model for specific

timberlands ownerships, assuming sufficient information is available of the ownership. The model has also been used to examine selection harvests, plantation culture, and conventional forestry. GORCAM's major limitations are based on the accuracy of assumptions about fossil fuel displacement and forest stand parameters. The model results will only be as good as the estimates used in its parameters.

G. PREDICTED OPPORTUNITIES FOR ENHANCING FOREST CARBON SEQUESTRATION

FORCARB results show that U.S. forests have been significant carbon sinks since 1952 (earliest inventory data available), and that additional carbon sequestration is likely to occur through 2040, but at a slower rate of accumulation. Trends suggest that eastern forests accounted for most of the increase since 1952, but that the Northeast and North Central is expected to account for most projected increases. Alternative forest management strategies could result in as much as 560 teragrams of additional carbon storage through 2040. Increased recycling and reforestation would produce the greatest gains in carbon storage, with early gains for recycling and long-term gains for reforestation efforts. Uncertainty about the fate of harvested wood products could change these projections as they become better understood.

The results of the GORCAM model suggest several opportunities for increasing carbon sequestration on forest lands. Simulations indicate that the efficiency with which forest products are produced and used can have large effects. This higher efficiency is associated with the amount of carbon emissions from fossil fuels that is avoided when biofuels are used instead and when the amount of fossil carbon not oxidized because wood products are used instead of other more energy-intensive materials (e.g., steel, concrete, etc.). Simulations also indicate that short-rotation forestry can have very large net carbon benefits due to very high biomass growth rates. Afforestation projects can also have significant carbon storage benefits in early years, but they level off over time. While management of existing forests produces net losses over the short-term, there are net benefits accrued over the long term.

H. OPPORTUNITIES FOR IMPROVEMENT OF FOREST CARBON MODELS

In order for state policymakers and planners to develop mitigation plans to optimize forest use in carbon sequestration, models will need to be applied to various regions, or even specific timberland ownerships, within each state. In the case of FORCARB or FASOM, this will entail simulations based on local inventory data. Further, since a variety of forest management and harvesting practices are applied to these forests, estimates for carbon storage in these management regimes may differ from those used in the model to date. Since smaller subsets of the states will be examined, it may be possible, based on research in these specific regions, to develop more precise carbon storage estimates.

According to Birdsey (pers. comm.), the FORCARB model can serve as a basis for analyzing specific questions about carbon storage and fluxes. Forcarb functions well as a research outline or method from which information can be used to run "custom" spreadsheet-type analyses for carbon sequestration. This application is probably the way in which the model will be used for much of the planning at the state level. Since the model's regional and national structure was not built for state-level analysis.

Using GORCAM, it may be possible to simulate carbon storage and flux for different forest types and age-classes in states to develop an "average" estimate per unit area that can be inflated to match the total acreage in each category for each state. The major challenge with GORCAM is in developing accurate estimates for each input parameter and accepting the assumptions in an illustrative model customizing those assumptions to local conditions would be needed.

It is not clear whether any of these models could be used to develop a system of energy credits of forest landowners that manage forests to sequester carbon. However, an accurate model for projecting carbon storage and flux will be essential if a scenario is pursued involving credits. Such a model should consider the amount of carbon stored in the forest ecosystem under different management regimes, and perhaps the fate of products harvested from the forest and the

energy used to harvest and process materials. These parameters are incorporated the models discussed, but additional work would probably be required to apply the models to smaller ownerships that are managed in different ways. In addition, the accuracy of the models would have to be "ground-truthed" as part of a carbon accounting system to ensure that projected results match with actual results.

As with any modeling exercise, the effectiveness of the model depends upon the accuracy of the data used. Complete and accurate data at the local-, or even state-level, is often lacking and presents a problem for all models. Where data are available and results accurate, the task of incorporating modeling results into public policy is not easy because much of the general public has a difficult time relating to these non-tangible predictions. Since models are built upon assumptions and estimates, they are often viewed as "open to interpretation" and not taken seriously by the public. With the wide range of uncertainty about estimates of soil carbon levels in forest ecosystems, a certain degree of doubt may be warranted.

Modeling efforts at the state-level to account for forest carbon levels over time may best be accomplished using simplified spreadsheet analyses based upon what has been learned from models like FORCARB. These spreadsheet applications can be complex, e.g., GORCAM, or simply a comparison data from different carbon pools over time. This type of analysis should also allow for the consideration of small timberland ownerships. Besides the ease of application, much of the general public has had experience with spreadsheets and the results should be better understood, and consequently trusted.

The use of these spreadsheet models could allow for estimates of carbon storage for timberland ownerships within states. Using growth and yield information for different forest types, productivity classes, etc., much of which might be obtained form geographic information system data on larger private ownerships, carbon storage levels might be predicted for different land management prescriptions. Using this type of information, planners and policymakers should be able to assign some carbon sequestering value to forest lands.

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VI. WOOD PRODUCT PATHWAY: RELATION TO CARBON STORAGE IN THE FOREST AND IN THE ECONOMY

The Product Pathway includes the ways in which forest products harvested and used affect storage of that carbon in buildings and other forms, and the recycling and disposal of wood products. It is difficult to understand the forest's potential contributions to carbon storage without understanding the product path, and yet the product path introduces new complexities and uncertainties of its own.

This chapter attempts to outline these issues. Its aim not to propose specific policies or programs, but to outline the factual issues that need to be confronted in order to make sound policies. Because of differing policies, supply and demand situations, and costs, policy assessment for any individual state would require a great deal of site-specific research.

A. THE PRODUCT PATHWAY

Three distinct product pathways affect the standing stock of wood in the forest, the volumes in use in the economy, and potential disposal pathways:

-- Lumber and solid wood products

-- Pulp and paper

-- Energy

Each pathway has different carbon storage implications. The mix of uses and the specific pathways for further utilization vary markedly from area to area, by product, and by industry. A considerable body of research has initially explored the complexities (Cannell, 1995; Heath and Birdsey, 1995; Heath, Birdsey, Row, and Plantinga, 1996; Plantinga and Birdsey, 1993;

Chapter Outline

A. The Product Pathway

B. Key Trends and Relationships

C. The Energy Factor

D. Utilization and Carbon Storage in the Forest

E. Carbon Storage Accounting

F. Some Tentative Conclusions and Implications

G. Summary

H. References

Rineholt, 1996; and Row and Phelps, 1996).

A simplified schematic of the product pathway is shown in Fig. 6.1. In this depiction, the pathway includes the harvesting function and proceeds into products, a household/business sector in which the stocks of products are held during use or recycling, and a disposal sector. At each stage, complex interrelationships exist with other sectors and regions. Wood products, after being converted to products in and near the region, may be shipped overseas or to other parts of North America. For example, a substantial log trade in softwood and hardwood logs flourishes, carrying logs northward from the northerly states to Canada. Canadian buyers purchase large amounts of lumber here for re-export to the rest of the world, making Canada the U.S.'s largest export customer for hardwood lumber. There is considerable interstate trade in recycled paper, mill residuals, land clearing wood, and urban woodwaste.

Further, the Northeast is a major net importer of lumber, structural panels, and paper products. Its utilization pathway includes the use of these products in long-lived structures and products. So, the northeast is a carbon sink as a product user, for wood produced elsewhere. Also, Eastern Canada is a major source of the region’s newsprint. So the usage of wood products by the region's consumers includes wood-based products from many different sources. The disposal of wood products after use is changing rapidly, and the pathways involved vary from state to state.

The economy includes pools or stocks of wood/paper products that fall into three general categories:

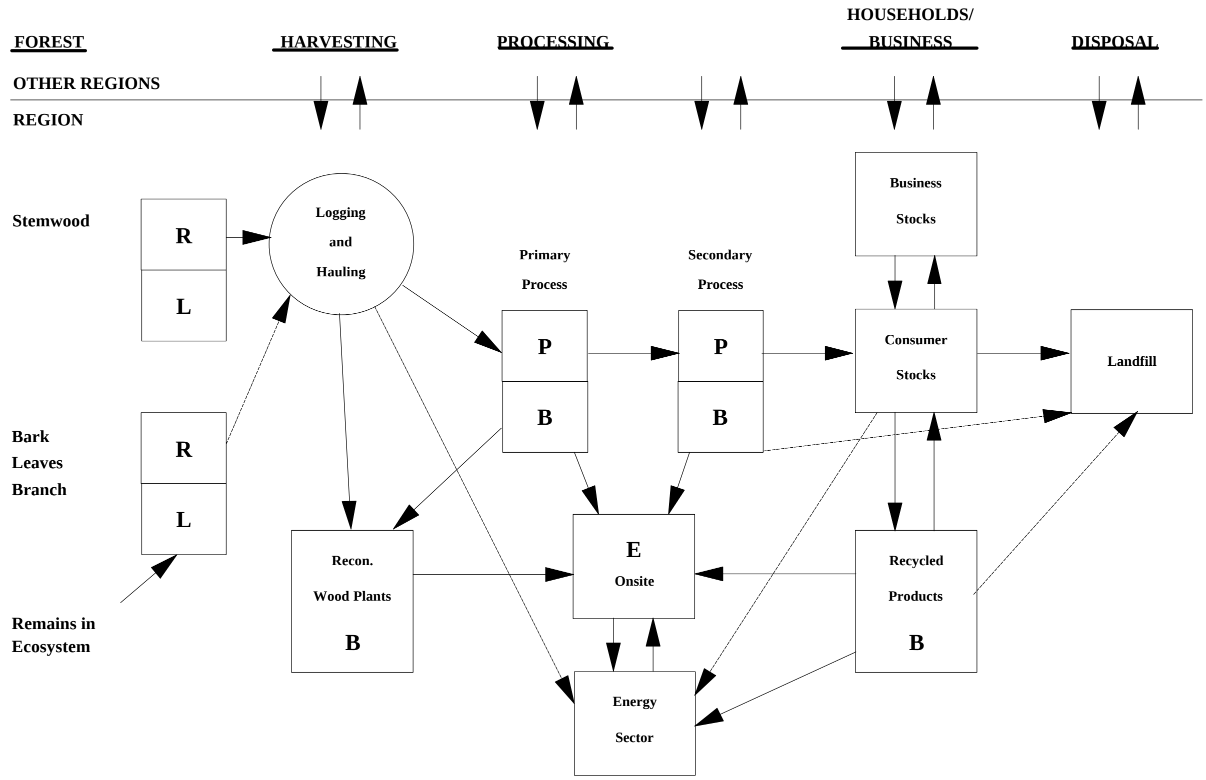
-- High turnover pools	Consumed within one year or less
-- Moderate turnover pools	Consumed/disposed with one to ten years
-- Low turnover pools	Lasting ten years or more

The implications for carbon storage vary between these categories, as do the policies that might affect their size. Over time, stored carbon may move from one pool to another, or be returned to the atmosphere, as, for example, when a furniture set is disposed of by burning.

Figure 6.1

PRODUCT PATHWAY: SCHEMATIC

R = REMOVED L = LEFT B = BY-PRODUCT P = PRODUCT E = ENERGY



Associated with each cell is:

1. An energy input to drive the process.
2. A "yield" split between wood becoming product vs. by-product (P vs. B in boxes).
3. A set of options for the fate of the by-products.
4. A "residence time" for the average time wood spends in that cell (= #/turnover).
5. A **stock** of wood present, and/or a **flow** into and out of the cell.
6. A current carbon emission.
7. A set of technical options for changing the stocks or flows.
8. Possible policies for affecting use of the technical options in (7).
9. An import/export balance relative to the region being considered.
10. One or more nonwood substitutes with different carbon and energy intensities.

High turnover pools include such items as firewood, burned once in a season, or newsprint, which typically spends more time in inventories at a newspaper than in a home while the paper is being read.

Moderate turnover pools might include items such as low-end furniture, pallets, or other products. Taking pallets as an example, there are hundreds of millions of pallets in use; they may last for one or more years. A large pallet recycling industry exists, but many are simply disposed of after a few uses. The pallet industry accounts for a significant percentage of all the hardwood lumber used in the U.S. each year.

Low turnover pools include decks, bridges, homes, fine furniture, industrial and commercial structures, and similar applications. The durability of residential structures is not well characterized in detail, but may be assumed to equal or exceed fifty years on average, based on limited estimates available on demolitions. Wood or paper sealed in landfills is considered a low turnover pool.

Tracing the flows of products through the economy on a life-cycle basis is the task of "Life-Cycle Analysis" (LCA). The extraordinary complexity of such analysis is indicated by the papers by Yaros and Denison (1997) in a recent National Research Council bulletin, who consider the paper sector. A considerable amount of work has been done on paper and wood flows to waste sites and to recycling outlets in the context of such analysis.

Analysts have found considerable variation in available estimates of the net energy content of wood products (Richter, 1998). An illustrative comparison of the global warming impact of alternative window and door systems was provided by Richter (1998). His analysis ranked alternate materials as follows: (high to low)

Aluminum

PVC

Steel

Wood-Aluminum

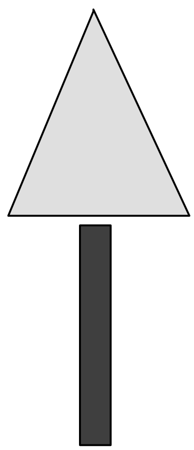
Wood

Another comparison prepared by Richter for utility poles showed a similar picture. Interestingly, for hazardous waste generation wood was not the lowest in all respects.

The possible fate of a single tree can illustrate the complexity of the product pathway.

Figure 6.2

Product Path
Fate of a Single Tree (Schematic)



	Allocation by Tons
Top, branches, unmerchantable portions	50%
Merchantable Stem: Bark	4%
Lumber	25%
Sawdust, shavings, trims --> inplant energy	6%
Chips to papermill	15%

Note: Percentages are illustrative and vary widely with species

The tree illustrated in Fig. 6.2 may be termed a "sawlog" tree, but it enters the product pathway in a complex way. Roughly half its weight is in leaves and branches and unmerchantable material. This may remain in the forest as a short turnover forest floor carbon pool, or be removed for energy. The merchantable stem may be divided between the portion that emerges from the sawmill as lumber, the portion going to a pulpmill as chips, and the sawdust, planer shavings, and trims that are burned onsite in a boiler for power. The bark, an appreciable tonnage of material in the aggregate, may be burned for energy or milled and bagged for the landscape bark market. Many sawmills and board plants are (or can be) essentially self-sufficient in energy based on their own residuals.

So, it is unusual for a single tree to enter the product pathway at only one point. Cases such as wholetree chipping for energy are the exception. In dedicated energy plantations, of

course, this would be the rule. In the case of multiproduct plantations, the wood produced from a single tree would enter a number of product pathways, in ways that might change as markets change over time. In most forest stands, the different species of trees and individual stems of differing quality would likely go into different kinds of wood products.

B. KEY TRENDS AND RELATIONSHIPS

A number of trends in the wood products sector are changing the relationships that control carbon flows in the region's wood product pathway. These changes are driven, in turn, by complex changes in world wood product supplies and utilization technologies.

Pathways involving primary mill residuals and disposal of products involve immense quantities of material. On a tonnage basis, wood is one of the most heavily utilized materials in the economy, second only to sand and gravel. The estimated byproduct weight for regional primary wood plants (e.g., sawmills, papermills) totaled 20 million tons per year in the early 1990’s:

Used For	Million Dry Tons, 1993
Fiber Products	4.9
Fuel	5.0
Other	6.9
Unused	3.0
Total	19.8

Source: Powell, et al., 1993, p. 112.

Nationally, the additional potential for recovery of paper and wood from waste streams has been estimated at some 67 million metric tons. Prorating (simplistically) by population, this would mean some 16-18 million metric tons per year of potential fiber recovery in the northeast.

How this fiber is being used now has significant C storage implications, and changes in its disposition would also have implications.

Utilization Standards Are Changing

In local areas of the most extreme fiber shortages, some sawmills in the region can now use trees as small as 4" in diameter coming from commercial thinnings in plantations. In Northern Maine, trees as small as 5-6" at the butt end are going to sawmills, where they are used for lumber. Roughly 40%-50% of the volume of these trees then become chips for papermills. Utilization as tight as this is not common elsewhere in the Northeast, however.

Product Mixes are Changing -- Shifting to Building Products

The Northeast is seeing a significant increase in conversion of low-grade wood to panel products. Under past markets, this wood would have been used for fuelwood if anything, and would likely have remained standing in the forest. In some of these areas, even pulpwood markets were meager.

In West Virginia and nearby areas, several OSB (oriented strandboard) plants have been built, which are producing products primarily used for construction. In Pennsylvania, there are now two mills producing medium density fiberboard, largely for furniture and industrial uses; another has been announced. In Lackawanna, New York, a new plant is under construction to use urban wood waste for particleboard. The net effect of such plants will depend on the previous fate of the raw material. Was it landfilled, or burned? Key traits of this plant are in the box.

Operating Data, Canfibre MDF Plant
Lackawanna, New York

Capacity:	70 MM sq. ft./yr.
Wood Consumption:	120 to140,000 tons/yr. wastewood
Source:	Industrial, commercial and institutional waste
Binder:	PF resin (low formaldehyde emission)
Development Incentives:	$87 million Econ. Devel. Board Econ. Devel. Zone -- 2.0 cents electricity (vs. 4.7 cents)

Trade Flows Are Changing

The entire region is exporting high grades of hardwood veneer and sawlogs to other countries. This business fluctuates depending on business cycles in the purchasing regions. Over time, there has been a trend toward greater exporting of lumber or semi-finished products as well. Thus, in response to market forces, a significant shift in the region's product pathway are under way. Difficulties this creates for accounting are noted below.

Paper Recycling is in Transition

The paper recycling industry has been through a number of cycles and its long-term future in the region is difficult to see. A number of recycling plants built in recent years are in financial difficulties, and the high cost of recycled fiber has caused some existing plants to close down. It seems likely that the paper industry will be about to outbid other users for recycled furnish, so that there may be further contraction in existing industries using recycled furnish, such as egg cartons and roofing materials.

Many observers feel that the region's recycle rate is nearing its practical limits, but this is always difficult to judge (Finchem, 1998). While paper recycling maintains fiber in the product pathway, and hence continues the sequestration of the carbon, the processing of recycled paper does not bring with it an energy credit as is true for fresh wood. It is not clear if existing analyses of the recycling option include this effect or not. Experts suggest that wood fibers can be recycled up to seven times before they suffer so much processing damage as to be unrecoverable for paper again. Recycled fiber is not a cheap source of paper furnish. At the highest prices reached in recent years, recycled was in fact the most costly furnish for northeastern mills, and a ton of wastepaper delivered to a mill cost more than the equivalent volume of pulpwood. Recycled fiber prices have been volatile, and it is difficult to foresee their future course.

The effect of recycling on the forest itself is much discussed in the modeling efforts on this topic. Some modelers conclude that the effect of recycling is to leave wood standing in the forest, thereby boosting C retention there. Based on production practices in some regions this may be true, but in other regions the picture is more complex. Fiber mixes for pulp mills vary by state. In some mills, large amounts of recycled fiber are used, in others very little. In some mills, recycled fiber replaces hardwood pulp, which would come from local hardwood stands or even from imported pulp. In most areas of the Northeast, sawmill chips are important sources of pulpwood. It is not clear that replacing such chips with recycled furnish saves any trees, however.

Paper grades most commonly recycled are newsprint and old corrugated cartons. These grades are not produced in the Northeast in any abundance. Mills recycling such grades within the region would probably sell their output within the region as well. The result would be the displacement of newsprint from Canada or the U.S. South, or of corrugated products from the South.

It is difficult to generalize on how added recycling would affect fiber mixes without area-specific information on fiber mixes and costs. The results will differ from grade to grade. In the

case of deinked pulp (DIP) mills, the products may be sold into a commodity market with little ability to track its downstream uses any farther. So, on a state by state basis, determining how recycling would affect the state's forest resource, its energy situation, and carbon storage within the region is very difficult. It should not be done by interpolation from national modeling exercises.

Complicated Market Responses Occur

A number of modeling exercises have examined various carbon based scenarios of the product pathway for the future, together with management scenarios. One result is that large programs of tree planting or increases in recycling could reduce prices of wood in the future compared to base case assumptions, thereby having feedback effects on private investment in planting, on wood utilization mixes, and on interregional trade flows. Further, a large acceleration in recycling would reduce consumption of virgin fiber, with significant negative effects on stumpage prices in some regions.

End Users Do Not Choose Materials on the Basis of Carbon and Energy Intensity

End users make materials choices between arrays of alternatives that meet their needs. Grocery stores choose between paper and plastic bags, usually on the basis of cost. Builders and building designers select materials on the basis of a number of factors, but initial installed cost and life cycle costs are important considerations. None of the key considerations are much affected by a products C or E intensity. So, while opportunities to store carbon or save energy by influencing materials choices may appear to be significant, they may be difficult to implement in practice. Further, policy instruments available to state governments may not be well suited to the task. Having a better understanding of how materials are selected would be useful to policymakers.

C. THE ENERGY SECTOR

The energy sector relates to the wood product pathway in a number of complex ways (Box). The relationships depend on local economic and energy policies, as well as on solid waste disposal costs and policies. The issues may differ depending on whether changing fuel mixes in existing plants are being considered (e.g., co-firing), or whether new plants using wood are being examined. At present, utility re-structuring casts doubt on the future of much wood-based capacity, even as interest seems to be increasing in co-firing (Comer, Gray, and Packer, 1998).

Most experts agree that replacing fossil fuels with biomass yields net carbon emission reductions. An IEA study concluded that wood-fired electricity would emit "20% or less" of the Greenhouse gas emissions from fossil fuels. The saving was equivalent to 5 tons per hectare in Europe and 6.5 tons in the U.S. The study accounted for a bewildering variety of variables, indicating the extreme complexity of this kind of analysis (IEA, 1994).

Wood Product Pathway and Energy Sector: Examples

Harvesting Sector	Sells tops/residues to energy plants Specialized WTC contractors Land clearing chips to energy plants
Sawmills	Sell wastes to energy plants Self-generation
Pulpmills	Outside power sales to grid
Disposal Sector	Waste to energy plants
Secondary Processors	Pellets or fireplace logs
Household Sector	Plant wastes to energy plants Purchase fiber (logs, pallets) for fuel

Additional supplies of wood fiber made available by more intensive utilization, or by energy plantations, could simply displace other wood fiber already in use, and not cause a net change in total wood fiber consumption in local energy plants. The possibility of such displacement needs to be considered in evaluating both the commercial feasibility of the proposed project and the carbon accounting outcome.

Also, the energy sector supplies power to the land management, harvesting, wood manufacturing, and recycling processes shown in Fig. 6.1 above. The documentation concerning the energy intensity of these processes is scant to nonexistent. Some of the publications reporting results concerning C storage in products are not explicit about whether process energy requirements are considered.

A second question is what assumptions to make about what alternative energy sources are displaced by an additional quantity of biomass based energy. Or, alternatively, what generation sources would be used if a biomass-based plant is closed? The carbon impacts and environmental implications depend on whether the source displaced is nuclear, hydro, coal, or gas. Ordinarily, it would be reasonable to assume that a new source would displace the highest cost existing source. But deregulation is changing our ability to measure plant level costs.

It is often tempting to look at energy supply contracts as defining the alternative power source. Thus, a utility may switch power sourcing from a nuclear plant to a wood-fired plant (or vice-versa). It seems that the relevant displacement is wood versus nuclear. But this approach ignores the fact that kilowatts are fungible and the output of the nuclear supplier is probably going to find a use somewhere. Only if it can be shown that the output of that nuclear plant permanently declines by an equivalent amount can we say that the wood has displaced nuclear energy. From the region's standpoint, the questions is how to define the with-without generation mix, allowing for the fungibility of kilowatts. If we cannot base judgments about displacement on the power contracts themselves, then how should it be done? This problem requires much

more discussion. It may not need to be answered until much more specific requirements for carbon accounting come into existence.

Comparisons of the carbon and energy content of different fuels have been made. An example is offered in Table 6.1 and Fig. 6.3. Because fossil fuels ultimately come from plant materials, it is not surprising that their C02 emission per unit energy content falls in a fairly narrow range. But the important carbon mitigation opportunity comes from the fact that biomass-based energy is not adding carbon to the atmosphere from stored fossil carbon in the earth.

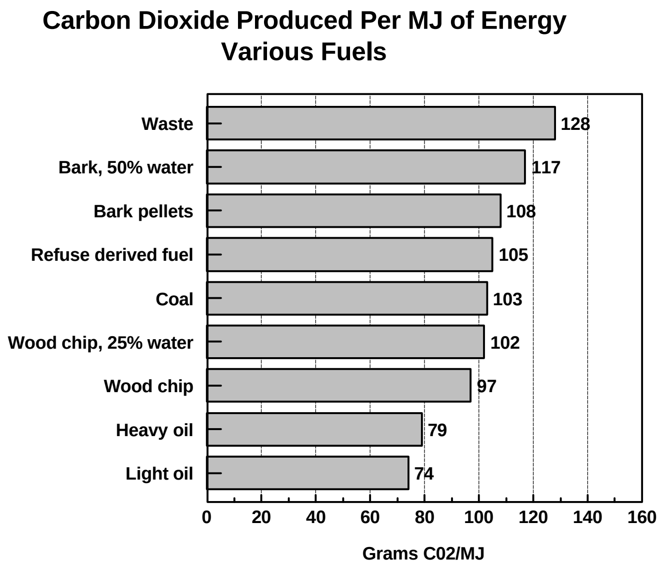
Table 6.1
Fuel Composition and Carbon Dioxide Production for Different Fuels

Fuel	Carbon Weight (%)	Hydrogen Weight (%)	Oxygen Weight (%)	Ash Weight (%)	kg C02/kg	g C02/MJ
Wood, chip	50.0	6.0	43,9		1.85	97
Wood, chip 25% water	37.5	4.5	32.3		1.38	102
Bark, 50% water	25.0-	3.0	21.5	2.3	.92	117
Bark pellets	50.0	5.5	42.0	2.5	1.83	108
Refuse derived fuel	47.0	5.0	38.0	10.0	1.72	105
Waste	32.0	4.0	26.0	37.0	1.17	128
Light oil	86.2	12.7	0.0	0.001	3.16	74
Heavy oil	85.7	11.0	0.0	0.03	3.14	79
Coal	88.0	5.0	5.0	3.7	3.23	103

Source: O. K. Sonju. 1991. The role of combustion of biofuels in reducing the release of carbon dioxide. *In*, C. P. Mitchell. (ed.) *Bioenergy and the Greenhouse Effect*. Narings-och technikutneck-bingsnerket, Stockholm, Sweden. Courtesy of John Zerbe, USDA-FS, FPL.

Note: Ash content of wood is not zero as suggested here.

Figure 6.3



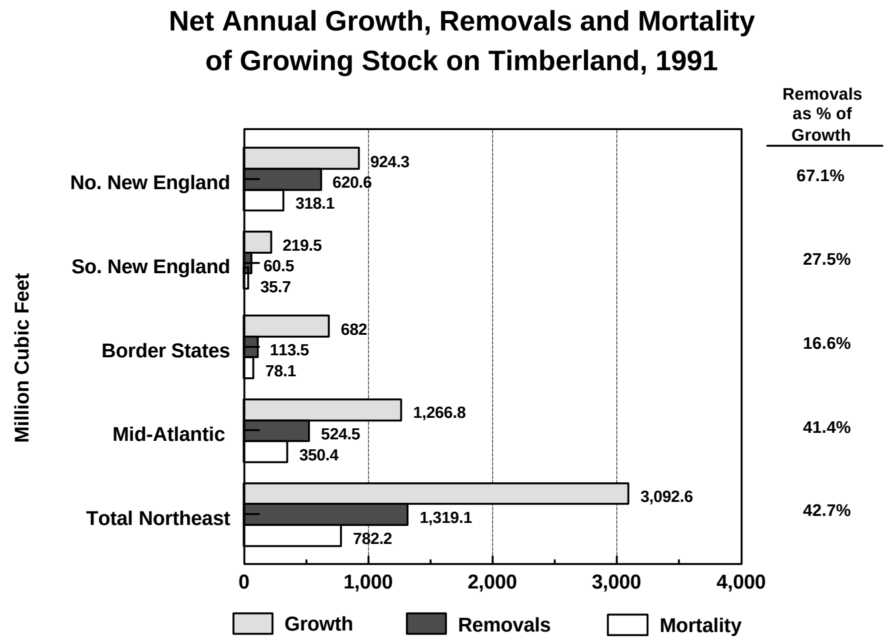
Source: O. K. Sonju, 1991.

Probably the most important lesson to be drawn from this discussion is that the Northeast's wood products/energy pathway is complex and varies within the region. It differs in significant ways from other regions in the country. Relative cost levels, and provisions for "green" or renewable sources, are changing rapidly with deregulation. Efforts to consider product pathway effects in state by state energy and carbon planning must be based on detailed analysis of local situations and not on relationships borrowed from national models.

D. UTILIZATION AND CARBON STORAGE IN THE FOREST

The current harvest rate relative to annual growth helps determine the rate of biomass accumulation in the forest. The proportion of growth immediately entering the product pathway through removals varies from as low as 14% in West Virginia to about 90% in Maine. The relative weight to be given to the product pathway can be judged from a given states' intensity of forest use, shown as removals as percent of growth in Fig. 6.4.

Figure 6.4

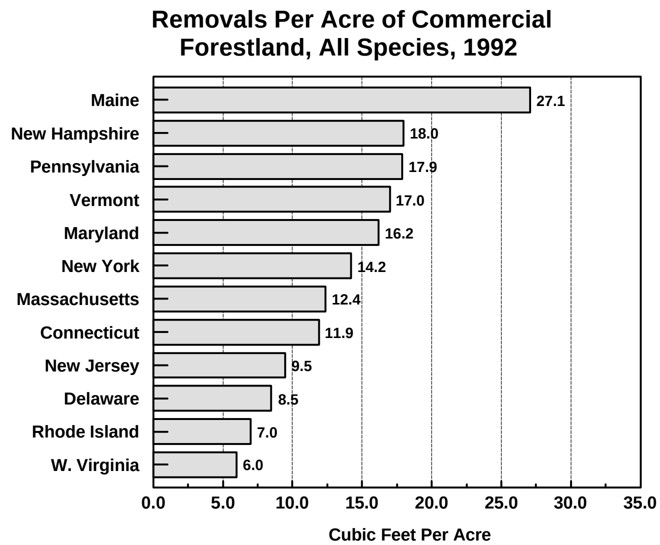


Source: Powell, et al., 1993, p. 108. See Appendix Table A.6.

According to USFS estimates, for the region as a whole, removals amounted to 70% of growth in 1992 (Fig. 6.4 and 6.5).[1] This means that better than two-thirds of the carbon fixed as tree growth was removed from the inventory by cutting, land clearing, or cultural operations. The surplus of growth over removals represents increased storage each year. Not all of the volume removed leaves the forest, only that portion converted onsite into products. Topwood and low value wood remains in the forest, contributing to short-term carbon storage there. Data used for these comparisons is developed partly by estimation for a national overview. The numbers will often not match those published in USFS publications for each state. But they are useful for regional depictions such as this.

[1] Data describing forest inventory volumes of merchantable wood, forest biomass, and carbon are described in the USFS publications cited in other chapters, e.g. Powell, et al., 1993; Birdsey, 1993.

Figure 6.5



Source: Powell, et al., 1993. See Appendix Table A.7.

An estimated five million acres of forest in the Northeast is in units managed for preservation or semi-preservation uses, so the acreage that will accumulate wood undisturbed by harvesting is very small.

E. CARBON STORAGE ACCOUNTING

Under various forms of joint implementation, credit for C storage will have to be assigned to policies, companies, products, and perhaps even subnational governments. This gives rise to "the accounting problem." The description of the utilization pathway outlined here indicates some of the difficulties to be faced in doing carbon accounting for wood in use and for recycling. The key, it seems, is to devise controls to prevent double-counting across products and regions, when trade at all levels of the pathway is so important.

Analyses integrating forest carbon stocks with stocks embodied in the forest product pathway have been conducted, at the level of individual stands (Cannell, 1995) and entire nations (Heath, Birdsey, Row, and Plantinga, 1996; EPA, 1995). These analyses indicate ways to visualize the important relationships. Attempts to duplicate such analyses at state and regional

levels would be extremely data intensive and probably would be warranted only to examine extremely large planting or other sequestration programs, or to analyze very radical policy changes. A substantial regional research effort will probably have to precede implementation of accounts.

A detailed discussion of the problems of C accounting for biomass energy was provided by Marland and Schlamadinger (1995), and Schlamadinger (1998). They reviewed the problems of accounting for flows of fiber, and noted that how the accounts are done could affect the incentives faced by decisionmakers. Also, they noted that net C storage outcomes may vary over time and must be viewed in a longrun context. The data requirements to conduct proper net energy analysis of all of the relevant pathways are imposing. Until some valid database on this point is developed, state planners will have to ignore this consideration unless they are in a position to spend heavily on data gathering and validation.

Harmon, et al. (1996), developed a model, FORPROD, to account for C storage in products and landfills. They applied it to old growth forests in the Pacific Northwest, estimating the fate of the historical harvest 1900-1992. They found that 25% of the wood harvested over that period remained in storage in products and landfills (p. 545). Plantinga and Birdsey (1993) have produced regional estimates of energy, product, and landfill storage using HARVCARB. For more details on HARVCARB, see Row and Phelps, 1996.

HARVCARB runs by Plantinga and Birdsey (1993, Table III) show illustrative disposition patterns of wood (presumably for carbon also) for the entire Northern U.S. These illustrate the proportions of an initial harvested volume as of year zero that will be found in the four categories of product, landfill, emission, and energy usage as time passes. The charts also show how the initial patterns differ by species and by type of timber. In essence, HARVCARB works by tracking all of these product flows and pools over time and summing the results.

There will be numerous claimants to the C storage benefits of plantings, changes in management, or altered wood utilization:

-- Landowners

-- Management Service Companies

-- Wood Processors

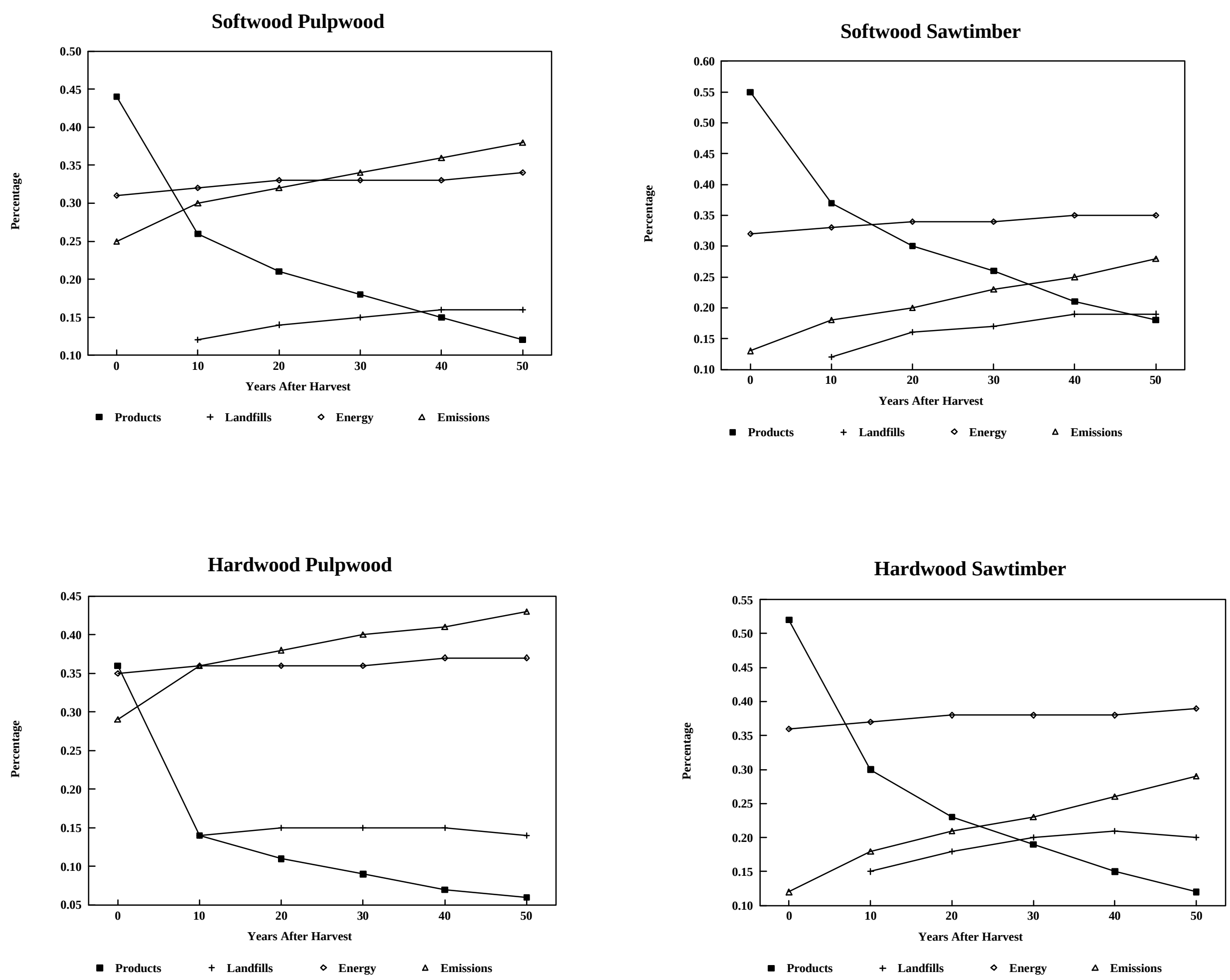
-- Utilities

-- Energy Users

-- Product End Users

A key role for the accounting system will be to devise protections against multiple counting.

Figure 6.6
Disposition Patterns of Wood Products
from HARVCARB, Northern U.S.



F. SOME TENTATIVE CONCLUSIONS AND IMPLICATIONS

Analysts agree that carbon storage in the product pathway should be considered in carbon storage planning, as "the carbon pools and fluxes from the disposition of C in harvested wood are large relative to the U.S. forest ecosystem carbon budget" (Heath, Birdsey, Row, and Plantinga, 1996, p. 276). Yet implementing this concept on a state-by-state or regional basis requires consideration of a formidable bundle of complexities that tend to wash out when the problem is considered on a national scale.

Previous studies have developed the following general conclusions that seem relevant for our purposes:

- Recycling and energy uses have high potential for C storage improvements.
- Many of the steps that would lead to short-term increases in carbon storage in the product pathway have natural limits. The time path for reaching these limits may not be readily defined. Once at equilibrium, further additions to storage cease.
- Defining carbon implications of market changes or policy changes requires detailed knowledge of adjustments occurring in the forest products sector, the energy sector, and the disposal sector.
- Analysts are not satisfied with our knowledge of residence times (turnover rates) of wood fiber in the various short-, medium-, and long-term storage pools in the economy.
- Interpolation from national studies for regional planning purpose is hazardous and must be done with care.
- In assessing carbon impacts of a given policy or market change, care must be taken to consider market-mediated displacements and price effects. If this is not done, offsetting market adjustments may be missed that effectively cancel the carbon storage benefit of the measure being considered.

- Differences in fossil fuel requirements of different energy uses and products need to be considered, though the data for doing this is difficult to find on a regional basis.
- Economic changes in the region's forest products sector that are now occurring are shifting wood fiber into longer-lived pools, but the ultimate endpoints of these trends cannot be foreseen.
- Many problems of C accounting have yet to be solved.

G. SUMMARY

The states hold policy levers that may affect important aspects of the product pathway, especially in relation to energy. So it is important that the current and potential effects of such policies be understood, if only in a general way. As a practical matter, while the product pathway is obviously important, the state of knowledge on these matters is not sufficiently well-developed to provide detailed operational guidance to state-level planners at this time, except for the simplest and most obvious cases. Further, it may be wiser for the moment to leave product path accounting for carbon stocks and flows to a national level of planning, where many of the complexities can be better handled and where the complexities introduced by interstate movements of fiber, energy, products, and disposal products will cancel out.

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VII. STATE POLICY OPTIONS

This chapter provides a terse overview of policy options related to forests and wood use for consideration in State carbon planning. Its purpose is to provide a menu for consideration and adaptation to the situation and needs of individual states. It is intended to serve as a basis for conference discussion and as a checklist for use by planners and policy analysts. A valuable overview of state climate change planning is in Mulholland (1998).

The relevant programs are described in a number of publications. No useful purpose would be served by duplicating that material here. An outline is in Canham (1998). Additionally, in the 1980's, many states prepared State Forest Plans that reviewed program activity and issues at that time. State and federal forestry and conservation agency annual reports and other documents provide current information on program activities, details, and funding levels.

Carbon storage has been given a significant forest policy role in U.S. discussions about long-term sustainability on the international front. In the Criteria and Indicators devised under the Santiago Declaration (1995), several indicators related to carbon were adopted (Box). State level plans for tracking these indicators and developing programs to contribute to sequestration goals will be important in helping the U.S. meet its commitments under such agreements. The future status of the Kyoto Protocol, as to U.S. participation, is uncertain at present. But the Protocol has fostered a good deal of work on methods for carbon accounting. Working groups have been assigned the task of working out details. The Protocol did not provide for comprehensive credits for all wood and forest-related storage. Instead, it emphasized credits for verifiable activities that result from actual actions and not ongoing circumstances, and sought an

Chapter Outline

A. Criteria for Policy
B. Plantation Establishment
C. Management of Existing Stands
D. Product Pathway: Policy Opportunities
E. Overview and Themes
F. References

approach that would be equitable (Dept. of State, 1998; Marland and Schlamadinger, 1998; IGBP Terr. Carbon Work Group, 1998).

Santiago Declaration Criteria

Criterion 5 -- Maintenance of forest contribution to global carbon cycles

Indicator 26: Total forest ecosystem biomass and carbon pool, and if appropriate, by forest type, age class, and successional stage.

Indicator 27: Contribution of forest ecosystem biomass to the total global budget, including absorption and release of carbon.

Indicator 28: Contribution of forest products to the global carbon budget.

Source: Sec. 6 of USFS, 1997.

A. CRITERIA FOR POLICY

In thinking about forest polices to support carbon storage, a variety of criteria need to be considered (Box). Unfortunately, there is not a full body of agreed upon social science research and evaluation on which to draw to make judgments on these matters. Instead, local experience and judgment of people familiar with the programs must be used. Essentially, selecting a mix of policies to support forest carbon storage in a given state would require a mini-research project to develop enough practical information to support program recommendations.

We assume that --

a) Carbon policies will link to existing programs.

b) Such policies will foster forest productivity and can be designed to meet environmental quality goals.

Criteria for Evaluating Forest Policy Proposals

Administrative Feasibility
- Number of participants required to cooperate
- Current Program in place
- Modification/extension of existing Program
- Staffing considerations

Compliance Cost

Equity Considerations

Environmental Impacts

Multiple Benefits in Addition to C Storage

Cost Per Unit C Sequestered
- Gross
- Net of other priced values

Pool Augmented: Short-term, Medium-term, Long-term

Lead Time for Achieving Effect

Political Feasibility

U.S. Commitments (Montreal, Santiago) for Forest Sustainability

B. PLANTATION ESTABLISHMENT

General

One option for some states is to establish additional acreages of plantings that will be managed in some manner that might maximize contribution to long-term carbon storage. Ways to provide incentives for increasing the area of such plantations are worth considering. This is an extremely complex subject, which can only be sketched here. Existing programs vary considerably from state to state. In several states, past programs have resulted in the creation of significant resources of planted stands. According to the U.S. Forest Service (1997, p. 3-6),

there are some 540,000 acres of planted stands in the Northeast. This is only two percent of the total national area of planted stands.

In most states, a basic set of programs is already in place, aimed at objectives other than carbon storage. In the Chesapeake Basin states, for example, several programs are under way to establish 2,100 miles of streamside tree plantings to filter sediment and other materials from the runoff from adjacent farmland. The purpose is to improve water quality in Chesapeake Bay. Being established on current farmland and often in very moist soils, tree growth rates might well be very high. Such programs could be expanded and adapted to the needs of carbon storage. At a minimum, their growth could be considered a C storage benefit in state assessments. Because of their purpose, they are likely to be managed in conservative ways and not clearcut and regenerated periodically.

A key concern is obtaining follow-through. Existing programs are not well designed and administered to ensure that plantations, once established, continue to remain in place over the planned rotations, and receive proper management follow-up to ensure the desired benefits, whether those are wood production, wildlife habitat, water protection, or other. In the past, many of the individual treatments made under cost-share programs in the Northeast have been quite small -- plantings or TSI treatments of 10 acres or less. The state and federal agencies administering the programs have not always been able to maintain records of where these treatments are located. If recordkeeping is not maintained, it is hard to see how accountability can be provided for long-term follow-through.

This has been a significant question in programs of this sort in the Northeast in the past, and takes on added importance in the carbon storage case. Earning -- and deserving -- credit for carbon storage places extreme demands on follow-through and on permanence of arrangements that are claimed to generate given amounts of storage.

Cost-Sharing and Incentive Programs

A number of programs providing cost-sharing for management practices exist. Their names change from time to time. Details of their administrative structure will be omitted here. Some of these programs are administered with the aid of County Committees who decide which specific practices will be eligible for cost-sharing within their counties. These committees may also approve the individual funding requests. So, it is difficult to generalize for the region as a whole concerning what practices are currently cost-shared. These programs are dominated by federal funding. Even with improving federal budget balances, higher funding may not occur.

State /Federal Cooperative Forestry Programs

- EQIP (formerly ACP/FIP)
- Stewardship Incentive Program (SIP)
- Forest Legacy
- Extension and Education
- Urban Forestry Programs

Private Financing/Leases/Contracts

In the South, there are various forms of leases in effect under which a managing partner leases plantation rights from a private owner who retains ownership of the soil. The lessee conducts management and pays the lessor an annual rent plus some stumpage payment at the time of harvesting the timber. Such arrangements originally merged to enable industrial wood buyers to manage land on behalf of absentee landowners. Today, however, at least one consulting firm (James Vardaman & Co.) is undertaking such leases to establish plantations on bare land and manage them to maturity.

In the state of Washington, Fort James Co. is leasing farmlands in the Columbia Basin to grow short-rotation (7-8 years) cottonwood for furnish for a paper mill (Shell, 1998). In Minnesota, Northern States Power is contracting with a group of farmers for production of alfalfa as a fuelstock. These leases could be studied for their applicability to Northeastern situations.

Leases of land of this kind are extremely rare, if they occur at all, in the Northeast. Their likely applicability would be in cases where a short-rotation plantation was to be grown for use by the lessee in one of its own facilities.

Land Acquisition/Management of State Lands

In many Northeastern states, areas of abandoned farmland were acquired, and in some instances planted to conifers. The kinds of land acquired were usually cutover and often burned or otherwise abused. It would be a reasonable guess that very few unplanted acres remain on such lands today. To the extent that they do, they are often managed to maintain grass or shrub vegetation. There may yet exist, however, specific opportunities to acquire derelict land such as mined areas, and establish tree plantations that will store carbon. Each parcel may be small, but in the aggregate over a large state the old gravel pits and other unused parcels could amount to something. Revegetation requirements could be reviewed to see if C storage gains are possible.

In some areas, mineral leases occur on public lands. An example would be lands cleared to install oil or gas wells and related roads. When the wells are exhausted, such lands could be revegetated in ways that maximize carbon storage. This would be costly in view of the scattered nature of these areas and their unusual shapes. But revegetation would usually be in order for environmental and habitat reasons.

Utility Programs -- Joint Implementation/C Offset

Utilities have the potential to become major facilitators of carbon storage in planted forests. They may have a motivation to obtain carbon offset credits, and they have the need for

fuels. They have the administrative and financial capacity to organize fuel procurement and contracting procedures to bring plantations into being if they have the need. A number of states are in various stages of developing Green Power provisions to take effect as utility deregulation proceeds. In at least some states, such provisions may lead to financial advantages for power defined as "green," or at least facilitate the development of a niche market for such power. It may be too soon to clearly assess the potential offered by such programs. But the ability to provide "green" power offers a potentially significant added benefit to wood-based energy.

Tax Incentives

Tax incentives include a variety of federal and state provisions related to investments in and income from forestland. A complex literature has arisen around these topics. Much of it is informally issued in the "grey literature" and hard to locate, other than by interviewing specialists. It is extremely difficult to determine to what extent these various provisions actually succeed in retaining land in forest use, or in influencing the degree of management intensity or the specific practices used. Our advice for the moment would be to set tax policies aside as a policy tool for carbon storage. At some point in time, after more promising and more targeted policies have been tested and have made their contribution, some look at tax policies may be warranted.

C. MANAGEMENT OF EXISTING STANDS

Various policy tools could be used to influence management of existing stands as well as to promote planting of bare land. The actual practices that could be applied are mentioned above.

Forest Practices Regulations

Several of the northeastern states have comprehensive Forest Practices Acts. Others regulate particular forest practices by means of water quality rules or wetlands acts. Designing such regulations is technically difficult.

It would be reasonable to assess such programs to identify any likely carbon storage implications, but it would not seem realistic to rely to any extent on such regulations to achieve carbon storage goals by significantly changing management practices. To the extent that they may have an effect at present, measuring that effect should be considered.

In a variety of ways, regulations affecting forest practices may have minor effects on carbon pools and flows at the margin. An example might be requirements limiting or banning cutting in forested wetlands, limiting volume removals in streamside management zones, or requiring prompt reforestation (Irland, 1996; Ellefson, Cheng, and Moulton, 1996). Actually designing such regulations to affect carbon storage is probably a low policy priority compared to traditional goals such as protecting timber supply, habitat, and water quality. Regulations requiring revegetation of areas disturbed in mining or other land uses could be examined.

Cost -Sharing

Cost-sharing programs can also be used to fund treatments in existing stands as well as plantations. Often such treatments are designed to improve quality of residual stands, or to shift species composition toward more valuable trees. If a set of practices were identified with clear carbon storage benefits, it could be identified for cost-sharing and promotion under one of the existing programs.

Riparian Areas

Existing water quality laws already provide for the retention of forest stands adjacent to waterways to protect water quality. Policies that would augment such protections using wider buffers or no-cut buffers could reasonably be expected to produce long-term carbon storage

benefits. Such policies might have the most likely application on publicly owned forest or game lands.

Landscape Management Areas

The forestry field is just beginning to consider methods of implementing ecosystem management plans in multi-owner landscapes consisting of many intermixed small and large landowners. If means could be found to effectively implement such plans, presumably they could lead to retention of more acres of mature forest than otherwise, and hence to increased carbon storage in the forest ecosystem (Sample, 1994; Williams and Ellefson, 1997).

One proposed approach is to devise policy incentives for landowners in selected areas to develop “Landscape Management Areas.” Within these areas, targeted tax and cost-share incentives would be provided for owners who follow coordinated plans to provide enhanced riparian area protection and to hold stands to longer rotations.

This approach is only a very general concept at present... it has not been done anywhere. The motivations for doing it would lie in other areas than carbon storage, but some feasibility study of a pilot test might be worth considering

Rental of “Long Rotation Rights”

A concept that may deserve consideration is to devise a way to essentially pay landowners to grow trees to longer rotations than they normally would. This concept might have merit on the grounds of aesthetic and habitat values as well as carbon storage. A key issue is identifying revenue sources and fair rentals for such management.

D. PRODUCT PATHWAY: POLICY OPPORTUNITIES

The first step of each state would be to examine its policies regarding forest products purchasing, recycling, disposal, and other matters and attempt to gain an understanding of how

those policies affect carbon storage. If those results are uncertain, then more research may be required. If the results are unsatisfactory, then policy changes may be indicated. It is not a straightforward matter, however, to judge how carbon storage considerations should be weighed in relation to competing objectives of such policies. Again, the most important point is to understand their effects clearly.

Land Clearing Regulations

In some local areas at times of vigorous suburban development, land clearing may entail larger removal volumes than harvesting for wood products. In some areas, onsite burial was practiced, creating a fairly long-lived carbon sink. In some states, onsite burial is no longer permitted, resulting in the woodfiber moving to facilities where it is converted to bark mulch or used for energy.

Recycling Incentives and Practices

From a carbon storage viewpoint, there might be a good deal to be said for burying wood and paper wastes in sealed landfills. Yet this approach has its own costs and disadvantages. States have a variety of policies designed to affect recycling choices at the margin.

Biomass Energy Policies

A series of public policies based on PURPA induced construction of major wood-based electricity plants in several states in the region, notably Maine and New Hampshire. In the wake of declines in oil prices and the initial steps toward utility restructuring, wood-fired electric generation has been declining. This market outlet for various categories of woodwaste served the region well as a destination for low-grade materials diverted from landfills, and probably resulted in some substitution for fossil fuels. Assessing how changing energy uses affect these product flows will be important.

As utility restructuring continues, some states are requiring that a certain amount of renewable energy remain in utility power mixes so that renewables are not entirely removed from the region's generation system. These provisions are in very early stages of implementation. Judging their likely effect will have to be done on a state-by-state basis.

Public Procurement Practices

State and local agency procurement practices could be reviewed to ensure that they do not embody unneeded restrictions that would hamper the use of recycled solid wood products. Many states already maintain purchasing policies that foster the use of recycled paper products. Such policies at a minimum will stretch the residence time of paper in the economy.

Solid Waste Disposal Regulations and Practices

Solid waste management practices can affect the utilization of newsprint and wastewood. Increasingly, waste facilities are turning aside wood and related products. This can create a market situation in which a generator of woodwaste may pay to have it removed, and a hauler can be paid at the other end by a wood user.

Regulations on Use of Wood Products

As an example, there is debate over the use and disposal of treated wood products. Proper treatment and installation of wood in decks or other structures may extend the life of the product two-fold, enhancing its carbon storage role as well. When wood treatment is restricted, substitutes may be used. Some of these may include composites of wastewood and recycled plastics, which offer other environmental benefits. In hotly debated areas like this, it may be difficult for regulatory agencies or consumers to obtain information they can rely on as objective. Much if not most of the treated wood in the Northeast comes from other regions. Systems are in development for the proper disposal of treated wastewood, usually by incineration.

Information Policies

An area in which public agencies could make a marked contribution is simply by providing objective information to consumers, local governments, special districts, and firms that must make decisions that might affect the wood products pathway from an environmental and carbon storage standpoint. As an example, business and consumers might benefit from clear, understandable information on the carbon implications of materials choices.

Economic Development Policies

States manage a host of economic development programs aimed at job creation, economic diversification, or economic adjustment. Economic development and forestry agencies could seek out ways to use these policies to support growth of firms whose operations support C-storage goals.

Environmental Certification

Interest is growing in using environmental ("green") certifications as a means of informing consumers about how their wood products are grown, harvested, and processed (Viana et al., eds., 1996). There may be opportunities to broaden the current focus of environmental certification to develop methods of rating how products and services contribute to C-storage goals.

E. OVERVIEW AND THEMES

A number of broad themes for policy analysis, planning, and implementation emerge from these points.

Connection to Other Fields of Policy

How forests and their products fit into C storage planning will be profoundly affected by decisions taken in other, related fields of policy, such as:

-- farm policy will control the acreage released from cropping, and may dictate how it can be used;

-- energy policies may determine the market for and price of woodfuel feedstock;

-- waste disposal policies may control the fate of wood and paper wasteflows.

In the northeast, a major role for C cycle assessment and planning will be to ensure that decisions in these other areas are made with a sound understanding of their impacts.

Assessment: Understand the Current Situation

Assessment will be a key part of Carbon planning. That is, gaining a sufficiently clear, accurate, and nuanced understanding of exactly how forests and forest products within a given state are contributing, or failing to contribute, to carbon storage goals. Further, understanding how current conditions are being affected by existing policies is difficult and often contentious. The Assessment process merges with the identification of research needs, in those instances where readily available information does not support sufficiently firm conclusions to support immediate planning decisions or precise characterizations of the situation.

Joint Benefit Analysis

Many forestry practices make sense on financial grounds based on wood growing benefits. Others are justified by nontimber benefits such as habitat retention or water quality protection. Managing programs aimed at such benefits will produce incidental carbon storage benefits, possibly at no net cost. If a program is designed entirely around carbon storage, however, its priorities and mode of operation could be totally different. The question of accounting for the value of joint products is a difficult one, but will need to be addressed in the long run.

Monitoring Change

Carbon planning related to forests can take advantage of existing data that is available at varying degrees of detail, precision, and timeliness. By taking thorough inventory of such information, an initial picture can often be pieced together. Further, informed individuals in State forestry agencies and in academia and the private sector can offer judgments and opinions that may be helpful. For many planning purposes, such sources may provide a general framework for monitoring current conditions and watching how they are changing. The inventory of existing information is likely to suggest ways to improve monitoring by tracking key trends more carefully.

Report Card

A straightforward and understandable way to summarize results of periodic monitoring can be in the form of a Report Card, noting numerically and qualitatively how a state is progressing in relation to relevant measures of carbon storage or intensity in its forests, forest products industry, and recycling and reuse policies and accomplishments.

Assess New Policy: "C Impact Statements"

As an ongoing planning function, the preparation of C Impact Statements" for selected policy proposals would serve a valuable educational function and could be used on a selective basis in efforts to influence policy decisions.

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VIII. GLOSSARY

Annual Mortality: The average annual volume of sound wood in growing stock trees that died from natural causes during the period between inventories.

Annual Removals: The net volume of growing stock trees removed from the inventory during a specified year by harvesting, cultural operations such as timber stand improvement, or land clearing.

Growing Stock: A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull trees are excluded. When associated with volume, includes only trees 5.0 inches d.b.h. and larger.

Net Annual Growth: The average annual net increase in the volume of trees during the period between inventories. Components include the increment in net volume of trees at the beginning of the specific year surviving to its end, plus the net volume of trees reaching the minimum size class during the year, minus the volume of trees that died during the year, and minus the net volume of trees that became cull trees during the year.

Poletimber Trees: Live trees at least 5.0 inches in d.b.h., but smaller than sawtimber trees.

Productivity Class: A classification of forest land in terms of potential annual cubic-foot volume growth per acre at culmination of mean annual increment in fully stocked natural stands.

Sawtimber Trees; Live trees containing at least one 12-foot saw log or two noncontiguous 8-foot logs, and meeting regional specifications for freedom from defect. Softwood trees must be at least 9.0 inches d.b.h., and hardwood trees must be at least 11.0 inches d.b.h.

Timberland: Forest land that is producing or is capable of producing crops of industrial wood, and that is not withdrawn from timber utilization by statute or administrative regulation. (Note: Areas qualifying as timberland are capable of producing more than 20 cubic feet per acre per year of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.)

IX. APPENDIX TABLES

Appendix Table A.1. Acreage, Total Tree Volume, and Total Tree Carbon for Different Size -- Classes of Forest Types in Selected Maine Regions

Appendix Table A.2. Changes in Acreage, Total Tree Volume, and Total Tree Carbon for Different Forest Types in Three Maine Counties for 1971, 1982, and 1995

Appendix Table A.3. Total Tree Carbon for Different Age-Classes of Unmanaged (unm) and Intensively Managed (int) Even-Aged Northern Hardwoods in New England on Sites With Different Productivity (Site Indices)

Appendix Table A.4. Tree Carbon From Thinnings and in Residual Standing Trees for Even-Aged Northern Hardwoods in New England on an Average Site (SI = 60).

Appendix Table A.5. Carbon Levels per Unit for Forest Ecosystems by Component in Regions of the U.S. and for Individual States in the Northeast/ Mid-Atlantic Region (1987)

Appendix Table A.6. Net Annual Growth, Removals and Mortality of Growing Stock on Timberland, 1991 (Thousand cubic feet)

Appendix Table A.7. Removals per Million Acres, All Species

Appendix Table A.1
Acreage, Total Tree Volume, and Total Tree Carbon for Different Size -- Classes of Forest Types in Selected Maine Regions

Species	Size-Class	Acreage (1000 A)	Total Tree Vol. (cu ft/A)	Total Tree Carbon (lb/A)
		Penobscot County, Maine		
White pine/ Red pine	Sawtimber	144.6	4,660	57,276
	Poletimber	43.9	4,021	49,422
	Seedling/Sapling	6.6	1,562	19,192
Spruce/Fir	Sawtimber	216.8	3,610	43,321
	Poletimber	354.4	2,975	35,695
	Seedling/Sapling	126.8	1,562	7,242
Northern Hardwood	Sawtimber	218.1	3,239	60,405
	Poletimber	202.9	2,956	55,137
	Seedling Sapling	157.9	525	9,782
		Casco Bay Region		
White pine/ Red pine	Sawtimber	261.9	5,717	70,256
	Poletimber	59.8	4,778	58,725
	Seedling/Sapling	7.2	2,132	26,202
Spruce/Fir	Sawtimber	0	0	0
	Poletimber	18.3	3,715	44,579
	Seedling/Sapling	6.5	979	11,742
Oak/Pine	Sawtimber	36.1	6,138	89,498
	Poletimber	7.9	2,736	39,891
	Seedling/Sapling	1.3	0	0
Oak/Hickory	Sawtimber	57.4	5,313	99,084
	Poletimber	126.1	2,408	44,911
	Seedling/Sapling	15.4	1,946	36,284
Northern Hardwood	Sawtimber	85.7	4,305	80,288
	Poletimber	241.9	3,394	63,291
	Seedling/Sapling	75.5	610	11,367

Source: Griffith and Alerich, 1996.

Table A.2
Changes in Acreage, Total Tree Volume, and Total Tree Carbon for Different Forest Types in Three Maine Counties for 1971, 1982, and 1995

Species	Inventory Year	Acreage (1000 A)	Total Tree Vol. (cu ft/A)	Total Tree Carbon (lb/A)
		Androscoggin County, ME		
White pine/ Red pine	1971	109.3	3,230	39,700
	1982	90.2	3,807	46,792
	1995	39.0	3,767	46,301
Spruce/Fir	1971	14.7	3,357	40,279
	1982	12.4	2,040	24,479
	1995	-	-	-
Oak/Pine	1971	31.6	2,306	33,619
	1982	4.3	4,173	60,844
	1995	-	-	-
Northern Hardwood	1971	10.7	2,620	48,863
	1982	59.4	1,621	30,237
	1995	90.7	2,768	51,618
		York County, ME		
White pine/ Red pine	1971	213.7	2,904	35,693
	1982	267.3	3,908	48,026
	1995	165.9	5,826	71,595
Spruce/Fir	1971	20.4	3,031	36,379
	1982	8.3	3,276	39,316
	1995	6.2	3,608	43,295
Oak/Pine	1971	71.4	1,962	28,609
	1982	4.2	463	6,755
	1995	8.5	6,410	93,453
Northern Hardwood	1971	36.6	2.326	43,184
	1982	92.1	1,754	32,720
	1995	135.1	3,270	60,976

Table A.2 (cont.)
Changes in Acreage, Total Tree Volume, and Total Tree Carbon for Different Forest Types in Three Maine Counties for 1971, 1982, and 1995

Species	Inventory Year	Acreage (1000 A.)	Total Tree Vol. (cu ft/A.)	Total Tree Carbon (lb/A.)
		Waldo County, ME		
White pine/ Red pine	1971	90.8	2,490	30,605
	1982	52.7	2,642	32,474
	1995	30.3	5,327	65,466
Spruce/Fir	1971	112.3	1,968	23,621
	1982	108.8	2,856	34,274
	1995	136.0	2,732	32,799
Oak/Pine	1971	19.5	1,145	16,688
	1982	-	-	-
	1995	-	-	-
Northern Hardwood	1971	37.4	2,037	37,992
	1982	141.2	2,008	37,453
	1995	94.6	2,063	38,479

Source: Griffith and Alerich, 1996.

Appendix Table A.3
Total Tree Carbon for Different Age-Classes of Unmanaged (unm) and Intensively Managed (int) Even-Aged Northern Hardwoods in New England on Sites With Different Productivity (Site Indices)

	-- Site 50 --		-- Site 60 --		-- Site 70 --	
Mean DBH (in)	(int) Tree Carbon	(unm) Tree Carbon	(int) Tree Carbon	(unm) Tree Carbon	(int) Tree Carbon	(unm) Tree Carbon
	-- 1,000 Pounds of Carbon/A --					
6.0	55.2	51.4	67.3	61.7	78.7	72.7
8.0	80.1	64.1	97.1	76.8	114.3	90.0
10.0	104.6	77.2	125.9	92.2	146.1	106.8
12.0	129.5	90.7	155.4	107.8	181.3	125.5
14.0	154.3	-	184.1	123.8	215.8	142.8
16.0	169.8	-	201.6	125.9	235.0	145.8
18.0	-	-	218.7	-	253.9	-

Appendix Table A.4
Tree Carbon From Thinnings and in Residual Standing Trees for Even-Aged Northern Hardwoods in New England on an Average Site (SI = 60).

Mean DBH (in)	Age (Years)	Cumul. Thinnings Carbon	Standing Trees Carbon	Total Carbon
		-- 1,000 Pounds of Carbon/A --		
4.0	30	-	-	-
6.0	48	10.7	56.6	67.3
8.0	61	49.6	47.6	97.2
10.0	72	49.6	76.3	125.9
12.0	83	74.0	81.4	155.4
14.0	95	103.8	80.3	184.1
16.0	107	103.8	97.7	201.5
18.0	119	135.5	83.2	218.7

Table A.5
Carbon Levels per Unit for Forest Ecosystems by Component in Regions of the U.S. and for Individual States in the Northeast/Mid-Atlantic Region (1987)

(kg of carbon/m^2)

Region	Total	Trees	Soil	Forest Floor	Understory
Southeast	13.9	5.5	7.5	0.6	0.3
South Central	13.0	5.4	6.7	0.6	0.3
North Central/Central	18.3	4.9	11.5	1.7	0.2
Rocky Mountain	14.4	5.4	7.1	1.8	0.1
Pacific Northwest	23.0	5.5	14.7	2.4	0.4
Northeast/Mid-Atlantic	18.5	5.7	11.1	1.5	0.2
Maine	22.3	4.9	15.3	1.9	0.2
New Hampshire	21.3	6.7	12.6	1.9	0.2
Vermont	21.1	6.4	12.8	1.7	0.2
Massachusetts	20.4	6.3	12.1	1.8	0.2
Connecticut	20.1	6.6	11.6	1.7	0.2
Rhode Island	18.5	5.3	11.3	1.7	0.2
New York	17.9	5.2	10.9	1.6	0.2
Pennsylvania	16.5	5.4	9.7	1.2	0.2
New Jersey	15.5	4.5	9.2	1.6	0.2
Maryland	18.5	8.0	8.9	1.4	0.2
Delaware	18.0	7.0	9.3	1.5	0.2
U.S. Total	18.5	5.5	10.3	1.6	0.3

Source: Birdsey, 1992.

Appendix Table A.6
Net Annual Growth, Removals and Mortality of Growing Stock on Timberland, 1991
(Thousand cubic feet)

	Growth	Removals	Mortality	Removals as % of Growth	Mortality as % of Removals
ALL SPECIES					
Maine	513,431	459,878	214,606	89.6%	46.7%
New Hampshire	205,240	85,670	54,972	41.7%	64.2%
Vermont	205,676	75,081	48,490	36.5%	64.6%
No. New England	924,347	620,629	318,068	67.1%	51.2%
Connecticut	61,486	21,059	16,550	34.3%	78.6%
Massachusetts	147,512	36,809	15,622	25.0%	42.4%
Rhode Island	10,487	2,587	3,479	24.7%	134.5%
So. New England	219,485	60,455	35,651	27.5%	59.0%
Delaware	13,504	3,204	4,113	23.7%	128.4%
Maryland	163,292	39,272	27,343	24.1%	69.6%
W. Virginia	505,167	71,060	46,659	14.1%	65.7%
Border States	681,963	113,536	78,115	16.6%	68.8%
New Jersey	51,193	17,646	12,256	34.5%	69.5%
New York	583,822	222,831	161,224	38.2%	72.4%
Pennsylvania	631,742	284,046	176,933	45.0%	62.3%
Mid-Atlantic	1,266,757	524,523	350,413	41.4%	66.8%
Total Northeast	3,092,552	1,319,143	782,247	42.7%	59.3%
SOFTWOODS					
Maine	287,525	306,021	163,188	106.4%	53.3%
New Hampshire	60,481	46,987	35,953	77.7%	76.5%
Vermont	53,277	41,308	18,869	77.5%	45.7%
No. New England	401,283	394,316	218,010	98.3%	55.3%
Connecticut	7,096	3,202	148	45.1%	4.6%
Massachusetts	46,562	11,257	5,749	24.2%	51.1%
Rhode Island	2,441	502	96	20.6%	19.1%
So. New England	56,099	14,961	5,993	26.7%	40.1%
Delaware	2,946	1,201	1,549	40.8%	129.0%
Maryland	28,863	11,372	7,351	39.4%	64.6%
W. Virginia	28,225	4,653	7,968	16.5%	171.2%
Border States	60,034	17,226	16,868	28.7%	97.9%
New Jersey	9,439	1,690	1,498	17.9%	88.6%
New York	117,205	60,482	27,647	51.6%	45.7%
Pennsylvania	69,693	10,825	11,015	15.5%	101.8%
Mid-Atlantic	196,337	72,997	40,160	37.2%	55.0%
Total Northeast	713,754	499,500	281,033	70.0%	56.3%
HARDWOODS					
Maine	225,905	153,857	51,418	68.1%	33.4%
New Hampshire	144,759	38,683	19,018	26.7%	49.2%
Vermont	152,399	33,773	29,620	22.2%	87.7%
No. New England	523,063	226,313	100,056	43.3%	44.2%
Connecticut	54,389	17,857	16,402	32.8%	91.9%
Massachusetts	100,950	25,552	9,873	25.3%	38.6%
Rhode Island	8,046	2,085	3,383	25.9%	162.3%
So. New England	163,385	45,494	29,658	27.8%	65.2%
Delaware	10,558	2,003	2,564	19.0%	128.0%
Maryland	134,429	27,900	19,991	20.8%	71.7%
W. Virginia	476,942	66,407	38,691	13.9%	58.3%
Border States	621,929	96,310	61,246	15.5%	63.6%
New Jersey	41,754	15,956	10,758	38.2%	67.4%
New York	466,617	162,349	133,577	34.8%	82.3%
Pennsylvania	562,049	273,221	165,918	48.6%	60.7%
Mid-Atlantic	1,070,420	451,526	310,253	42.2%	68.7%
Total Northeast	713,754	499,500	281,033	70.0%	56.3%

Source: Powell, et al., 1993, p. 108.

Appendix Table A.7
Removals per Million Acres, All Species

	Acres (M)	Removals (MM cu ft)	Removals cu. ft. per Acre
Maine	16,987	459,878	27.1
New Hampshire	4,760	85,670	18.0
Vermont	4,429	75,081	17.0
No. New England	26,176	620,629	23.7
Connecticut	1,768	21,059	11.9
Massachusetts	2,960	36,809	12.4
Rhode Island	371	2,587	7.0
So. New England	5,099	60,455	11.9
Delaware	376	3,204	8.5
Maryland	2,424	39,272	16.2
W. Virginia	11,916	71,060	6.0
Border States	14,716	113,536	7.7
New Jersey	1,864	17,646	9.5
New York	15,744	222,831	14.2
Pennsylvania	15,850	284,046	17.9
Mid-Atlantic	33,458	524,523	15.7
Total Northeast	79,449	1,319,143	16.6

Source: Powell, et al., 1993.