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# An inventory-based procedure to estimate economic costs of forest management on a regional scale to conserve and sequester atmospheric carbon

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**Abstract**

Estimation of the costs of managing forests to conserve and sequester atmospheric carbon is necessary to define the role of forests to mitigate the onset of projected global climate change. The role of forests as both carbon pools and an element in the flux of atmospheric carbon dictate new requirements in estimating the costs of forest management to mitigate climate change. These requirements include recognition of the inventory as a capital stock in the estimation of the costs; the need to allow the integration of biological, social and economic considerations across nations and regions; and the need to facilitate consideration of the distributional impacts of forest policy alternatives. An inventory-based procedure is presented to estimate forest management costs based on recognition of the opportunity costs of holding forest inventories. To demonstrate this procedure, the costs of four policy scenarios projected in the carbon budget of the United States are examined. Based on the demonstration, the inventory-based procedure is shown to meet the requirements for estimating forest management costs to conserve and sequester atmospheric carbon on a regional scale. The demonstration also illustrates the potential of the procedure to provide insights into differences in costs associated with management of forest ecosystems among geographic regions and forest policies.

*Keywords:* Economic costs; Forest management; Global climate change; Carbon sequestration

## 1. Introduction

The role of forest ecosystems as carbon pools and in the flux of atmospheric carbon has created international interest in the potential for forest management to aid in mitigating the increase in atmospheric carbon dioxide (Marland, 1988; Lashof and Tirpak, 1989; Sedjo and Solomon, 1989; Moulton and Richards, 1990). This interest is reflected in a number of international agreements (Noordwijk Ministerial Conference, 1989; Sedjo, 1992) culminating in

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the Climate Change Convention (Keating, 1993). This Convention commits nations to stabilizing greenhouse gas emissions at 1990 levels by the year 2000 and identifies the potential for international exchange of carbon credits to aid in achieving these goals. Along with the Climate Change Convention, the nations participating in the Earth Summit adopted the Agenda 21 Agreement that estimates that 83 billion ($10^9$) U.S. dollars will be required to implement the programs in forest multiple use, protection and reforestation (Sitarz, 1993). Ten billion ($10^9$) U.S. dollars of this are expected to be as international grants or aid to developing nations. The Climate Change Convention and possible grant and aid programs create a need to compare the costs of forest management alternatives between nations and regions.

### 1.1. Objective and considerations

This paper proposes an economic approach, called the "inventory-based procedure," to estimate the costs of carbon conservation and sequestration through forest management. The procedure is applicable on large geographic scales such as nations or regions within continents.

This scale requires consideration of three elements: the elements are: forest inventory; integration of biological, social and economic components; and the distribution of impacts. A fourth element involves the limitations of cost-benefit analysis when applied to forest management generally and in this case carbon conservation and sequestration. Briefly, the elements are as follows.

#### 1.1.1. Forest inventory

Managing forests to mitigate increases in atmospheric carbon involves two processes simultaneously: (1) conservation of carbon *in* the forest inventory; and (2) fixation of carbon *by* the inventory. To account for both processes in one analysis, an approach is needed to explicitly recognize the forest inventory (conserved carbon) and forest growth (carbon fixing) as a flow to the forest inventory. This is achieved by the procedure presented here through the recognition of the forest inventory as a capital stock.

#### 1.1.2. Integration of biological, social and economic components

The second element is to allow for integration of a broad array of biological, social and economic components. Historically, forest policy formation has been limited to national or sub-national areas. In this context, policy alternatives have included a smaller array of these considerations so that evaluation methods were based on incremental changes in the flow of monetized inputs and outputs. This placed the focus on the efficiency of alternatives through time and consideration of forest inventory and growth was limited (Clutter et al., 1978; Leuschner, 1984; Johnson et al., 1986; Davis and Johnson, 1987).

The importance of differences in the forest inventory required to sustain a forest ecosystem and the rate of forest growth in international comparisons of forest management was demonstrated by Winjum and Lewis (1993). These differences are also recognized here through the treatment of the forest inventory as a capital stock and forest growth as a flow of increments to capital.

#### 1.1.3. Distribution of impacts

The third element is the estimation of the distribution of impacts resulting from new forest policies (i.e., who gains and who loses). Potier and Jones (1992) identify the need to understand the distribution of impacts of proposed forest policies on nations and global economic sectors. They also pointed out the need to understand the impacts in terms of economic growth and international trade.

Regional input–output analysis (Miller and Blair, 1985) is the preferred analytical pattern to examine the distribution of costs and benefits within an economy. If policies impact an economy so that its structure is changed, the appropriate analytical pattern is a derivative of input–output analysis, based on general equilibrium theory (Dervis et al., 1982). The purpose of regional input–output and computable general equilibrium analyses are to reflect resource flows within an economic system. As such, they do not derive an efficient solution. Instead they reflect existing efficiencies in the case of input–output models and derived efficiencies based on elasticities in general equilibrium models. The failure of existing forms of marginal analysis (Clutter et al., 1978; Leuschner, 1984; Johnson et al., 1986; Davis and Johnson, 1987) to develop complete summaries of information, in a compatible form for use in regional input–output analysis, limit their contribution to estimation of the distribution of impacts.

### 1.1.4. Costs and benefits

Ideally, this procedure would consider both costs and benefits of managing forests. However, the procedure proposed here will focus only on costs since the methodology for estimating benefits is complex and does not provide definitive numerical estimates of total value.

The complexity of valuing total benefits arises because of the broad array of benefits, including both marketed and non-marketed benefits, produced by forests (Kramer et al., 1992). The values assigned to these benefits also take a variety of forms (Sinden and Worrell, 1979; Peterson and Sorg, 1987; Peterson et al., 1990; Randall, 1991; Pearce, 1993). Finally, the complementarity and substitutability of forest benefits and their assigned values result in confounding of value estimates. This complementarity and substitutability can be observed in the dynamic within and between the floral and faunal components of forest ecosystems as they pass through successional states (Kimmins, 1987, pp. 384–429).

Altogether, valuing forest benefits without complete markets creates two problems. One, it prohibits full expression, in a numerical form, of the value of total or marginal benefits of managing forests. Two, it results in an inability to clearly understand the distribution of impacts from the combinations of benefits produced. These two problems together rule against the application of formal benefit/cost analysis to evaluate carbon conservation and sequestration alternatives through forest management. However, the procedure proposed here will allow the integration of benefit values in the future when suitable methods are developed to allow legitimate numerical comparisons.

## 1.2. Forest carbon budgets and economics

To satisfy agreements under the Climate Change Convention, interest has grown in developing national carbon budgets, particularly for the forest sector (Kurz et al., 1992; Kolchugina and Vinson, 1993; Turner et al., 1995a, b). In this context it is important to examine alternative forest management policies and their costs for carbon conservation and sequestration.

To date, cost accounting for this purpose has been inconsistent. In a recent review of the subject, Sedjo et al. (1994) point out three issues that contribute to the inconsistency. The first issue is the difference in estimates of cost resulting from variations in the procedure used to estimate carbon sequestered. This has occurred because estimates of carbon mass per unit area in some studies have been based on industrial stem wood while other studies have been based on portions or all of total biomass. The second issue is the result of differences in the rate of organic detritus accumulation and oxidation on the forest floor and in forest soils.

The third issue is the variation in costs recognized in the analyses. For example, Dixon et al. (1991a, b) base their analyses on stand level costs of implementing forest practices and ignore other costs of managing forest ecosystems. Moulton and Richards (1990) base their analysis on land rental costs, annual management costs and costs of plantation establishment. Swisher (1991) ignores land costs while incorporating costs associated with project management, extension, maintenance and performance monitoring. Finally, Winjum and Lewis (1993) include the costs of holding forest growing stock capital and ignore land costs.

There are a limited number of studies that address the cost of silvicultural options on a regional or global scale. Sedjo (1983) compared a broad array of plantation and product options in a global assessment of plantation forestry. However, the analysis pattern used in his study does not lend itself to the examination of options involving natural forests. Studies by Dixon et al. (1991a, b) examine the cost of a global array of silvicultural options, but are incomplete in their treatment of rents associated with the use of land and growing stock. Swisher (1991) reported a financial analysis of plantation projects to sequester carbon in Latin America. His analysis is unique in its introduction of the idea of a trust to provide for the management of the plantations during their lifetime. Winjum and Lewis (1993) identify the importance of growing stock rents in the comparison of stand management alternatives. However, their examination is limited and ignores many of the inputs required to estimate the distribution of impacts. All of these analyses are forms of partial analysis focused on choice through time. As such, they do not easily meet the information requirements of a regional analysis of impacts.

A number of studies have carried the estimation of costs of conserving atmospheric carbon through forest management a step further and developed cost functions as opposed to point estimates (Moulton and Richards, 1990; Adams et al., 1992; Parks and Hardie, 1992). While these studies make a significant contribution to the estimation of costs associated with the scale of forest management, they fail to recognize some of the costs associated with the management of forests (Winjum and Lewis, 1993). This limitation means that these procedures are unable to clearly estimate the cost of management alternatives on a national or regionally within continents scale.

Besides the lack of consistency in methods used to accumulate costs, previous studies do not examine the costs of forest management in the context of a carbon budget. All the previous studies examine forest management alternatives in terms of incremental changes in the relationship between forests and atmospheric carbon. This has the potential for error in the quantity of carbon in the forest ecosystem pool and rate of net carbon sequestration as demonstrated in the analysis by Turner et al. (1995a, b) and associated simulations by Haynes et al. (1994).

## 2. Procedure

As an approach to meet the objective and considerations above, the inventory-based procedure is proposed. The procedure adapts the framework used by Duerr (1960, 1993) to identify "Best Combinations of Forest Capital" and "Financial Maturity of Divisible Timber Capital." This adaptation of the "cost of capital" approach allows comparisons of costs to mitigate global climate change that are consistent with the economic principles of choice through time. To meet the requirement to integrate a broad array of biological conditions, the procedure is based on standard forest inventory statistics (FAO, 1992, 1993). The array of social and economic conditions are accommodated by limiting the need for economic information to real prices for land and standing timber (stumpage) as well as real discount rates. All information is for the local economy. Real domestic prices, including discount rates, are appropriate for these analyses because the resources required to sustain forest ecosystems are captive in the nations they occupy.

The requirement to recognize physical inputs and costs associated with the use of forest inventory is accomplished by explicitly including holding costs, as rents, in the analysis. By recognizing the inputs and outputs included in national income and product accounts, on an annual basis, the inventory-based procedure achieves compatibility with regional input–output analysis.

The essence of the inventory-based procedure is the summary, on an annual or periodic basis, of forest management based on total inputs. The cost of capital inputs (land, forest growing stock inventory and improvements) as rents is based on real prices including discount rates. Annual monetary inputs required to tend the forest (costs of silviculture, protection and management) are also based on real prices. Outputs, included in income and product accounts, are also recognized on an annual or periodic basis.

This procedure has the shortcoming of not allowing the identification of an optimum management regime for a forest or a combination of forests. However, it does allow the comparison of forest management alternatives on the basis of relative efficiency. These measures of relative efficiency, such as cost per ton of carbon sequestered or present value of costs required to sequester a ton of carbon, are the basis of least cost strategies to achieve an environmental objective.

The cost of capital inputs, forest land and growing stock, is an annual rent. This rent is the product of the real opportunity cost and the real, long-term, discount rate. The opportunity cost of forest land and growing stock is the product of their quantity and real price. Algebraically these are expressed as:

$$LC_R = (Q_L \times RP_L) \times RDR_{LT} \tag{1}$$

where $LC_R$ = forest land cost as an annual rent, $Q_L$ = quantity of forest land, $RP_L$ = real price of bare forest land, and $RDR_{LT}$ = real long-term discount rate (expressed as a decimal).

$$GSC_R = (Q_{GS} \times RP_{GS}) \times RDR_{LT} \qquad (2)$$

where $GSC_R$ = growing stock cost as an annual rent, $Q_{GS}$ = quantity of growing stock, $RP_{GS}$ = real price of growing stock, and $RDR_{LT}$ = real long-term discount rate (expressed as a decimal). The costs of management and other inputs, which accrue on an annual basis, are real annual costs.

Outputs are limited to those recognized in income and product accounts. To maintain this compatibility, forest growth is recognized as it occurs, on an annual basis. Output value is the product of quantity produced and real price. To separate them from inputs, all outputs are valued as negative costs in the calculation of net total costs. Only the value of removals (harvest) is recognized in income and product accounts. As noted earlier, there is no agreement on how to value non-market benefits, on a national or regionally within continents scale and they are not considered in this procedure.

The annual total cost of forest management is illustrated algebraically as:

$$NTC_A = LC_R + GSC_R + MC_A - GV_A \qquad (3)$$

where $NTC_A$ = net total costs per annum, $LC_R$ = land cost as an annual rent, $GSC_R$ = growing stock cost as a rent, $MC_A$ = annual management costs (all annual costs), and $GV_A$ = value of annual growth (output).

Note that revenue derived from removals (harvest) is not recognized in the calculation of net total costs per annum ($NTC_A$, Eq. 3). This is because the calculation of net total costs per annum ($NTC_A$) is in terms of opportunity costs that incorporate the value of growth. To include revenues from removals would involve double-counting a portion of the annual growth.

This inventory-based procedure adopts the standards for measurement of physical inputs and outputs described by Lewis (1976), for the evaluation of stand treatments for timber production and Row (1987), for comparison of forest vegetation management alternatives. This standard requires the measurement of all inputs and outputs on an interval scale and the unit of measure must be associated with a real price expressed on a ratio scale. Lewis's argument (Lewis, 1976) for completeness in the inclusion of inputs and outputs because of their relevance in the estimation of wealth-based criteria is relevant for this procedure. This is for reasons related to wealth as a basis for outcome criteria as well as their importance in meeting the requirements of regional input–output analysis. Lewis (1976) and Row (1987), also defined standards for the measurement of prices used to estimate value. These require the expression of prices, in units of constant value; based on after tax, including tariffs, conditions of exchange; measurable on a ratio or interval scale; and directly convertible into a quantity that defines the real conditions of exchange for any other good in the economic system. Generally, these conditions define real prices.

In summary, this inventory-based procedure for estimating forest management costs meets the economic requirements for comparing the efficiency of forest management alternatives and compatibility with regional input–output analysis. This is accomplished through recognition of all the inputs required to sustain forest ecosystems and all the outputs included in regional income and product accounts on an annual basis. Further, the procedure includes: (1) the summary of all inputs and outputs on an annual or periodic basis recognizing the costs of capital inputs, including forest land and inventory, as rents; (2) management costs as they occur; and (3) outputs, as defined in income and product accounts. The measurement of physical inputs and outputs as well as prices follows principles established in previous studies and is consistent with the values summarized in regional income and product accounts.

## 3. Demonstration

To demonstrate this inventory-based procedure, the costs of four policy scenarios are summarized from the forest sector carbon budget of the United States (Turner et al., 1993, 1995a, b). The four alternatives are: (1) the 1989 RPA Assessment; (2) Afforestation—Moulton and Richards $110 million; (3) Afforestation—Moulton and Richards $220 million; and (4) High Paper Recycling. These scenarios will be referred to in this paper as RPA, MR110, MR220 and HPR.

Table 1
Year 2000 RPA summary of growing stock, annual growth, annual removals and annual costs (1990 U.S. $) by region

| Region | Forest land | | Growing stock | | Annual growth | | Annual removals | | Annual management costs | Net annual total costs [1] |
|---|---|---|---|---|---|---|---|---|---|---|
| | Area | Value | Volume | Value | Volume | Value | Volume | Value | | |
| | (ha × 10⁶) | ($ × 10⁶) | (m³ × 10⁶) | ($ × 10⁶) | (m³ × 10⁶) | ($ × 10⁶) | (m³ × 10⁶) | ($ × 10⁶) | ($ × 10⁶) | ($ × 10⁶) |
| North | 66.917 | 18516 | 6868 | 200571 | 195 | 6013 | 147 | 4660 | | |
| Annual cost @ 6.15% | | 1139 | | 12335 | | −6013 | | | 1191 | 8653 |
| South | 79.932 | 15459 | 6841 | 222824 | 306 | 8282 | 282 | 7998 | | |
| Annual cost @ 6.15% | | 951 | | 13704 | | −8282 | | | 2453 | 8825 |
| Rocky Mountain and Great Plains | 57.097 | 4157 | 3778 | 33663 | 39 | 407 | 32 | 377 | | |
| Annual cost @ 6.15% | | 256 | | 2068 | | −407 | | | 240 | 2157 |
| Pacific Coast | 42.025 | 2808 | 6020 | 184036 | 118 | 3723 | 116 | 3897 | | |
| Annual cost @ 6.15% | | 173 | | 11318 | | −3723 | | | 701 | 8469 |
| Total US | 245.971 | 40940 | 23507 | 641064 | 658 | 184426 | 577 | 16932 | | |
| Annual cost @ 6.15% | | 2518 | | 39425 | | −18426 | | | 4586 | 28103 |

[1] NTCA, Eq. 3.

The RPA scenario is from the base projections prepared for the 1989 USDA Forest Service RPA Assessment (Haynes, 1990; Turner et al., 1993). In these periodic assessments the TAMM forest sector economic model (Adams and Haynes, 1980) is coupled to the ATLAS inventory projection model (Mills and Kincaid, 1992) to simulate long-term trends in timber supply and costs. The two afforestation scenarios, MR110 and MR220, are from the analysis of costs of sequestering carbon through forestry in the United States by Moulton and Richards (1990). MR110 is based on the expenditure of 110 million 1990 U.S. dollars per year for 10 years to afforest marginal crop and pasture lands ($2.3 \times 10^6$ ha). MR220 is based on the expenditure of 220 million 1990 U.S. dollars per year for 10 years to afforest

Table 2
Year 2000RPA summary carbon pools and fluxes with annual costs (1990 U.S. $) to hold and sequester carbon by region

| Region | Carbon | | | | | Annual net total costs | | |
|---|---|---|---|---|---|---|---|---|
| | Pool | Flux | | | Total sequestered carbon [4] | Total [1] | Average to hold | Average to sequester |
| | | To pool [2] | From pool [3] | To storage | | | | |
| | | | (g-C × 10¹⁵) | | | ($ × 10⁶) | ($/t-C) | ($/t-C) |
| North | 13.530 | 0.057 | 0.020 | 0.008 | 0.045 | 8653 | 0.64 | 192 |
| South | 12.281 | 0.062 | 0.069 | 0.029 | 0.022 | 8825 | 0.72 | 408 |
| Rocky Mountain & Great Plains | 5.101 | 0.005 | 0.002 | 0.001 | 0.004 | 2257 | 0.42 | 526 |
| Pacific Coast | 6.587 | 0.014 | 0.014 | 0.006 | 0.007 | 8469 | 1.29 | 1300 |
| Total US | 37.499 | 0.138 | 0.105 | 0.044 | 0.077 | 28103 | 0.75 | 364 |

[1] NTCA, Eq. 3.
[2] Uptake less decomposition.
[3] Growing stock removals.
[4] Includes long-term forest products storage in use and land fills.

pasture lands ($4.0 \times 10^6$ ha). HPR is based on increases in waste paper recycling from 20.9% in 1986 to 45% in 2000 and a constant level (45%) of waste paper recycling through 2040 (Turner et al., 1993). A separate run of TAMM/ATLAS was made for each of the of the four alternative policy scenarios using similar background assumptions.

Estimates of timberland area are those reported by the USDA Forest Service (1989) and Turner et al. (1993). Forest growing stock, growth and removals are from Haynes (1990), Turner et al. (1993) and Haynes et al. (1994). Carbon pools and fluxes are from Turner et al. (1993). The portion of carbon in growing stock removals going into some form of long-term storage (> 5 years) is estimated at 42% (Harmon et al., 1990). Timberland prices for bare forest land are estimated in constant 1990 U.S. dollars from the land rents used by Moulton and Richards (1990). Growing stock stumpage prices are from Haynes et al., (1994) and expressed in 1990 U.S. dollars. Annual management costs are from the costs summarized by Moulton and Richards (1990), in 1990 U.S. dollars. The discount rate used to estimate annual rents for timberland and forest growing stock (6.15%) is estimated from the average yield of U.S. Treasury, taxable, long-term bonds (more than 10 years) for the period 1981 through 1990. The average yield is adjusted to a real rate by the gross national product implicit price deflator (U.S. Department of Commerce, 1989, 1991, 1992).

These estimates are combined to produce summaries of: forest inventory, growth, removals; associated carbon pool and fluxes; and economic estimates of costs and revenues (Tables 1 and 2).

### 3.1. Geographic comparison

To demonstrate the application of this procedure to estimate of the cost of forest management for interregional comparisons, information from the RPA policy scenario for the year 2000 is summarized by USDA Forest Assessment Service Region (Fig. 1). The inventory statistics are for the year 2000 and annual growth and removals are for the decade 2000 to 2009 (Tables 1 and 2).

#### 3.1.1. Results of geographic comparison

Results of the geographic comparison are presented for the average net total cost to hold carbon as well as the average net total cost to sequester carbon. These illustrate the role of forest ecosystems in maintaining the terrestrial carbon pool and as agents for the sequestration of atmospheric carbon.

The annual average net total cost ($NTC_A$, Eq. 3)

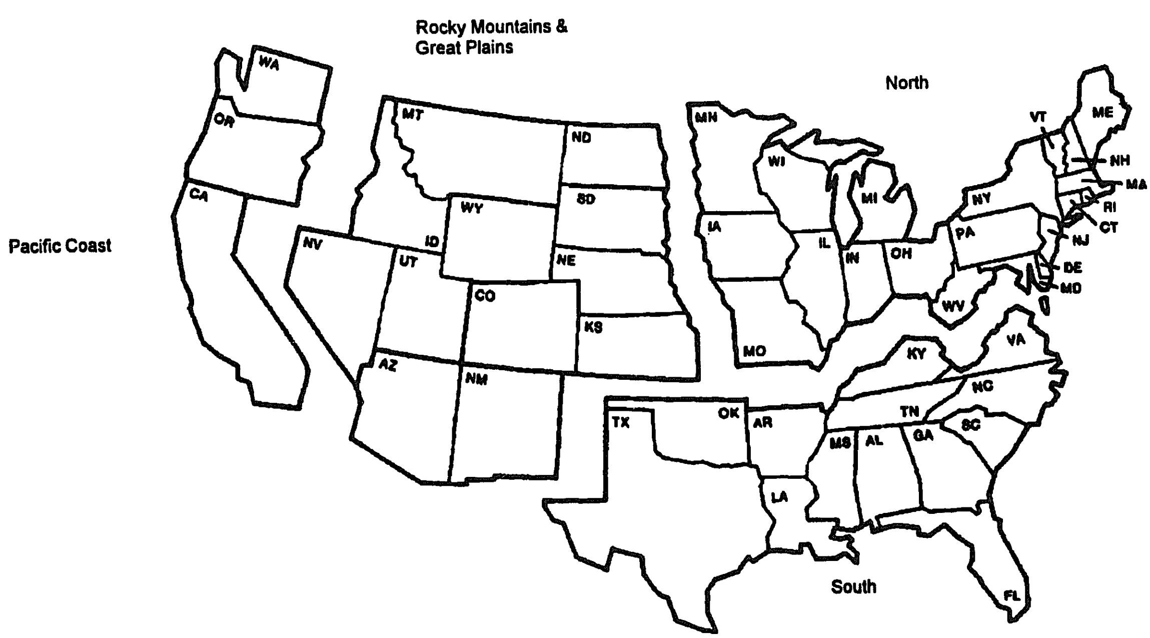


Fig. 1. USDA forest assignment regions.

to hold a ton of carbon in the forest inventory ranges from 0.42 1990 U.S. dollars in the Rocky Mountain and Great Plains Region to 1.29 1990 U.S. dollars in the Pacific Coast Region (Table 2). The average net total cost ($NTC_A$) for the contiguous 48 States is 0.75 1990 U.S. dollars per ton (Table 2). These regional differences reflect varying prices for timberland, standing timber and the annual costs of forest management. Rental cost for use of forest growing stock is the major component (85%) of the cost of holding forest inventories (Fig. 2). Annual management costs and timberland rent are relatively minor components (10 and 5%, respectively) of the cost of holding forest inventories (Fig. 2).

The average net total cost ($NTC_A$) per net ton of carbon added to long-term storage, either in the form of an increase in carbon in the forest ecosystem or in the pool of forest products still in use as well as in landfills, ranges from 192 1990 U.S. dollars in the Northern Region to 1300 1990 U.S. dollars in the Pacific Coast Region (Table 2). The average net total cost ($NTC_A$) for the contiguous 48 States is 364 1990 U.S. dollars per ton (Table 2). These regional differences are due to the interaction between the mass of carbon sequestered in long-term storage and the cost of inputs required to sequester the carbon. Note that the mass of carbon sequestered in long-term storage is a function of the harvest, the portion of the harvest allocated to long-term storage and the biological processes of growth and decomposition. In this demonstration the mass of carbon fixed to long-term storage varies from 0.007 petagrams per year in the Pacific Coast Region to 0.045 petagrams per year in the Northern Region (Table 2). The mass of carbon sequestered in long-term storage in the contiguous 48 States is 0.077 petagrams per year (Table 2).

### 3.1.2. Discussion of geographic comparison

Regional differences in the rate of carbon added to the forest carbon pool are a function of the growth capacity of the forest growing stock inventory and differences in the biological potential due to climate (Table 2). Regional differences in the growth capacity of the forest growing stock inventory are reflected in differences in the biomass required to add a unit of carbon from the atmosphere. These range from 198 metric tons of carbon in the Southern Region to 1020 metric tons of carbon in the Rocky Mountain and Great Plains Region. The biomass required to add a metric ton of carbon in the contigu-

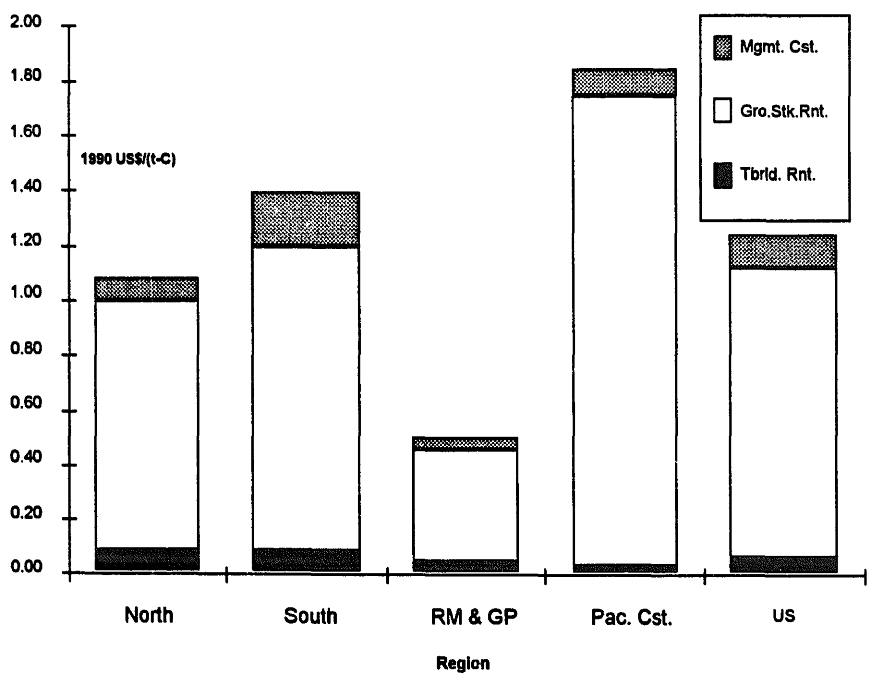


Fig. 2. Year 2000 RPA annual gross total cost of annual inputs required to hold one metric ton of carbon by region. Note: RM & GP = Rocky Mountain and Great Plains; Pac. Cst. = Pacific Coast.

ous United States is 272 metric tons. These differences in the ability of the forest growing stock inventory to sequester atmospheric carbon are confounded by differences in the structure of the inventory. However, they do provide an insight into differences in the potential of the growing stock inventory between regions.

The biological potential of forest ecosystems to concentrate atmospheric carbon is determined by the combination of climatic and edaphic conditions. An incomplete explanation of differences in regional potential is represented by the area of forest land required to sequester a unit of carbon. In this demonstration, these range from 1.2 hectares per metric ton in the Northern Region to 10.4 hectares per metric ton in the Rocky Mountain and Great Plains Region (Tables 1 and 2). The average area of forest land required to sequester a metric ton of carbon in the contiguous United States is 1.8 hectares (Tables 1 and 2). As in the example of the potential of the forest growing stock inventory, these differences are confounded by differences in the structure of the inventory.

These differences in physical productivity interact with land use shifts and differences in the harvest level to determine the rate of annual accumulation or loss of carbon in a region. The ratio of growth to removals is greatest (1.3) in the Northern Region (Table 2) where large areas of hardwoods are accumulating carbon (Haynes, 1990). The costs of regional gains in carbon storage, in turn, are influenced by the varying price of inputs required to sequester a ton of carbon (Table 2). The largest element of these costs is the rent associated with the use of the capital stock represented by the forest inventory. In this demonstration, these vary from 80 percent of gross total costs $(LC_R + GSC_R + MC_A)$ per gross ton of carbon sequestered in the Southern Region to 93 percent of gross total costs $(LC_R + GSC_R + MC_A)$ per gross ton in the Pacific Coast Region (Tables 1 and 2). For the contiguous United States the rent associated with the use of the forest growing stock inventory is approximately 500 1990 U.S. dollars, 85 percent of the gross total cost $(LC_R + GSC_R + MC_A)$ per gross ton of carbon sequestered from the atmosphere (Tables 1 and 2).

These comparisons are based on average regional net total costs. No attempt is made to distribute total costs among the array of benefits derived from forest ecosystems because of the inseparability of the benefit array. An estimate of incremental cost differences between regions can be calculated by dividing the differences in net total costs $(NTC_A)$ by the differences in the mass of carbon held or added to long-

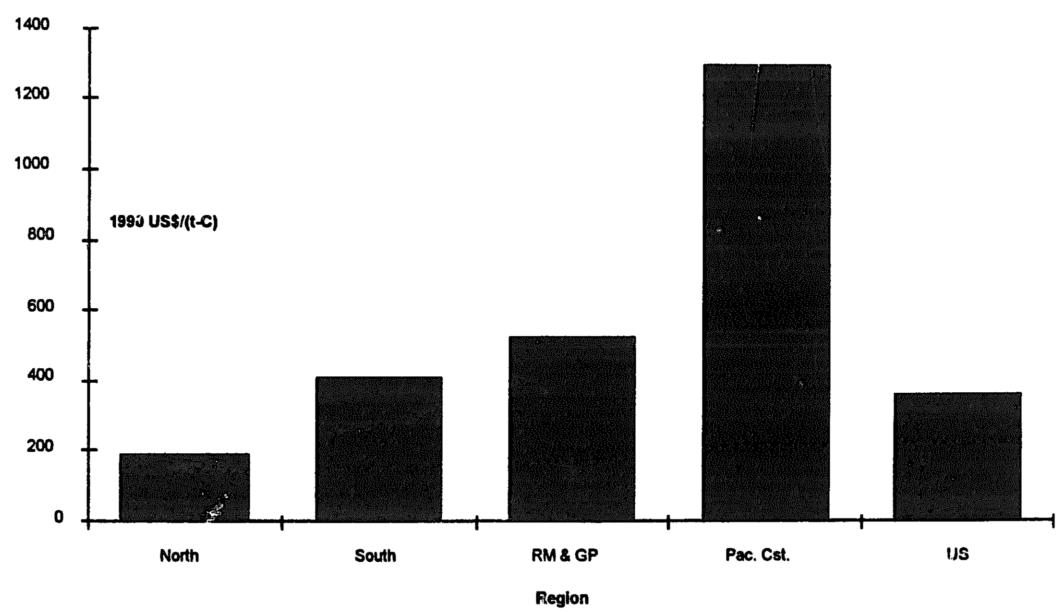


Fig. 3. Year 2000 RPA net total cost of annual inputs required to sequester one metric ton of carbon by region. Note: RM & GP = Rocky Mountain and Great Plains; Pac. Cst. = Pacific Coast.

Table 3
Total and incremental carbon sequestered with costs (1990 U.S. $) by policy scenario, 1990 to 2040

| Scenario | Total carbon | | Mean total cost | | PV of total costs | |
|---|---|---|---|---|---|---|
| | Sequestered (50 years) | Increment from RPA | | Increment from RPA | At 6.15% | Increment from RPA |
| | (T-C $\times 10^9$) | | ($/t-C) | | ($ $\times 10^9$) | |
| RPA projection | 4.1 | | 407 | | 487 | |
| | | 0.33 | | 2.6 | | 52 |
| Moulton and Richards—$110 $\times 10^6$ | 4.5 | | 410 | | 538 | |
| | | 0.48 | | −16.1 | | 49 |
| Moulton and Richards—$20 $\times 10^6$ | 4.6 | | 391 | | 536 | |
| | | 0.29 | | 0.3 | | 47 |
| High recycling | 4.4 | | 407 | | 534 | |

term storage. It is necessary to estimate incremental or marginal costs in this way because of the dynamic interaction between regional inventories, rates of carbon flux and prices.

This demonstration is an example of the interaction between the productivity of a region's forest, based on climatic potential and the potential of the forest inventory. The biological potential is influenced by the level of removals, either in the form of harvest or conversion and the portion of removals allocated to forms of long-term storage. These physical and biological processes interact with the prices of resources necessary to sustain regional forest ecosystems to create the regional differences observed in this demonstration (Table 2 and Fig. 3).

### 3.2. Comparison of policy scenarios through time

This inventory-based procedure can also be applied to questions of efficiency through time. To

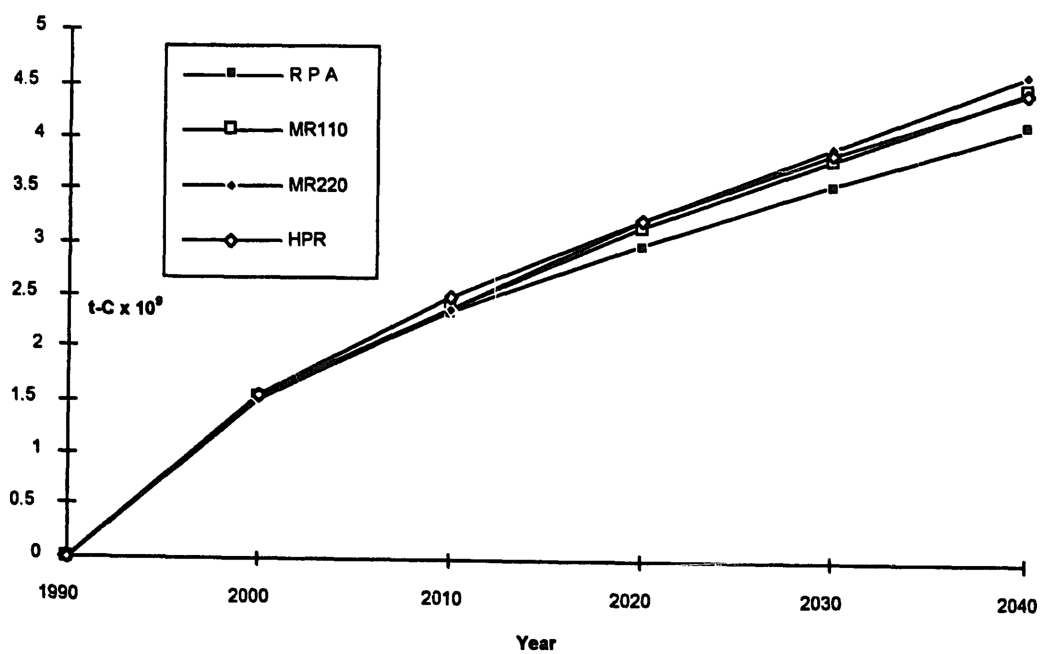


Fig. 4. Cumulative carbon sequestered from the atmosphere to long-term storage by year and policy scenario.

demonstrate this application, forest management costs for the four policy scenarios (RPA, MR110, MR220 and HPR) are estimated for the 50-year period 1990 to 2040 for the contiguous United States (Turner et al., 1993). The results of these estimates are summarized in Table 3 and Fig. 4.

### 3.2.1. Results of comparison through time

The four policy scenarios vary in the total carbon they sequester during the 50-year analysis period. The MR220 scenario sequesters the most carbon because four million hectares were added to the forest land base. Carbon sequestration on these lands was not maximized because through harvesting and regeneration a mixed age class inventory was achieved by the end of the analysis period (Table 3). In the MR110 scenario, only 2.3 million hectares were planted, with a corresponding reduction in total carbon sequestered. The lower harvest level in the HPR scenario allowed more carbon storage in forest inventory and incurred higher inventory holding costs. This was exacerbated by the assumed fixed proportion of the harvest going into long-term storage and the resulting reduction in total carbon sequestered. A more sophisticated forest products model would not have indicated a difference in long-term storage because the harvest reduction is related to paper which has a relatively short turnover time (Row and Phelps, 1990). Average annual net total costs per metric ton of carbon sequestered during the analysis period vary from 391 1990 U.S. dollars for the MR220 scenario to 410 1990 U.S. dollars for the MR110 scenario (Table 3).

### 3.2.2. Discussion of comparison through time

These differentials are the result of the interactions between the quantity and characteristics of inputs and their prices. As discussed in the regional analysis, the quantity and price of growing stock inputs are the dominant cost elements. This element of the demonstration is also based on average net total costs and no attempt is made to distribute costs among the array of forest benefits.

Policy scenarios also differ in their rates of carbon accumulation during the analysis period (Fig. 4). During the first two decades of the analysis the HPR scenario has the highest rate of carbon sequestration because reductions in harvest levels are rapid after the increase in paper recycling is implemented (Fig. 4). However, by the third decade the MR220 scenario is sequestering carbon at a higher rate than the HPR scenario and by the fourth decade the HPR scenario is being surpassed by both the MR220 and MR110 scenarios. This occurs because the maximum accumulation rates in the afforestation scenarios occur about the third decade because growth rates, on the afforested area, are near their maximums and harvests have yet to begin. The loss of harvest and resulting inventory accumulation and aging, toward the end of the analysis period, cause the declining rate of carbon accumulation for the HPR scenario.

In total the policy scenarios differ in the amount of carbon sequestered over the 50-year period and in their relative efficiencies. Harvest level is a strong determinant of the total carbon sequestered because approximately 80 percent of the increase in carbon storage was in the pool of forest products still in use or in landfills. The efficiencies of the afforestation scenarios are high relative to the HPR scenario because harvest levels on private land and resulting carbon storage in the products pool, are greater.

This demonstration is limited to one country, so it does not reflect the differences in discount rates that would be reflected in the rents for bare forest land and growing stock. The expected differences, between nations and regionally within continents, in the proportion of the harvest utilized in forms of long-term storage are also not reflected in the demonstration.

## 4. Summary

This inventory-based procedure is designed to meet the specific objective of assisting the international comparison of management alternatives to conserve and sequester carbon. To this end, the significant findings and caveats summarized here are intended to identify the key advances toward the objective and its requirements.

Foremost, the procedure includes all relevant cost categories. On an international scale, costs of forest management, including land rent, have been addressed before, but the cost of holding the forest inventory is new. Inventory holding costs have historically been considered in stand management decisions *within* forest areas. However, they were ignored in decisions on a regional scale because such decisions were seldom required. Inventory holding costs must be included for comprehensiveness when making choices *among forested nations* or *regions* within continents. Such choices are starting to be considered to mitigate the threat of global warming. The inventory-based procedure meets this need.

A further contribution of the procedure is that it facilitates the analysis of the distribution of impacts resulting from forest policies to mitigate global climate change. The procedure provides an annual summary of total costs that is the basis for regional input–output analyses to determine the distribution of impacts.

Finally, the procedure meets the requirement to accommodate the range of biological and economic considerations encountered in regional examinations of forest policy. The biological data on forest growth, inventory, area, and harvest removal are integral to estimates of national and regional carbon budgets for the forest sector; and equally important these data are used in a form that is generally available in the literature for many forests within nations or regions around the world. The economic data, which includes costs of forest management, land, inventory values and discount rates, are likewise generally available in the literature.

Results of these features of the inventory-based procedure are shown in the findings of the demonstration. Both the geographic analysis and the analysis through time elements of the demonstration have key findings as illustrations of the capability of the procedure.

For example, in the geographic analysis, the procedure effectively identified the U.S. forest region with the least cost per unit of carbon stored: i.e., the Rocky Mountain and Great Plains Region at 0.42 1990 U.S. dollars per metric ton of carbon (Table 2). Further, the reason is apparent when comparing the Region's favorable price differential of 0.22 1990 U.S. dollars per metric ton of carbon which is 0.7 as much as the price in the Northern Region with the second least price per unit of carbon stored.

Also from a geographic viewpoint, the procedure identified the North as the U.S. Region that *sequesters* carbon for the least cost at 192 1990 U.S. dollars per metric ton (Table 2). It is important to note that this is a different region from the one identified above for carbon storage. Again the reason is apparent from the interaction of the price differential for forest growing stock and the forest growth/growing stock relationship. That is the price of forest growing stock is 3.40 1990 U.S. dollars per cubic meter less in the Northern Region than in the Southern Region and the ratio of net carbon fixed/to the carbon pool in the Northern Region is 1.9 times the same ratio in the Southern Region.

Turning to the analysis through time, the procedure identified MR220 as the forest policy with the lowest total cost per metric ton of carbon sequestered over the period 1990 to 2040 (Table 3). In this case the MR220 policy scenario has a total cost per ton of carbon sequestered of 391 1990 U.S. dollars compared to the other policy scenarios that are approximately 410 1990 U.S. dollars. These differences occur because four million hectares of young plantations were added to the forest inventory during the analysis period which in turn led to increased levels of harvest from private lands. The increased level of harvest was reflected in increased short-term supplies in stumpage markets that resulted in reduced stumpage prices. Reductions in stumpage prices reduce the holding costs of forest inventory, which is the largest (approximately 80%) component of the cost of forest management.

The demonstration also yielded an interesting ancillary finding concerning changes in the asset value of forests. The policy scenarios examined in the demonstration induce changes in the supply of standing timber offered in stumpage markets. Haynes et al. (1994) estimate that stumpage prices will be reduced from RPA levels by between 9 and 14 percent during the analysis period. The inventory-based procedure estimates that stumpage price reductions of this magnitude would result in a loss in wealth for owners of forest growing stock of between 100 and 160 billion ($10^9$) 1990 U.S. dollars. A loss of this magnitude is approximately 1/6 to 1/4 the loss suffered by equity owners of publicly traded corporations in the stock market crash of October 1987 (Gammill and Marsh, 1988). Losses of this magnitude in addition to the losses in income derived from the sale of timber identified by Winnett et al. (1993) provide additional information to assess the impact of forest policies on landowner behavior.

Several caveats to the use of the inventory-based procedure are important to note. One is that the procedure as demonstrated does not discriminate between growing and harvesting young-growth over old-growth forests based on the cost of carbon sequestration. This is because the level of resolution used in integrating the economic information with the forest inventory and carbon budget does not allow recognition of carbon emissions associated with the harvest of old-growth forests identified by Harmon et al. (1990). For this reason, the procedure should not be used to argue for the harvest of old-growth forests to make way for more rapidly growing second-growth forests.

Other caveats are: (1) As noted earlier, the current state of science does not allow the valuation of all benefits derived from the management of forest ecosystems, especially non-market benefits such as watershed services, recreation and tourism, wildlife products, protection of wildlife diversity, climate regulation and carbon sequestration and release (Kramer et al., 1992). When comprehensive numerical estimates of benefit value can be added to the decision process, different choices about best regions and policies will be identified. (2) There is a need to address the accumulation of errors that occur when data from a variety of sources with unknown precision are combined as was done in this demonstration. Rigorously applied, such a statistical treatment would probably show unacceptably low probabilities of true differences in the outcomes of analyses like the demonstration analysis in this paper. Given the state of current information, the best recognition of the problem of error terms remains sensitivity testing.

Overall, however, the procedure proposed here is a step that promises the capability to effectively identify least-cost alternatives for sequestering and storing carbon through forest management. Two important directions are seen. Within a forested nation or region, the procedure could help select the least-cost forest policy and compare its cost per ton of carbon to the other non-forest policies to determine the most efficient carbon mitigation alternative. Among forested nations or regions of the world, summing all the geographic and intertemporal costs of forest carbon would provide an opportunity to determine the least-cost locations for investing in forest management for mitigation purposes. Both outcomes of the inventory-based procedure would provide vital aid to international decision making on the use of forest management to sequester and store carbon.

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