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Soil Carbon Accounting and Assumptions for Forestry and Forest-Related Land Use Change

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Introduction

Comprehensive, large-scale carbon accounting systems are needed as nations agree to work toward reducing their greenhouse gas (GHG) emissions. However, adopting a standard accounting system is difficult because multiple science and policy uses for such a system help fuel the debate about the nature of an appropriate system. Accounting systems must address all major sources and sinks of GHGs, or more pragmatically, focus on subsets of important sources and sinks and feature transparent, fundamental rules that may be adopted easily by all nations. Here, we review some issues in carbon accounting of a major GHG sink: forest soils, at a national scale. Specifically, we concentrate on how land use change and harvesting affect forest soil carbon, and how those effects may be described clearly in an accounting system that is easy to use.

Organic carbon in soil below the forest floor is one component of forest carbon that is particularly contentious. Measuring soil carbon is time-consuming, costly, and operationally difficult, partly because variability in soils tends to be high, requiring many samples to statistically test results. Relationships between easily characterized aboveground vegetation and belowground soil carbon may be weak because soil carbon may have been affected by past land use, long after visual traces of the previous use disappear. However, carbon pool size alone makes forest soils quite important, despite the uncertainties (EIA 1997; US EPA 1998). Soils of the world are estimated to contain twice the amount of carbon as in the atmosphere or vegetation (Bouwman 1990).

The accounting frameworks described in the global guidelines for national greenhouse gas inventories released by the Intergovernmental Panel on Climate Change (IPCC/OECD/IEA 1995, revised in 1997) increasingly discuss soil carbon, thereby reflecting the importance of accounting for carbon in soil. In the United States, Birdsey and Heath (1995) presented forest carbon estimates, including soil carbon, in a technical document (Joyce 1995) accompanying a larger assessment framework: the USDA Forest Service analysis for the Forest and Rangeland Renewable Resources Planning Act (RPA) Assessment (USDA FS 1994). These accounting systems feature two main components: input measures or samples to characterize forests, and a core of assumed relationships to estimate the amount of carbon in that forest. Carbon is generally described as a function of forest age, area, volume, or biomass.

In this chapter, we discuss the accounting system by Birdsey and Heath (1995) used by the RPA and the accounting system of the IPCC National Greenhouse Gas Inventories (1997) for soil carbon in the forest sector and land use changes involving forests. Basic assumptions are compared in light of new scientific studies on forest soil carbon. We outline important components in the accounting frameworks with an emphasis on land use change activities such as afforestation, deforestation, and reforestation. We then review recent scientific developments that affect soil carbon assumptions used to calculate carbon estimates.

Forest Carbon Accounting

We use the phrase "soil carbon" to mean soil organic carbon in horizons beneath (and not including) the forest floor. Usually soil beneath the forest floor is called mineral soil. Some soils developing under a waterlogged condition may contain a high level of organic matter, and these soils are called organic soils, or Histosols. Thus we can differentiate between soil organic carbon in mineral soils and soil organic carbon in organic soils. Some soils also contain a great deal of carbon in inorganic form such as carbonates. However, inorganic carbon is relatively inert and therefore we do not include it in this study.

Carbon accounting quickly becomes complicated in practice, because we are most interested in carbon flux, which may be calculated as change in successive carbon stocks (inventories). At the simplest level, two variables are needed to calculate net carbon flux in forests: area and total carbon per area. Multiplying area and carbon per area yields total carbon inventory stored in forests. Net carbon flux is then estimated by the difference in total carbon estimated at two consecutive times divided by the length of time between inventories. However, there are a number of methods to model carbon inventory and flux. The methods vary by data requirements, system definition, boundary conditions, and even identity of carbon pools. The two methods we discuss focus principally on estimating stocks of carbon, and flux is simply the annual difference in stocks.

Data and information issues make forest carbon accounting particularly difficult. Ideally, a comprehensive accounting system would provide the best estimates for GHG emissions associated with forests. A comprehensive system would include these components at the beginning of each year: living and dead tree biomass carbon, carbon in seedlings, understory, forest floor, root, and soil carbon. No nation measures all these components, although some nations do measure many items strongly related to these components. Further, scientists do not agree on generalized assumptions that may be used as a way to convert measured data (such as area and volumes) to carbon. Without scientific consensus on assumptions, some nations may prefer to exclude incomplete information, while other nations may have adequate information. No matter how detailed the information, the goal is to develop estimates of the area of forest and carbon per unit area.

The comparison of the two accounting methods does not include a quantitative estimate formed using the IPCC method. A summary of U.S. carbon totals from previous estimates is included here to provide some perspective on the magnitudes involved. Forests in the conterminous United States were estimated to contain about 37.7 billion metric tons of carbon in 1992, sequestering 127 million metric tons per year in soils and forest floor, and 84 million metric tons per year in live vegetation (see table 4.2, Birdsey and Heath 1995). These results included estimates of forests of very low productivity, which tend to be located in arid or mountainous regions, and are for the most part not managed commercially for timber. Productive forestland available for harvest is called timberland. Carbon estimates in 1992 for timberland, including timberland in Alaska, are 34.3 billion metric tons, sequestering 84 million metric tons per year in soils and forest floor, and 74 million metric tons per year in live vegetation (see table 4.3, Birdsey and Heath 1995). The two tables are not strictly comparable because of definitional changes over time. For instance, the carbon estimates on timberland during the period 1977–1992 are noticeably affected by Congressional designation of some timberland as Wilderness—an example of how land use change can affect apparent carbon budgets.

Soil Carbon Accounting Systems For Forest and Land Use Change

A comparison of two carbon accounting methods designed for national-level totals can usefully illustrate some of the links among the state of scientific understanding, model assumptions, and assessment priorities. The first method was developed to estimate total carbon inventory of U.S. forests, with emphasis on change in storage brought about by growth and management activities. The second method is from an international effort designed to be generally applicable. It is focused on determining forest GHG emissions induced by human activities.

The two methods are not simply alternate approaches to estimating the same values, but there are some parallels in assumptions and goals. Comparisons are essentially qualitative overviews of the conceptual organization of the two methods. We emphasize assumptions and approaches to modeling land use change, especially afforestation, deforestation, and reforestation. Although the focus of our study is on soil organic carbon, we also discuss carbon in other components of forests because often the soil carbon information inextricably depends on other forest components.

Carbon Estimates Used by the RPA Assessment, 1995

The carbon accounting method of Birdsey and Heath (1995) was used for the 1995 RPA assessment and included comprehensive estimates for carbon in all components of U.S. forests. These were developed specifically for U.S. forestland and designed to utilize the extensive base of forest information in this country. We first discuss some basic assumptions of the method, and we then discuss accounting for effects of changes in land use.

The estimates were based on forest inventories conducted by the USDA Forest Service Forest Inventory and Analysis Program (Hansen et al. 1992; Woudenberg and Farrenkopf 1995). The inventory survey and associated sampling errors are designed for measuring total timber volume over an aggregated forest area. Forest areas are estimated because they are needed to calculate volumes, but the design of the survey does not require designating sampling errors for area or soil carbon. As a result, forest inventory data provide good above-the-stump information, yet are also useful for deriving belowground information calculated as assumed functions of collected data. The inventory does not directly measure soil carbon.

The carbon model is based on aggregations of forests within each of nine regions of the United States. Each aggregation is called a management unit. Forest type, ownership, and sometimes productivity and previous land use delineate each management unit. The forest inventory for each management unit includes number of hectares and average volume by age class. Soil carbon per hectare is estimated for management units according to empirical relationships specific to management unit characteristics (Birdsey 1992; Plantinga and Birdsey 1993). Similar estimation procedures are also established for other forest carbon pools, including carbon in trees. Net annual soil carbon flux is calculated by multiplying hectares of forest by carbon per hectare in each of two consecutive inventories and dividing the difference by length of the period.

The number of hectares of forest inventory may change as land use changes between forest and non-forest vegetation. Such area change influences on flux are allowed in this method to provide an accurate accounting of carbon in the forest sector. If land was transferred into the agricultural sector from the forest sector, then it is assumed the additional hectares are accounted for in agriculture. This apparent loss of forest soil carbon to the atmosphere is really only a transfer to a different sector. Similarly, if forested area increased during the interval, this accounting method produces an effect of additional carbon sequestration from the atmosphere. In the 1992 and prior inventory estimates, areas are based on historical estimates from forest inventories; in the projected years, areas are based on land use projections (Alig et al. 1990) used in the RPA Timber Assessment (Haynes et al. 1995).

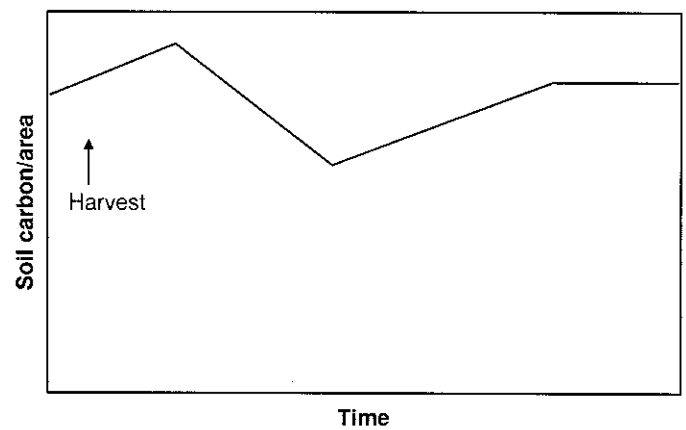

Figure 6.1—Generalized trajectory of forest mineral soil organic carbon following clearcut harvest. (Adapted from Moore et al. 1981.)

RPA Accounting System and Land Use Change

Assumptions about the dynamics of soil carbon over time are discussed in Plantinga and Birdsey (1993) and Birdsey (1992); these include effects of both previous land use and harvesting. Initial soil carbon estimates for forests developing on cropland and pasture–that is, the land use is changing from cropland or pasture to forest–were derived from regression equations for soil organic carbon in Burke et al. (1989). Regional estimates were based on mean annual temperature and mean annual precipitation for each of the regions, assuming percent clay and silt were equal to 20 percent and 40 percent. Birdsey (1992) developed a comparable regression equation for forestland, with the results equal to soil organic carbon of mature forests, which was assumed to occur at age 50 in the South and at age 55 in other regions. With these three base soil carbon estimates (that is, forest originating on cropland, pasture, or forestland) developed by region, the dynamics of soil carbon with forest growth were functions of previous land use and time. Forests regenerated on pasture were assumed to start (at forest stand age 0) with soil carbon characteristic of pasture, and then increase linearly as forests aged to the amount of soil carbon found in mature forest stands of that region. Soil carbon of forests regenerated on cropland was estimated similarly. After clearcut harvest (at forest stand age 0), soil carbon is assumed to equal the calculated base carbon estimate, decline up to 20 percent (Woodwell et al. 1984; Pastor and Post 1986) over a 10–15 year period following harvest, and accumulate gradually to a base forest carbon by maturity (approximately 50 years). These qualitative trends in soil carbon are illustrated in figures 6.1 and 6.2 for a clearcut with reforestation and harvest with a non-forest interval before regeneration, respectively.

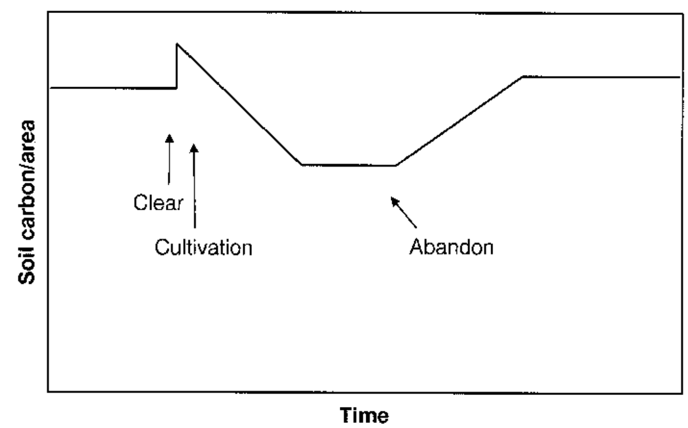

Figure 6.2—Generalized trajectory of forest mineral soil organic carbon after clearing, cultivation, and forest regeneration following abandonment. (Adapted from Moore et al. 1981.)

Management units are not partitioned into areas of previous land use, so we cannot simply adopt soil carbon estimates for forests originating on cropland, pasture, or forestland. We currently have only general estimates of previous land use over an aggregated area. Therefore, weighted averages of soil carbon were calculated, based on percentages of previous land use on which current forest were regenerated. These percentages were estimated using various USDA Forest Service inventory statistics, coupled with assumptions about management, ownership, and regional influences (Birdsey, personal communication). It was the weighted soil carbon equations that were used in the analysis.

The effect of the weighting procedure is illustrated in figure 6.3, which shows the soil carbon trajectories for planted pine on productive sites of different previous

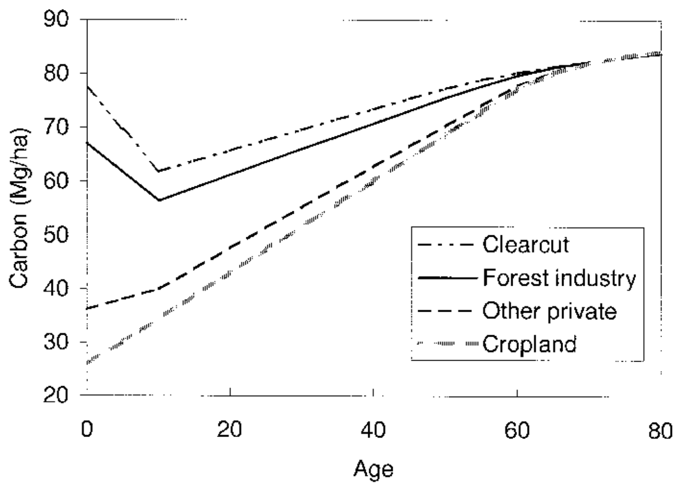

Figure 6.3—Soil organic carbon (0-1 m) by forest stand age for planted pine on high productivity sites in the southeastern United States, based on old assumptions. The estimates are weighted averages based on percentages of forest in previous non-forest land use. (This is but one example set of equations available for each combination of region,forest type, and ownership.) Source: Personal communication. 1994. Data from Richard Birdsey, Program Manager, USDA Forest Service Northeastern Research Station, Radnor, PA 19087.

land use in the southeastern United States. One of the trajectories illustrates how soil carbon per hectare would accrue by age for forestland that had been clearcut and replanted. The second trajectory represents soil carbon per hectare for forest growing on land that was previously cropland. However, neither of these trajectories accurately represents the aggregate soil carbon trajectory for a mixture of previous land uses. On forest industry lands, for example, 80 percent of the forestland was previously forest, while 20 percent was cropland. The soil carbon trajectory is an average of the carbon on clearcut forests and carbon on cropland, weighted by percentage of land in each use. This average trajectory is labeled "Forest industry." The trajectory for "Other private" ownership is based on the estimate that 80 percent was previously in cropland and 20 percent was previously forested. Soil carbon trajectories of other forest types and regions were calculated using the same weighting procedure.

Previous land use heavily influences soil carbon as illustrated in figure 6.3. In this example, soil carbon per hectare at age 0 ranges from 26 Mg C per ha on cropland to 78 Mg C per ha on a clearcut. After about 65 years of forest development, soil carbon is about 80 Mg C per ha regardless of previous land use. Age is often difficult to determine in naturally regenerated forests, and forestland is often not fully occupied by trees. Although this figure illustrates a relationship between soil carbon and forest age, the accounting method used by RPA often employs a relationship between forest merchantable volume and soil carbon. However, relationships with forest age are used for stands less than 15 years of age, when merchantable volumes are zero or close to zero. Volume is thought to more accurately reflect the level of soil carbon when characterizing older stands (Plantinga and Birdsey 1993; Birdsey and Heath 1995).

The IPCC Method of Estimating Carbon, 1997

One of the objectives of the IPCC/OECD/IEA Programme on National Greenhouse Gas Inventories (IPCC/OECD/IEA 1995, 1997) was to develop a default methodology, with the concurrence of the international scientific community, which nations could follow or use as guidelines to report GHG emissions and sinks. A goal was to be both extensive and simple. This would produce a methodology appropriate for use by any nation, yet estimates could be determined even with limited data. Nations are strongly encouraged to use local information if doing so would increase accuracy of estimates. We review the methodology of the Land Use Change and Forestry (LUCF) section of the guidelines (IPCC/OECD/IEA 1997) by first discussing some basic assumptions. We then address some issues of accounting for carbon under changes in land use.[1]

Classification of land and activities on that land are important first steps in the IPCC guidelines. Areas of forests that are currently not significantly disturbed by humans are excluded from calculations. That is, areas of land which feature a carbon flux of approximately zero are ignored for carbon accounting purposes. The distinction between forestry and other agricultural activities also distinguishes how carbon is counted. The LUCF section of the guidelines includes land use change and carbon emissions from agricultural activities. There is a separate extensive section on agriculture; however, it focuses on nitrous oxide emissions from agricultural soils, emissions from agricultural burning including prescribed burning of savannas, and methane and nitrous oxide emissions from domestic livestock. Prescribed burning of savannas is handled in the agriculture section, yet burning of savannas for the purpose of changing land use is handled in the LUCF section.

The IPCC guidelines categorize forestland as tropical, temperate, or boreal. We review the overall methodology,

[1] At the third Conference of the Parties in Kyoto, Japan, the Parties agreed to count forest carbon from afforestation, deforestation, and reforestation since 1990. However, definitions for these three terms are still under discussion so we review the current published guidelines.

Table 6.1—Headings of major categories for changes in forest and other woody biomass aboveground carbon stocks suggested by IPCC (1997) for calculating national greenhouse inventories.

Latitude	Woody biomass stocks		Changes in harvesting	Conversion & abandonment
Temperate	Plantations	Douglas fir	Specified by user	Coniferous
		Loblolly pine		Broadleaf
	Commercial	Evergreen		Grasslands
		Deciduous		
	Other			
Boreal	ND	ND	Specified by user	Mixed
				Broadleaf/coniferous
				Coniferous
				Forest-tundra
				Grasslands/tundra
Tropical	Plantations	*Acacia spp.*	Specified by user	Wet/very moist
		Eucalyptus spp.		Moist, short dry season
		Tectona grandis		Moist, long dry season
		Pinus spp.		Dry
		Pinus caribaea		Montane moist
		Mixed hardwoods		Montane dry
		Mixed fast-growing hardwood		Tropical Savanna/grassland
	Other forests	Moist		
		Seasonal		
	Other			

ND = No default specified.
Source: IPCC/OECD/IEA 1997.

but we focus on temperate forests because they constitute the majority of U.S. forestlands. Aboveground and belowground carbon pools are estimated separately. Temporal responses to perturbations differ for two systems: several decades may be needed for soil carbon to respond to change and stabilize, while only a few years may be adequate to describe responses of aboveground biomass to the same changes.

The default approach for estimating aboveground carbon inventories features biomass tabulated by the categories of forest and other woody biomass stocks, forest and grassland conversion, and abandonment of managed lands. Each of these categories is further divided by vegetation types under tropical forest and grasslands, temperate forest and grassland, boreal forest and tundra, and other. The category "forest and other woody biomass stocks" features more specific forest types. The default headings for these three categories are displayed for comparison in table 6.1. The categories, with the exception of harvesting which has no defaults specified, are based on vegetation type.

Soil carbon emissions are tabulated by the categories of soil carbon emissions from mineral soils, organic soils (Histosols), and liming of agricultural soils. Liming is not a common treatment in forestry in the United States, so it is not addressed here. Organic soils are commonly bog soils and are most prevalent in localized areas of the United States, with the largest contiguous areas in Minnesota, Louisiana, and Florida. Most of the change in organic soils is due to cultivation for agriculture, particularly vegetable crops. The default headings for mineral and organic soil carbon categories are displayed in table 6.2. Note that soil carbon is classified by climate, soil type, and then vegetation and management system. Although the forest-related vegetation/management system is broadly categorized (for example, one category is forest), IPCC recommends that forest and grassland management systems be subdivided into relevant categories.

Soil carbon emissions are estimated by first multiplying the current area of a given vegetation/soil type/management system by the amount of soil carbon estimated in each hectare to produce total soil carbon stock. Soil carbon flux at a designated time in the past is calculated for the same land base using the areas at the previous time, and then subtracting the previous soil carbon total from the current soil carbon total. Dividing by the length of the period between measurements converts net soil carbon flux to an average annual basis. The calculation for net soil carbon flux is expressed in equation form as:

Table 6.2—Headings of major categories suggested by IPCC (1997) for calculating changes in soil carbon for areas undergoing land use change·

	Soil Carbon Change In Mineral Soil			Carbon Emissions From Organic Soils	
Latitude	Climate	Soil type	Vegetation and management systems	Climate	Soils use
Temperate	Cold, dry	High clay	ND	Cool	Upland crops
		Low clay			Pasture/forest
		Sandy		Warm	Upland crops
		Volcanic			Pasture/forest
		Wetland			
	Cold, moist	High clay	Forest		
		Low clay	Forest set-aside		
		Sandy			
		Volcanic			
		Wetland			
	Warm, dry	High clay	ND		
		Low clay			
		Sandy			
		Volcanic			
		Wetland			
	Warm, Moist	High clay	Forest		
		Low clay	Forest set-aside		
		Sandy	Reverted forest		
		Volcanic			
		Wetland			
Boreal	ND	ND	ND		
Tropical	Dry	High clay	Savanna	All	Upland crops
		Low clay			Pasture/forest
		Sandy			
		Volcanic			
		Wetland			
	Moist	High clay	Forest/woodland		
		Low clay	Plantations		
		Sandy			
		Volcanic			
		Wetland			
	Wet	High clay	Forest/woodland		
		Low clay	Agroforestry		
		Sandy	Plantations		
		Volcanic			
		Wetland			

ND = No default specified.

[1] Source: IPCC/OECD/IEA 1997

[2] Management systems involving forest. Examples of agricultural management systems not listed in this table are small grain with continuous cropping, hay improved pasture, successional grassland, irrigated cropping systems and intensive grain production.

$$\text{Soil carbon flux} = \left[\sum(\text{Area}_{i,t} \times C_i) - \sum(\text{Area}_{i,t-\text{LP}} \times C_i)\right] / LP \qquad [1]$$

where $\text{Area}_{i,t}$ = total area of the *i*th vegetation/soil type/management system at time t, C_i = soil carbon per area of the *i*th vegetation/soil type/management system, and LP = length of period in years.

If area of each vegetation/soil type/management system does not change over the period, then soil carbon emissions are zero. Total land area across all vegetation/soil type/management system categories should always remain constant.

Tables 6.1 and 6.2 are presented here as examples of the main variables of interest currently included in the IPCC guidelines. However, they also show the dichotomy induced in the accounting system by the characteristics of the underlying inventory system. Aboveground carbon is based on volumes of wood growing in or harvested from forests, while soil carbon is based on hectares categorized by land use. This system becomes unwieldy when carbon accounting is focused on only a part of the land base. That is, accounting for only afforested or deforested hectares can be difficult when independent variables predicting the aboveground and belowground portions do not coincide.

IPCC Accounting System and Land Use Change

Estimates of mineral soil carbon per unit area are based on default values provided in the IPCC guidelines for native vegetation by climatic region and soil type. These estimates are then multiplied by a use factor, tillage factor, and an input factor. The tillage factor is used only for agricultural soils. When temperate native soils are cultivated, soils are assumed to lose 30 percent of the soil carbon in the 0–30 cm soil layer, with the exception of wet soils that are assumed to lose 40 percent. Forested lands cleared and put under long-term cultivation are assumed to lose 30 percent of the soil carbon (Davidson and Ackerman 1993). Soils under long-term cultivation, but then set aside and not managed for less than 20 years, are assumed to contain 20 percent less soil carbon than native soils; soils set aside and not managed for more than 20 years are assumed to contain 10 percent less soil carbon than native soils. However, set-aside land apparently does not include land planted to forests. The current default accounting does not include accumulation of carbon in soil in plantations established on previously unforested (for at least the last 50 years) lands. Default values are less likely to be used by countries with significant activities that can affect soil carbon such as establishing plantations, for example (see note on page 5.15 of Volume 3, IPCC/OECD/IEA 1997). Soils under improved pasture gain 10 percent more carbon than the same soil under native vegetation, an assumption attributed to work by Fisher et al. (1994); Cerri et al. (1991); and Grace et al. (1994).

Organic soils are handled differently than mineral soils. Estimates of losses of organic soils under introduced pasture and forests average 25 percent of the loss rate under crops. This translates into an annual loss rate of 0.25, 2.5, and 5.0 Mg C per ha per year, for pasture or forestland intensively managed in cool temperate, warm temperate, and tropical areas. This simple relationship is a good illustration of the stated IPCC goal of generally applicable methods. Emissions are calculated for only those hectares currently under intensive use by multiplying number of hectares in each land use by the default annual loss. Organic soils under native vegetation are not included because they are assumed to have stable or increasing carbon stocks.

The current IPCC method employs simple assumptions about the dynamics of soil carbon. Soil carbon is presumed to tend toward equilibrium after many years under a specific land use. Spatial and temporal bounds are set as the top 30 cm and within 20 years. Only soil carbon in the 0–30 cm soil depth is considered for both mineral and organic soils. This area typically has the greatest concentration of carbon and the fastest response time to disturbance. The default guidelines suggest that soil carbon stock estimates include carbon in the forest floor (litter layer), as well as carbon content to a 30 cm depth, but at present the defaults do not account for the litter layer. The IPCC guideline default for the length of period between inventories of areas for land use is 20 years, a compromise for simplicity, particularly in light of little information. This default is based on work by Davidson and Ackerman (1993), who calculate that most soil carbon loss after clearing occurs within 10 years, and work by Jenkinson (1971) which showed a buildup of soil carbon after abandonment occurs more slowly. It is also expected that response time in soils in the Tropics would occur faster than the response time in the Temperate Zone. If a soil carbon response time longer than 20 years is warranted, IPCC recommends that cohorts of areas be tracked. For example, perhaps land abandoned less than 20 years ago should be one group, and land abandoned more than 20 years ago be another group.

Comparison of Accounting Systems

The two methods–RPA and IPCC–are based on inventories of wood volumes and forest area. These sampled variables are converted to carbon estimates using relationships taken from scientific literature. The two methods can potentially produce similar estimates of carbon budgets for the United States. This is principally due to the flexibility of the IPCC method to utilize U.S. inventory data and the estimators developed by Birdsey (1992). The RPA method was based on an extensive database and developed to be specific to U.S. forests. In addition to forest identity and area, this method used age and volume to predict aboveground and belowground pools of carbon. Independent variables were chosen according to what was considered the better predictor. The IPCC method is characterized by generality and flexibility. The most general application used area and identity of land use and vegetation type to drive model predictions. Flexibility does allow for use of assumptions more appropriate for local conditions. Thus, some of the elements of the RPA method can be adopted within the IPCC framework. However, soil carbon estimates would remain largely a function of area.

Exclusions from forest carbon inventories are part of both methods. Relatively undisturbed areas are excluded from calculations under IPCC recommendations, with human disturbance as the criterion. The RPA method excludes areas characterized by low productivity and, thus, low flux per hectare. For example, the interior of the state of Alaska is excluded from the carbon calculations used by the RPA assessment. The effect of excluding lower productivity lands in the United States is estimated to alter projected inventories of carbon by less than 10 percent (see tables 4.2 and 4.3, Birdsey and Heath 1995).

Accounting for total land area is important because examining changed area in isolation will cause apparent changes in soil carbon although the changes are simply reflecting transfers between categories. Afforestation and deforestation activities affected carbon inventory simply through the movement of area in or out of forestland in the accounting of the RPA method.

Carbon inventory of these afforested and deforested lands was not counted when in the non-forest state. Because the IPCC method made a comprehensive estimate, total area remained constant. Afforestation and deforestation simply produced a transfer of area among land uses and vegetation types. Although methods differed slightly, the net effect on carbon accounting was the same for the two methods.

Previous land use is an important consideration under both systems, but different effects are assumed for the two methods. Soil carbon of afforestation is assumed to increase in the RPA analysis following regression equations developed by Birdsey, while the IPCC methodology does not include accumulation of soil carbon on these lands. IPCC methodology does include soil carbon accumulation under different land uses such as improved pasture. IPCC assumes soil carbon is constant after forest harvest and reforestation. The method used in the RPA analysis assumes that soil carbon declines by 20 percent in the 10–15 years after harvest, and then increases back to the base amount by forest age 50. IPCC methods assume a 30 percent loss of soil carbon in the 0–30 cm soil depth when temperate native soils are cultivated, with the exception of wet soils which are assumed to lose more carbon. The RPA analysis covered only the forestland, so areas of deforestation were completely removed from the analysis. Therefore, no assumptions were made about the effect of deforestation on soil carbon. IPCC recommends that cohorts of areas be tracked when soil response time is longer than 20 years, and the RPA analysis does this by tracking forest area by stand age. The discussion here focuses on qualitative implications of assumptions about trends in soil carbon in response to land use change. Further detail requires a quantitative comparison of the two methods.

The RPA accounting method does not differentiate between organic and mineral soils, nor does it identify wet soils. The IPCC method does make these distinctions. However, these distinctions are applied mostly to agricultural soils in the IPCC default methods. Ignoring this distinction probably affects the soil carbon results for the RPA method less than adopting the assumption that soil carbon accumulates under afforestation.

Recent Developments

Assumptions about trends in soil carbon following land use change can be important to carbon accounting results of both methods. Each method is designed to reflect effects of forestry practices on carbon sequestration. Thus, it is important that assumptions about soil carbon dynamics reflect scientific studies. Much of the relevant literature over the last several years has indicated that reforestation produces transient changes in soil carbon, yet other studies suggest little change occurs. In this section, we first discuss soil carbon assumptions used in the 1993 RPA analysis (Birdsey and Heath 1995) and examine how the results would change to reflect no changes in soil carbon due to harvesting. We then review current literature, focusing on the effects of harvesting, afforestation, and deforestation on soil carbon.

Soil Carbon Assumptions, Mid-1990s

The carbon analysis used in the RPA Assessment (Birdsey and Heath 1995) was based on assumptions that soil organic carbon decreased in the first 10–15 years after harvest by perhaps as much as 20 percent, with a gradual increase as the forest stand aged to maturity around age 50. At about the same time, scientific consensus leaned toward the theory that harvesting had little-to-no effect on soil carbon (Johnson 1992). Johnson (1992) concluded in his review that cultivation of forested soils results in a large loss of soil carbon, up to 50 percent in most cases, and that soil carbon usually increases substantially when non-forested land reverts to or is planted to forest. Clearing and cultivation of forests was estimated to affect soil carbon regionally by 30 percent (Davidson and Ackerman 1993), and these soil carbon changes occur mainly in the upper horizons, probably within the 0–30 cm soil depth. Deep mineral soils were seen as passive carbon pools, remaining relatively unchanging for hundreds of years.

Birdsey (1996) recalculated forest soil carbon trajectories in response to this development in the scientific literature. The model assumed no harvesting effect on soil carbon, with a 33–50% increase due to land use change to forest. For pastures becoming forested, soil carbon at age 0 was the greater of the base pasture carbon, or two-thirds of the average of the base forest carbon. For croplands, soil carbon at age 0 was taken to be the greater of the base cropland carbon, or half the average of the base forest carbon. Figure 6.4 illustrates an example of soil carbon trajectories under these revised assumptions. The effects of assumptions on soil carbon dynamics may be easily seen by comparing trends in the solid line on figure 6.3 and figure 6.4. However, note that much of the difference in absolute magnitude (as opposed to trends) between the figures is due to climatic and vegetation differences of different regions and forest types.

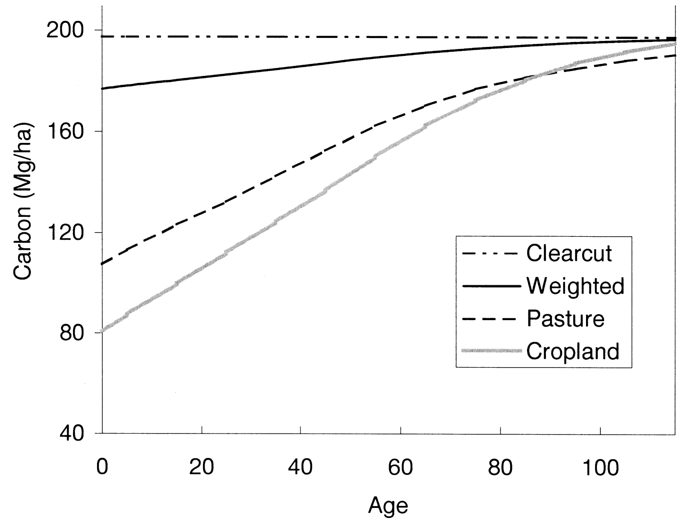

Figure 6.4—Soil organic carbon (0-1 m) by forest stand age for white-red-jack pine forest type in the northeastern United States (Birdsey 1996) under previous land use using updated assumptions. The estimates are weighted averages based on percentages of forest in previous non-forest land use.

Recent Scientific Studies on Harvesting and Reforestation Effects on Soil Carbon

Harvesting may affect soil carbon through loss of nutrients, temporary increase of slash incorporated into the soil by removal of the biomass, changes in soil physical properties such as bulk density due to physical disturbance from logging equipment, and loss of forest canopy, which affects the microclimate (Pennock and van Kessel 1997). Reforestation may act to reverse these effects. However, the actual act of regenerating the forest, including site preparation such as ripping and vegetation control, may cause soil carbon to decrease.

We are interested in changes in total soil carbon (Mg per ha). Total soil carbon is calculated by multiplying percent carbon content times volume of soil in a hectare. Davidson and Ackerman (1993) pointed out that examining percent carbon content of soil only addresses part of the carbon sequestration issue. Johnson's (1992) review, concluding that harvesting has little effect on soil carbon, was based on effects of activities on percent carbon. The number of relevant soil carbon studies has increased since 1992, and much of the results present more than simply "percent carbon." These recent studies have been more rigorously designed specifically for soil carbon. Important experimental considerations include longer duration of study, inclusion of greater amount of the soil profile, and a greater sample size that is needed to reveal significant differences under extant variability.

Clearcutting on the Hubbard Brook Experimental Forest in the northeastern United States produced a number of soil carbon changes (Johnson 1995; Johnson et al. 1995; Johnson et al. 1991; Huntington and Ryan 1990). Northern hardwoods inhabit the site, with some spruce-fir at higher elevations. Forests were logged around 1915, and there was no evidence of fire or previous cultivation. A whole-tree harvest was performed using local commercial operators; boles were removed using rubber-tired skidders. Soils were intensively sampled before, three years after, and eight years after clearcutting. Sampling intensity was such that a 10–20 percent change in total mineral soil carbon could be detected (Johnson et al. 1995). After three years, total mineral soil carbon increased 8 percent compared to pre-harvest values (which was not statistically significant at $p=0.05$). After eight years, total mineral soil carbon decreased 17 percent relative to pre-harvest values, significant at $p<0.25$. The carbon pool in the 0–10 cm layer did not differ ($p=0.92$) from pre-harvest values, but the carbon pools in the 10–20 and 20-C horizon layers decreased significantly ($p<0.05$). Percent carbon of the organic matter changed significantly ($p<0.05$) after eight years in several of the lower layers (Johnson et al. 1995), and significant ($p<0.05$) increases in bulk density were noted in the top 20 cm after three years (Johnson et al. 1995). Surprisingly, the mineral soil organic matter pool remained basically unchanged eight years after cutting (279 Mg C per ha versus 288 Mg C per ha). Thus, measuring only soil organic matter and assuming a fixed ratio of organic matter to carbon, may obscure the true carbon dynamics.

The contrast between the Hubbard Brook results and previous studies that showed no significant effects of harvesting on soil carbon was discussed by Johnson (1995). One reason proposed for the contrast was that studies may differ in sampling rules concerning disturbed areas. For instance, Covington (1981) carefully excluded disturbed sites in his study, while Federer (1984) allowed some disturbance. In this study, samples were taken across the site, regardless of soil disturbance. Huntington and Ryan (1990) reported a noticeable amount of disturbance on the site mainly due to the establishment of an extensive network of logging roads. Mixture of the top layers made delineation of the forest floor and mineral soil much more difficult and may have contributed to the 0–10 cm layer increasing in soil carbon eight years after harvest (Huntington and Ryan 1990). The apparent effect of harvesting on soil carbon in mineral soil may be more directly a function of soil disturbance at the time of harvest. Another possible reason is that the use of chronosequences in some studies may inadvertently include unknown site-specific effects.

Soil carbon dynamics qualitatively similar to those found at Hubbard Brook have also been identified in other forest types as well. Van Lear et al. (1995) combined sampling at mostly the 0–50 cm soil depth (12–20 samples at three to five permanent sampling locations at several watersheds at three depths) with modeled information at mostly the 50–100 cm depth. They studied soil carbon dynamics after harvest of a 55-year-old loblolly pine forest on an eroded, previously cultivated site in the Piedmont of the southeastern United States. They found an increasing soil carbon trend after harvest, which quickly decreased below pre-harvest carbon, but by 13 years after harvest it had increased above pre-harvest soil carbon levels. This is illustrated in figure 6.5, which somewhat resembles the older accepted theory of soil carbon dynamics shown in figure 6.1. However, some of their information in the 50–100 cm horizon was estimated, not measured.

Pennock and van Kessel (1997) conducted a study on chronosequences to examine the effects of clearcutting in six aspen-white spruce stands in central Saskatchewan, Canada. They sampled from 0 to 45 cm. Results showed a significant ($p<0.05$) increase of 8 percent in soil carbon less than five years after the clearcut, with a significant decrease of 23 percent 6–20 years after clearcutting as compared to mature forests. However, one caution in interpreting the results is that they did not separate the forest floor from the mineral soil surface on clearcut sites that had been prepared for tree planting. The surface layer was missing or very thin on these sites, and it was felt that measuring the forest floor separately would have introduced more error than measuring it with the mineral soil.

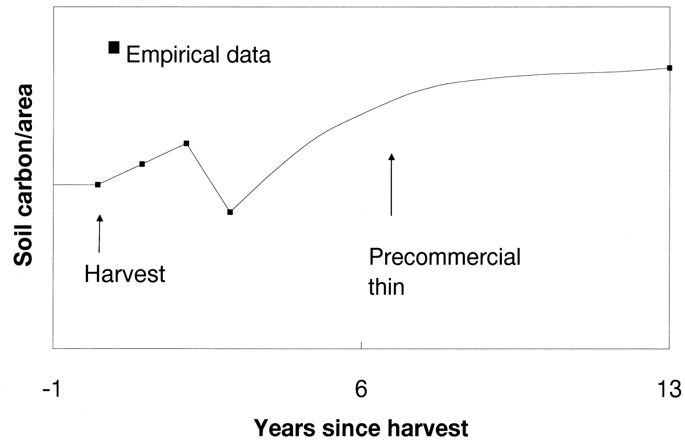

Figure 6.5—Trend of soil organic carbon after pre-harvest low intensity burns, and clearcut harvest of a 55-year-old loblolly pine stand on eroded soil (following Van Lear et al. 1995).

Sampling from a chronosequence suggests an increase in soil carbon with reforestation, even where the transitory increase immediately after harvest did not appear. Using a chronosequence, Entry and Emmingham (1995) found an increase in soil carbon in the top 10 cm of Douglas fir stands of increasing age. The stands were categorized as young-growth (about 30 years old), second-growth (about 66 years old), and old-growth (from 120 to 300 years old). Soil carbon almost doubled between young-growth and second-growth but the increase was not significant at $p<0.05$. Soil carbon of the old growth was almost three times that of young-growth, and it was significantly greater ($p<0.05$) than both younger groups.

Strong (1997) studied five cutting treatments with three replications each in northern hardwoods in northeastern Wisconsin using a chronosequence (pre-treatment values were not known for each treatment). The forests were logged in the early 1900s, and were generally even-aged. The study was initiated in 1952 and has been continuing for 40 years. The treatments included replications of control, diameter-limit cut, and three levels of individual tree selection. No trees were cut in the control, all trees 20.3 cm and larger were cut in 1952 in the diameter-limit cut, and heavy, medium, and light individual tree selection was performed in 1952, 1962, 1972, and 1982. There was no statistical difference ($p<0.05$) in soil carbon in the 0–40 cm horizon, but there was a significant difference in the 3–10 cm depth, and there was a trend of increasing soil carbon as basal area increased. This implies that soil carbon may decrease with increasing harvest intensity. Unfortunately, because this study uses a chronosequence, it may be that the soil carbon differences between treatments are due to initial site differences, not to harvesting intensity.

Other studies were reviewed but may be of limited usefulness. We reworked the data in Frazer, McColl, and Powers (1990) and found soil carbon increased 13 percent by five years after clearcutting, and decreased 11 percent by 18 years after clearcutting under regeneration, relative to an uncut area. However, there were no replications and therefore no statistics, and they sampled only to a depth of 14 cm. Olsson et al. (1996) studied soil carbon in Scots pine and Norway spruce at four sites in Sweden. They examined the top 0–20 cm some 15–16 years following harvest, and bulk density was assumed to remain constant in their calculation of total soil carbon. The three types of harvests studied were conventional stem harvest (residues left on site), harvesting all aboveground tree parts except needles, and whole tree harvesting (no residues left on site). If we assume harvesting did not impact bulk density, soil carbon increased fairly consistently in the 0–20 cm layer by about 5 Mg C per ha (not statistically significant at $p<0.05$) on each site. There were no significant trends of harvest intensity over all sites; however, disturbance from harvesting was carefully avoided. Operators tried to avoid soil compaction and mixing of soil layers. Black and Harden (1995) studied the effect of clearcutting in a mixed conifer stand in California. They sampled soil in the 0–20 cm layer in stands of six different ages but found no strongly consistent trend. They did note the younger stands (0–79 years old) in general contained more soil carbon than the old-growth stand. They concluded that other factors besides harvesting confound results. We also reviewed other studies, but we decided not to include them because they included only percent carbon, or were limited in duration or in depth (for instance, Knoepp and Swank 1997).

Afforestation and Deforestation

We review afforestation and deforestation studies together, because soils in U.S. forests are generally accepted to lose soil carbon when cleared and cultivated and then accumulate soil carbon after the land is revegetated with forest. Forest soil eventually accumulates carbon to a maximum level regardless of previous land use, unless severe erosion has occurred. Similarly, expected decreases in soil carbon partly depend on use after deforestation such as annual crops, pasture land, or urban development. For example, as mentioned previously Davidson and Ackerman (1993) conclude soil carbon decreases regionally by 30 percent (ranging from 20 to 40 percent) in the entire soil column when forests are cleared and the land cultivated.

The 30 percent loss is generally accepted as the magnitude of soil carbon change for deforestation and cultivation; however, the length of time over which the loss takes place is still being debated. How long does it take to reaccumulate soil carbon to its "maximum" level? Huntington (1995) studied a chronosequence of sites in the Piedmont of the southeastern United States, measuring soil carbon to the depth of 1 m for some sites. An upper bound for soil carbon for a cultivated, eroded forest soil was estimated using current soil carbon in the 50–100 cm layer, and the lower bound was estimated using soil carbon in similar soils currently under cultivation in the area. Using these upper and lower bounds, Huntington (1995) estimates a range within which soil carbon accumulates after forest regeneration on these lands. His results are shown in figure 6.6. He estimated an increase of 0.34 to 0.79 Mg C per ha per year (34–103 percent) accumulated over 70 years. Most soil carbon was lost within the first 35 years following clearing and cultivation. Van Lear et al. (1995), working on the Piedmont in South Carolina, estimated an increase of 0.47 Mg C per ha per year (220 percent) over a period of 55 years. This percentage is high because of the low initial soil carbon content of the site. Schiffman and Johnson (1989) estimated about 0.50 Mg C per ha per year (about 35–57 percent) accumulated on eroded soils in Virginia. Eroded soils present a special problem for accounting because eroded soil carbon may not decompose and be released to the atmosphere. It may be deposited elsewhere as soil carbon.

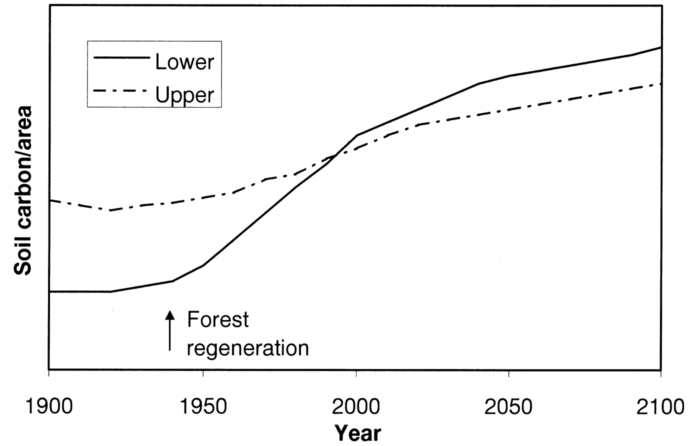

Figure 6.6—Upper and lower range of dynamics of soil carbon after forest regeneration on eroded cultivated soil in the southern United States. (Adapted from Huntington 1995.)

Trends of Soil Carbon in Current Literature

Based on this preliminary review, soil carbon dynamics following harvest appear to depend on the amount of disturbance caused by logging operations. The disturbance associated with some commercial harvests may cause soil carbon to increase initially in the first few years by 8–13 percent, then decline to below initial values by 11–20 percent by 10–20 years after harvest, and eventually increase again. Some studies showed changes in soil carbon below the 0–30 cm depth, indicating that experimental soil studies should sample lower soil depths. Severely eroded soils also create additional problems concerning depth because much of the original soil may be eroded. Results compared at apparently equivalent depths in eroded and non-eroded soils may be difficult to interpret. Other aspects of sampling designs identified as potential problems include initial site differences in the use of chronosequences, use of percent carbon as a proxy for total carbon, and the need for appropriate sample size to produce significant results. Soil carbon following deforestation and cultivation declines about 30 percent in the entire soil column within 30 years of cultivation. Soil carbon increases gradually following afforestation with good stocking, increasing by 30 percent at a rate more gradual than the decline following deforestation.

Summary

We reviewed two accounting systems, one developed by the IPCC (1997) and the other from the 1993 RPA assessment (Birdsey and Heath 1995). Both systems base predictions on the forest inventory variables of volume and area. Both methods recognize the importance of previous land use. The IPCC default system explicitly counts soil carbon loss when forests are cleared and cultivated but does not include the accumulation of soil carbon due to afforestation, although soil carbon increases due to differing agricultural tillage practices are included. Birdsey and Heath (1995) explicitly account for the accumulation of soil carbon due to afforestation but do not explicitly count soil loss after deforestation. This is because the RPA analysis focused only on carbon in the forest sector. Deforested areas were assumed counted in the agricultural or urban sector, not forests, and over the last 30–40 years more land has become afforested than deforested.

Recent scientific studies indicate that harvesting may influence soil carbon, an initial slight increase followed by a decrease, and finally an increase. We speculate that soil carbon will eventually return to pre-harvest levels. This corresponds to the pattern in the soil carbon assumptions in the RPA analysis. The magnitude of the effect seems to depend on the level and type of disturbance from logging operations. Countries with active forest management, such as the United States, should give further consideration to the overall level of disturbance in harvesting operations and revise soil carbon assumptions accordingly. Soil carbon decreases for 20–30 years following deforestation and cultivation and then remains relatively constant; following afforestation, soil carbon increases at a more gradual rate than the rate at which it had decreased, eventually becoming somewhat stable.

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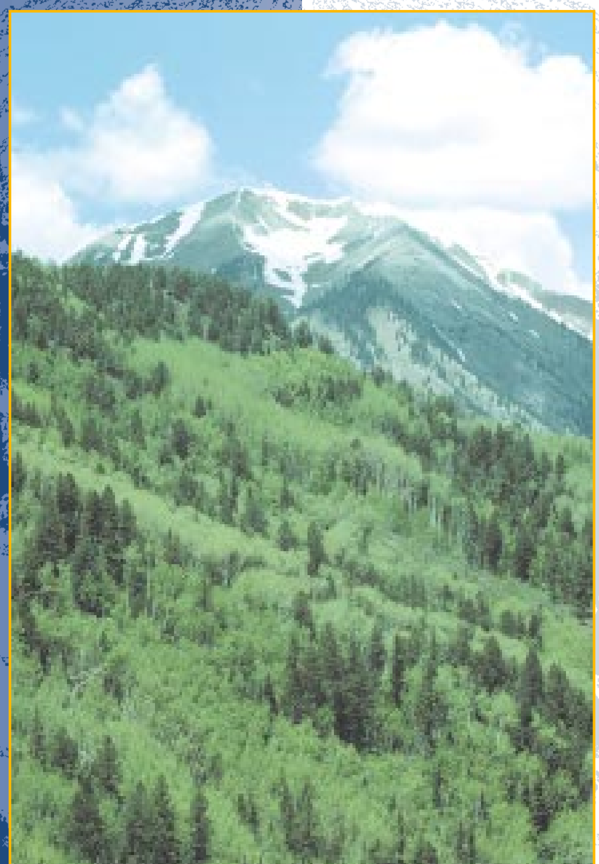
The Impact of Climate Change on America's Forests



A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment

U.S. Department of Agriculture   Forest Service

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Keywords: forest productivity, vegetation change, carbon sequestration, mitigation, forest sector, timber inventory, soil carbon, carbon accounting, afforestation, deforestation

Abstract

This report documents trends and impacts of climate change on America's forests as required by the Renewable Resources Planning Act of 1974. Recent research on the impact of climate and elevated atmospheric carbon dioxide on plant productivity is synthesized. Modeling analyses explore the potential impact of climate changes on forests, wood products, and carbon in the United States.

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