AN ABSTRACT OF THE THESIS OF

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Title: Carbon Flux Patterns on U.S. Public Timberlands Under Alternative Timber Harvest Policies

Abstract approved:

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This study considers trade-offs between timber harvest and carbon sequestration on National Forest and other public lands by contemporaneously linking a model of public harvest and inventory to a carbon accounting system. The public harvest model treats three harvest scenarios. The first minimizes the cost of meeting harvest requests that approximate current harvest policy. The second and third models represent two extremes of harvest policy: maximum strict even-flow scheme and no-harvest. The current harvest scenario results in a maximum average net carbon sequestration of approximately 35 Teragrams per decade. The maximum strict even-flow scenario results in a maximum of 19 Teragrams of net carbon sequestration on an average decadal basis, because of losses to forest product decay and reduced understory growth. The no harvest scenario results in the highest total carbon holdings, 164 Pentagrams at the end of the 100 year planning horizon, and has an average net sequestration rate of 65 Teragrams each decade.

Carbon Flux Patterns on U.S. Public Timberlands Under Alternative Timber

Harvest Policies

by
Alyssa V. Shanks

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Alyssa V. Shanks, Author

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INTRODUCTION:

For decades there has been interest in the role of forests in global climate change mitigation via their carbon sequestration potential. As methods for carbon stock and net sequestration quantification were devised, interest extended to quantifying changes in forest carbon due to timber harvest, forest management methods, and afforestation of non-forested land. The aim of much research has been to understand if it is possible to increase carbon sequestration through changes in land management. Initial studies focused on private timberland with the result that public timberland – federal, state, county and municipal ownerships – remained understudied until the last decade. Recent research on public lands has yielded groundbreaking papers that have helped shape how practitioners think about and quantify forest carbon. This work is particularly important because small management changes across the vast areas of public timberland have potential to greatly impact the ability to sequester carbon in the US.

Past public timberland models have treated either timber harvest or carbon sequestration as exogenous. The approach developed in this thesis combines timber harvest and carbon sequestration into a single interactive model. This allows simulations of a broad range of timber harvest and carbon sequestration scenarios. Modeling harvest and carbon sequestration also yields a more complete picture of the tradeoffs between harvest volumes and carbon. If the U.S. creates or participates in

markets for trading carbon, joint modeling of harvest and carbon could assist public land managers in making management decisions that yield more efficient land use allocations.

To understand the full impact of carbon sequestration from National Forests, state, county, and municipal lands it is necessary to use national scale models. The ATLAS (Aggregate Timberland Assessment System) model was created in 1989 for the national RPA (Resources Planning Act) timber assessment and has continued to be the model used for subsequent RPA assessments (Mills and Kincaid, 1992). ATLAS projects inventories using assumptions concerning growth and yield, harvesting, land use and forest cover. TAMM (Timber Assessment Market Model) and FASOMGHG (Forest and Agriculture Sector Optimization Model – Greenhouse Gas version) are national market models. TAMM models national markets for forest products (Adams and Haynes, 1996). FASOMGHG models forest product and agriculture markets and how changes in those markets can result in changes in net greenhouse gas emissions (Adams et al., 2005).

A previous study by Depro et al. (2008) modeled public timberland harvest and the resulting carbon sequestration. They modeled current harvest levels, pre-1989 harvest levels, and a no-harvest case. The harvests in the first two cases were distributed by allocating harvest volumes according to the percent of regional volume present in a given stand. This study builds on the work of Depro et al. by constructing a formal harvest scheduling model to simulate alternative harvest regimes on public lands across the United States. Carbon accounting is integrated in the timber harvest model. The model created here is similar to FASOMGHG in that costs are included in

the model and carbon can be given a unit price. Unlike FASOMGHG this model does not simulate markets.

The model can be used for both state and federal agencies to assess the carbon and timber potential on their lands and identify forest characteristics that make lands better suited for carbon sequestration, timber harvest, or are compatible for both uses. Modeling different harvest scenarios enables us to see how different levels of harvest affect the total levels of carbon sequestered in the forests and also in the resulting forest products. The model's compatibility with FASOMGHG allows researchers to model the effects that public timberlands can have on timber, agriculture, and carbon markets when incorporated into FASOMGHG.

The objective of this study is to analyze the potential for trade-offs between net carbon sequestration and timber harvest on National Forests and other public timberlands in the U.S. The model created for this study allows the estimation of changes in carbon sequestration levels as harvest changes. We compare a range of potential harvest policies and the associated carbon inventories and flux rates over time. The analyses of the various harvest policies are conducted for the U.S. as a whole.

National forests in the United States total approximately 182 million acres while other public lands total 46 million acres, excluding Alaska and Hawaii (Smith et al., 2004). Of these public forest areas, 138 million acres are classified as timberland. Although not necessarily managed for timber, timberlands are those lands that accumulate at least 20 cubic feet of industrial wood per acre per year. To meet the timberlands classification, the lands must also be available for timber harvest and not

made inaccessible by statute or regulation. The majority of these public timberlands are located in the western United States (Alaska and Hawaii are excluded from study due to insufficient data).

These lands, holding over 40% of the nation's growing stock, presently contribute less than 10% of the US timber harvest. Separately, National Forests contribute approximately 2% of all timber harvest and hold 30% of the growing stock (Smith et al., 2004). With growth currently outstripping harvest, natural mortality alone cannot reverse the accumulation of carbon as the current age class distributions yield large blocks of densely growing younger stands. One contributing factor to the rapid accumulation of carbon and growing stock is the age class distribution on public timberlands (Haynes, 2003).

Most of the timberlands under consideration have been harvested in the past; and the distribution and timing of those previous harvests have determined the age distributions of the current forests. Other public lands have not been as intensively harvested as National Forest timberland and contain larger percentages of older timber (Mills and Zhou, 2003). National Forest lands, although sparsely harvested in recent years, were heavily logged and densely reforested for decades with the result being a large accumulation of trees in relatively young, rapidly growing and heavily stocked stands.

PAST STUDIES:

Although little work has been done on joint harvest optimization and carbon

sequestration on public lands, much research has been conducted on methods for

calculating carbon in forests and forest products. Equations for estimating carbon have

been continually improving, with coefficients being honed for more specific forest

types and regions (Smith et al., 2004). These equations require detailed inventory data

on the forest lands for which carbon is being estimated. Smith et al. (2004) outlined

straightforward methods for computing live tree, standing dead tree, understory,

coarse woody debris, forest floor and soil carbon. Using representative average values

for tonnes of carbon per hectare allow for quick and widely accessible carbon

calculations. While still employing average values, Smith et al. (2006) improve upon

commonly used methods for calculating coarse woody debris by incorporating the

pulse of debris that remains on-site after harvest. Turner et al. (1995) calculated

decomposition rates of logging residues and mortality rates of live trees that contribute

to coarse woody debris to more accurately model the extended effects of harvesting on

forest carbon.

Harvest not only impacts carbon levels by removing standing trees and adding

debris, but also by converting standing timber into wood products. Accounting for

carbon held in the resulting forest products is necessary to accurately estimate net

carbon sequestration over time rather than assuming that all product carbon is

immediately released at time of harvest (Turner et al., 1995). Incorporating this slowly

decaying pool of carbon has become more detailed over time. Originally, product

carbon incorporation was very general. In currently accepted methods, harvested

carbon is divided into four categories (products in use, products in landfills, energy, and emissions) as carbon sequestration and disposition through time for each category vary separately. Accounting for the carbon offsets by burning wood products as a replacement for fossil fuels started with a publication by Marland and Marland in 1992 recognizing that sequestering one ton of carbon is just as useful to climate change mitigation efforts as reducing carbon emissions by one ton. Modeling net carbon sequestration with and without the energy credit is common practice (Smith et al., 1996, Depro et al., 2008). Depro et al. (2008) estimate 7.5 Teragrams of carbon would be sequestered in wood product carbon in 2010 if public harvest remains at current levels. Smith et al. (1996) projected a net carbon sequestration of 24 to 67 Teragrams of carbon in wood products between 2000 and 2009 depending on harvest levels.

Estimates of future carbon sequestration on public lands vary dramatically depending on harvest level assumptions. Depro et al. estimate carbon sequestration on public lands at between 20.86 and 74.64 million metric tones per decade depending on harvest. The highest decadal sequestration, 93.3 MMTC, was found under a no harvest scenario, while the lowest decadal sequestration, 12.9 MMTC, occurred under their pre-1989 harvest level scenario. Depro et al. use the same current harvest levels as this study; they report an average of between 51.68 and 53.88 MMTC sequestered each decade from 2000 to 2050.

METHODS:

Scenarios:

Three scenarios are projected with the model. The first scenario, current harvest, is simulated by minimizing the cost of harvesting preset, policy-driven volumes of timber, mimicking current harvest regimes. The second scenario, maximum strict even-flow, maximizes first period harvest subject to the constraint that all subsequent periods must be the same. The third scenario is a no harvest option. Each of the three scenarios considers the U.S. as a whole.

Data:

Inventory data for National Forests and other public timberlands come from Forest Inventory and Analysis (FIA) measured plot data. John Mills and Xiaoping Zhou (2003) projected the growth and yield for National Forest and other public timberlands using the ATLAS model. For this analysis the data were projected without land use change or changes in forest cover type. Stand growth includes assumed changes in growth rates due to changes in temperature and rainfall associated with global climate change.

ATLAS inventory data are classified by region, owner, forest type, management intensity, site class, area, wood type (softwood and hardwood), and age class. (See appendices B and C.) Of these variables, site is assigned an average value of medium site class for all stands. Geographic regions in ATLAS and the national regions used in this model are the same, which are shown in figure 1. Oregon and Washington from the crest of the Cascade Mountains west comprise the Pacific

Northwest West region, while to the east of the Cascades crest lies the Pacific

Northwest East region. California comprises the entire Pacific Southwest region. The

Rocky Mountain area includes both a north and south region. The Rocky Mountain

North region holds Idaho and Montana; this is far less forest land than the Rocky

Mountain South region which holds Nevada, Utah, Colorado, Arizona, New Mexico,

and Wyoming. Most of the Corn Belt region holds comparatively little forest land and

includes North and South Dakota, Nebraska, and Kansas. The Lake States region is

made up of Minnesota, Wisconsin, Ohio, Indiana, Illinois, Iowa, and Missouri. The

North East region includes Connecticut, Delaware, Maine, Massachusetts, New

Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West

Virginia. There are two regions in the South, South Central and the South East. South

Central encompasses Texas, Oklahoma, Louisiana, Mississippi, Alabama, Arkansas,

Tennessee, and Kentucky. South East region covers Florida, Georgia, South Carolina,

North Carolina, and Virginia. (See figure 1.)

National Forest and other public are the only owners in the simple ownership

category. Forest type comprises over twenty five types. Specific forest types exist for

each region ranging from Maple-Beech-Birch and Oak-Pine stands in the Corn Belt

region to Douglas-fir and Western Hemlock in the Pacific Northwest West region. The

harvest categories that describe the management intensity set include low, low-partial-

cut, and reserved for all regions. Reserved stands are stands that have been removed

from harvest by political or departmental mandate. These stands were removed from

management in this study. Low-partial-cut stands are stands available for partial

harvest only, while low management intensity stands are available for both partial

harvest and clear cut harvest. In this model, all stands were treated as partial harvest only. Growth after partial harvest was very conservative; no additional increase in the rate of growth occurs after partial harvest and in this way harvests are similar to small patch cuts. Given the current harvest practices of the Forest Service, this appears to be the most accurate way to model National Forest and other public lands.

Initial age classes in ATLAS were converted to starting cohorts for harvest scheduling model. Cohorts consist of age classes from 0-4 years increasing in five year increments up to 90+ years for the Southern Regions and 250+ years for all other regions. Cohorts exist only for existing stands that have been planted prior to the start of the planning horizon, 2000-2100, and grow until harvested. Although acres grow and age throughout the projection period, the starting age cohorts remain the same, because starting age class is a key identifying characteristic. New stands are stands that have been planted after harvest since the start of the planning horizon. New stands use the set "age" to define their age classes and differentiate their acres from the cohorts of the preexisting stands. The age set extends from 0 to 100 years in five year increments, because harvests occur at the end of every five year period throughout the 100 year projection period.

Inventory volumes were converted to product proportions – saw timber, pulpwood, and fuel wood — using product proportions from the 1990 FASOM. This conversion was done in order to make the ATLAS volume projections compatible with optimization modeling in GAMS. (See table 1.) These product proportions represent the amount of each of these products in standing timber. ATLAS tracks stands by their acreage, while the GAMS model tracks stands by their starting age

cohort, or age class. To rectify the tracking methods of the two programs, the ATLAS age cohorts were manually altered to represent the starting age cohorts. Data quality was assured through a series of automated error checks in Excel and GAMS. Starting volumes and acreages were also compared to the results of previous studies and inventories to catch any irregularities that might indicate underlying errors.

Other than the stand level data, the model uses carbon coefficients, percent decay, and mortality rates to calculate the carbon volumes in each of the six carbon pools. These six pools are standing live trees, standing dead wood, downed dead wood, understory, soil, and forest floor. These pools and most of the coefficients come from multiple publications of previous carbon modeling work by Smith, Heath, Jenkins, and others. Smith et al. (2003) calculated the carbon coefficients in their 2003 paper. The various sets of coefficients were applied to the stand age, total volume, or growing stock volume depending on the carbon pool being estimated. Coefficients link are specific to each region, forest type, age, and wood type. (See table 2.)

The current harvest model used harvest levels projected by Alig (2005) based on harvest levels in the 2002 Resources Planning Act (RPA) Timber Assessment (Mills and Zhou, 2003). The harvest request levels are based on the "business as usual" harvesting by the Forest Service and other public land managers in recent years. These harvest requests specify harvest volume removals only by region and year; the non-specific nature of these harvest requests allows the model to choose which stands to harvest to achieve the minimum cost. Harvest levels for public lands are set by policy; forest managers on-the-ground operate to meet those target harvest levels at the minimum budget costs. Harvest costs are not incurred, only growing

costs. Growing costs include planting and forest management costs. Since public lands contract to private companies, private sector growing costs can accurately characterize, and be used as a proxy for, public growing costs (Adams, 2006). This equality allowed the use of private industry cost data compiled by Latta (2006) of Oregon State University for all of the growing costs in the model. Although these costs are growing costs, the costs are accrued when stands are harvested. Thus, only when a stand is harvested is it possible to know what effort, and therefore cost, has been applied to the stand. These costs are used when model objectives include minimizing cost. To maximize even-flow harvest only available volume and age class information are needed.

Model:

To project future harvests and inventory on public lands we employ a model II

harvest scheduler (Johnson, and Scheurman, 1976).[1] The model has two forms,

depending on the scenario being simulated. The current harvest model forces cut to

follow pre-specified harvest levels by minimizing the discounted present value of all

future management costs subject to constraints on available acres, starting volumes per

acre, regeneration volumes per acre, minimum harvest ages, and the creation of

regenerated acreage. The maximum strict even-flow model finds the highest

sustainable harvest level over the planning horizon subject to constraints on minimum

harvest age, available acres, starting volumes per acre, regeneration volumes per acre,

and the creation of regenerated acreage. There is no preset harvest level in the

maximum strict even-flow model and the objective function maximizes only first

period harvest, because of the additional restriction that harvests in all subsequent

periods be equal to first period harvest. (See appendix A.) The no harvest model

simply projects the uncut inventory through the projection period

The model projects the volume growth in existing stands and new stands

created by harvesting stands during the projection period.[2] The model removes any

harvested volumes from stands and continues to track the remaining non-harvested

volume to the end of the projection period or until all volume is harvested. Along with

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[1] Model II programs pool forest acres with identical forest characteristics such as age, forest type, management intensity, region, and site class. Harvests are removed from the pools of acres and all regeneration from that period with identical forest characteristics are pooled together.
[2] Existing stands are stands that had volumes greater than zero at the start of the projection.

tracking the remaining forest volume and the resulting carbon, the model also tracks

the path of harvested volume and determines the amount of wood products in use,

transferred to landfills, consumed as energy, and ultimately emitted to the atmospheres

as emissions.

Under each scenario, the model first projects harvest and inventory volumes

through the planning horizon The model then calculates the product proportions of the

harvest volumes– softwood saw timber, softwood pulp wood, softwood fuelwood,

hardwood saw timber, hardwood pulp wood, and hardwood fuelwood. Carbon stock is

calculated based on unharvested volumes, logging residues, and harvested volume in

wood products. Carbon stock volumes are calculated using Smith et al. (2004)

coefficients for standing live and dead tree carbon, understory carbon, and forest floor

carbon. Coarse woody debris is calculated using mortality rates and logging residue

decay rates from Turner et al. (1995). Harvested carbon is calculated as product

carbon based on the product proportions of the harvested volumes.

For each scenario, the resulting forests are analyzed by age class distribution

and net carbon sequestration.[3] These model results are compared and analyzed to

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[3] Stand age must be computed because the model uses age classes and tracks existing
stands by their starting age cohort using 5 year age classes. A map was created in
GAMS that relates each starting age cohort to the mean age for that cohort. For
example the cohort '5 to 9' is set equal to its mean age of 7 years. That starting age is
then added to the current period, which also uses a map, minus the starting year, 2000.
(See below equation.) A similar calculation is used to calculate new stand age. The
year the stand was planted is subtracted from the current age. This simple calculation
shows if stands are aging correctly, and what forest age distributions will likely be
under various management objectives. This calculation of stand age also allows the
imposition of minimum harvest age constraints.

Existing Stand Age= starting age + (current year-2000)

understand the trade-offs under each management objective between timber verses

carbon. Resulting product carbon is tracked as each product carbon pool decays and

turns to emissions at a different rate. Understanding how long carbon is held in

different product pools and when the release of these products occurs can aid

management and policy decisions.

Volume Growth:

As the model proceeds through the planning horizon, 2000-2100, it looks up

the volumes per acre for each existing stand in each period which are obtained from

yield tables derived from ATLAS (Mills and Zhou, 2003). Per acre volume for each

stand is tracked in six product categories as previously noted. The model also tracks

volume per acre for new stands (stands created when a stand or any part is harvested)

from yield tables created by ATLAS. Forest types for new stands are assumed to be

the same as the preceding stand that was harvested. Figures 2 and 3 outline the flow of

computations in the harvest scheduling models.

Harvest:

In current harvest analysis, harvest volumes intended to represent a

continuation of current timber supply policies on public lands are removed from the

inventory in each period (Haynes, 2003). The harvest requirements are filled assuming

that public agencies meet the required harvest volumes in a way that minimizes the

New Stand Age = current year- year planted

present value of all future silvicultural costs. This approach is used to approximate the actual harvest allocation policies of public timber management agencies, which are unknown. Note that the cost minimization does not include harvest or transportation components, only the silvicultural investments of planting and subsequent treatments.

In the maximum strict even–flow analysis, the model finds the highest strict even-flow level that can be maintained during the projection period, subject to minimum harvest age restrictions. Reserved stands are unavailable for harvest by political mandate and do not enter consideration for harvest in either approach.

The disposition of harvested volume removed in each region and period is tracked to product use and disposal stages. These harvested products are classified as product carbon that is tracked to determine the fate of each cubic foot of harvested volume and assign its decay rate throughout the projection period.

Carbon:

Carbon calculations vary by carbon pool of which there are six; standing live tree, standing dead tree, understory, coarse woody debris, forest floor, and soil. (See figure 4.) Some carbon pools depend on the standing or growing stock biomass in the forest. Other pools depend on only the age of the stand or the particular region in which the stand is located. These independent variables in each carbon pool make the carbon coefficients and equations very different for each pool.

Standing Carbon:

Standing live trees and standing dead wood calculations are similar, although they use necessarily different coefficients. Both equations depend on the volume of growing stock in the forest. Standing dead wood carbon depends on live tree carbon, which in turn depends on growing stock. The decay rates of the carbon in standing dead trees are built into the coefficients and equation. Standing live tree carbon equations come from Smith, Heath and Woodbury (2004). They calculate live tree mass density in dry weight tons per hectare (see equation below).

Live Tree Biomass Density Equation:

Live tree mass density (entire tree, tons carbon per hectare) = F * (G + (1 – exp(-volume/H)))

where F, G, and H are coefficients specified by region and forest type.

Standing dead tree carbon mass density is also calculated in tons per hectare.

Standing Dead Tree Mass Density Equation:

Standing dead tree mass density (tons carbon per hectare) = (predicted live biomass density) * A *exp(-((volume/B)^C))

where A, B, and C are coefficients specified by region and forest type.

Live and dead tree carbon amounts are computed in tonnes per hectare as biomass density instead of carbon mass density. To convert hectares to acres, biomass density is divided by 2.471 acres per hectare. To further convert biomass density to carbon mass density, biomass density is multiplied by 0.50 kg of carbon per kg of biomass,

because carbon mass is approximately 50 percent of dry biomass (Birdsey, 1992).

With these conversions, the standing live and dead tree carbon equations yield tons of

carbon per acre.

Forest Floor Carbon:

Forest floor carbon includes litter and debris smaller than 7.5 cm in diameter.

Forest floor carbon density is calculated using two equations in Smith et al. (2004).

Net accumulation and decomposition are two separate equations; to calculate total

forest floor carbon at any given time the two equations are summed. Unlike standing

carbon, forest floor carbon is calculated using age as below.

Forest Floor Carbon Equations:

Net accumulation = (A * age)/(B + age)

Decomposition = C * exp(-age/D)

The equations yield carbon density tons per hectare, and therefore only need to be

converted from hectares to acres. Using the difference of these equations assumes that

all stands undergo constant reforestation after harvest, and no land use change is

allowed. Because all land being modeled is publicly owned, consistent land use is a

reasonable assumption.

Understory Carbon:

Understory carbon calculations use ratios of live tree carbon to estimate carbon

held in understory vegetation. These ratios of understory carbon to live tree carbon

used to calculate understory carbon come from a 2003 EPA document on US

greenhouse gas emissions and sinks (EPA, 2003). Each region and forest type has a specific ratio of understory carbon to live tree carbon, and the understory carbon is calculated by dividing the ratio by 100 and multiplying the resulting percentage by the live tree carbon biomass. (See example in table 2.)

Coarse Woody Debris:

Estimates of carbon in coarse woody debris use the years since harvest to compute decay and mortality accumulation rates. Carbon accumulations due to natural mortality were calculated using mortality rates from Turner et al. (1995). Carbon resulting from logging residue was calculated by first estimating logging debris and then accounting for the decay of the debris. Logging debris was assumed to be twenty percent of all harvested volume and includes stumps and roots (Birdsey 1996). Decay rates applied to logging residues came from Turner et al. (1995). The carbon in decaying logging residues and naturally accumulating mortality were summed over each period, region and forest type to calculate total coarse woody debris carbon. These per acre totals were multiplied by Birdsey's 0.5 to arrive at carbon mass per acre.

Soil Carbon:

The stands in this model do not change land use; all stands that are harvested are assumed to be immediately reforested. According to Heath et al. (2001) this results in little change within soil carbon. These negligible changes in soil carbon under

reforestation management regimes allow the assumption that soil carbon remains constant over the planning horizon.

Product Carbon:

Once a stand is harvested, some of the carbon that was in standing live trees is converted to product carbon. From each acre harvested, a given volume of hardwood or softwood sawtimber, pulpwood, and fuelwood are removed. The carbon paths for harvested wood products are again: products in use, products in landfills, products used for energy, and products that go directly to emissions. The dispositions of the products change each period after harvest and product carbon shifts from being heavily sequestered in use to mostly in landfills and eventually into emissions. Once in these dispositions, the different decay rates from the various products were used to determine the total emissions. Accounting for the carbon held in wood products is important, because some timber products, like wood beams in houses, are designed to last over 100 years. To assume that decay rates of carbon sequestered in wood beams and carbon sequestered in paper are equivalent would be a significant generality, as would assuming all harvested carbon is immediately released into the atmosphere. Using the decay rates of Smith et al. (2006), product carbon in short-lived pulpwood decays faster than product carbon in long-lasting sawtimber, resulting in differences in product decay rates. On a 100 year planning horizon, a significant percentage of harvested carbon would still be sequestered in some of these long-used products at the end of the planning horizon.

As product carbon decays, the released carbon is added to carbon emissions. Although all harvested carbon will eventually be released, accounting for the carbon as it is released provides a more accurate picture of carbon sequestration and emission in each period for use in policy and decision making.

The products used as energy can be a source or a sink depending on how they are treated. Energy is a sink if one ton of carbon sequestered is equal to one ton of carbon not released as fossil fuel emissions. In this model, the methods are considered separately.

The coefficients used to calculate harvested carbon dispositions are given in the form of percentages of harvested carbon in each product type. (See table 3.) These percentages are multiplied by harvested carbon each period after harvest to create a continuous account of harvested carbon sinks and emissions.

Optimization:

Formulating the model as a linear program allows the harvest scheduling problem to be specified as an optimization problem; harvest plans for each stratum need not be specified in advance. Instead of assuming a management regime for each stand and calculating the associated carbon impacts, the linear program can optimize the management regime over a region given a set of constraints within which to operate. Using harvest requirements as the constraints, the model minimizes costs by choosing which stands to harvest in each period and which to let grow. The restrictions and objectives can be switched at will to investigate tradeoffs and changes in optimal management under different objectives. For example, the constraint on

harvest levels in one model becomes the maximized objective function in another. With costs for management given, a harvest target can be set and costs minimized to achieve the harvest goals in the most cost efficient manner. The model can also maximize strict even-flow harvest given minimum harvest age constraints to explore how much timber and carbon can be jointly produced in a sustainable fashion.

Costs in the model are discounted at a four percent real rate. Since projecting any change in this discount rate would be arbitrary, the discount rate is assumed to remain constant over the planning horizon. (See appendix A.) To maximize even-flow harvest the linear program actually minimizes the negative of even-flow harvest. Since maximizing an objective function can to lead to problems with unbounded variables, minimizing the negative of the desired objective is preferable when possible.

Figure 1. FASOM regions.

Model Inputs:

Existing Stands	New Stands	Harvest	Carbon
Costs per acre	Costs per acre	Requested Volume	Carbon coefficients
Volume per acre	Volume per acre	Minimum Harvest Age	
Initial acres			

Model 2 style, linear program

Model Outputs:

Existing Inventory	New Acres	Product Carbon	Forest Carbon
	New Inventory	Total Cost	
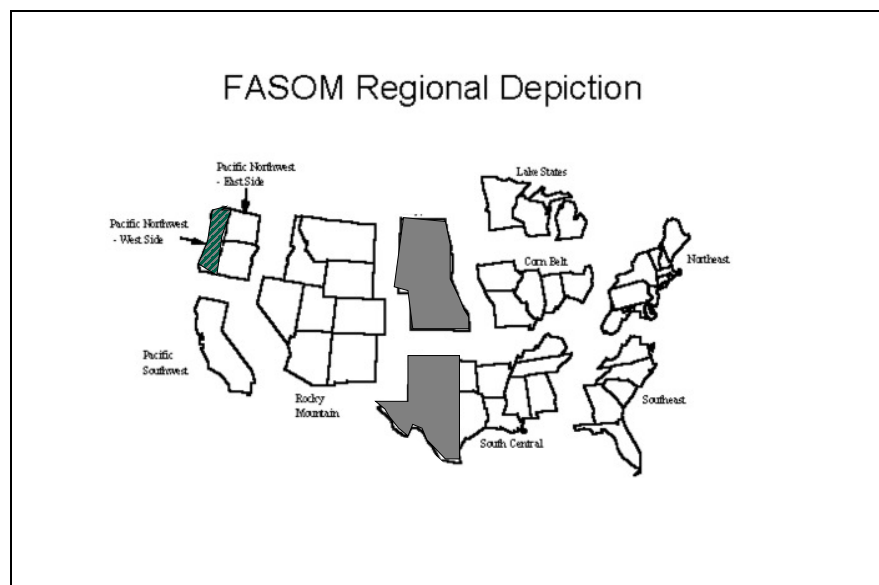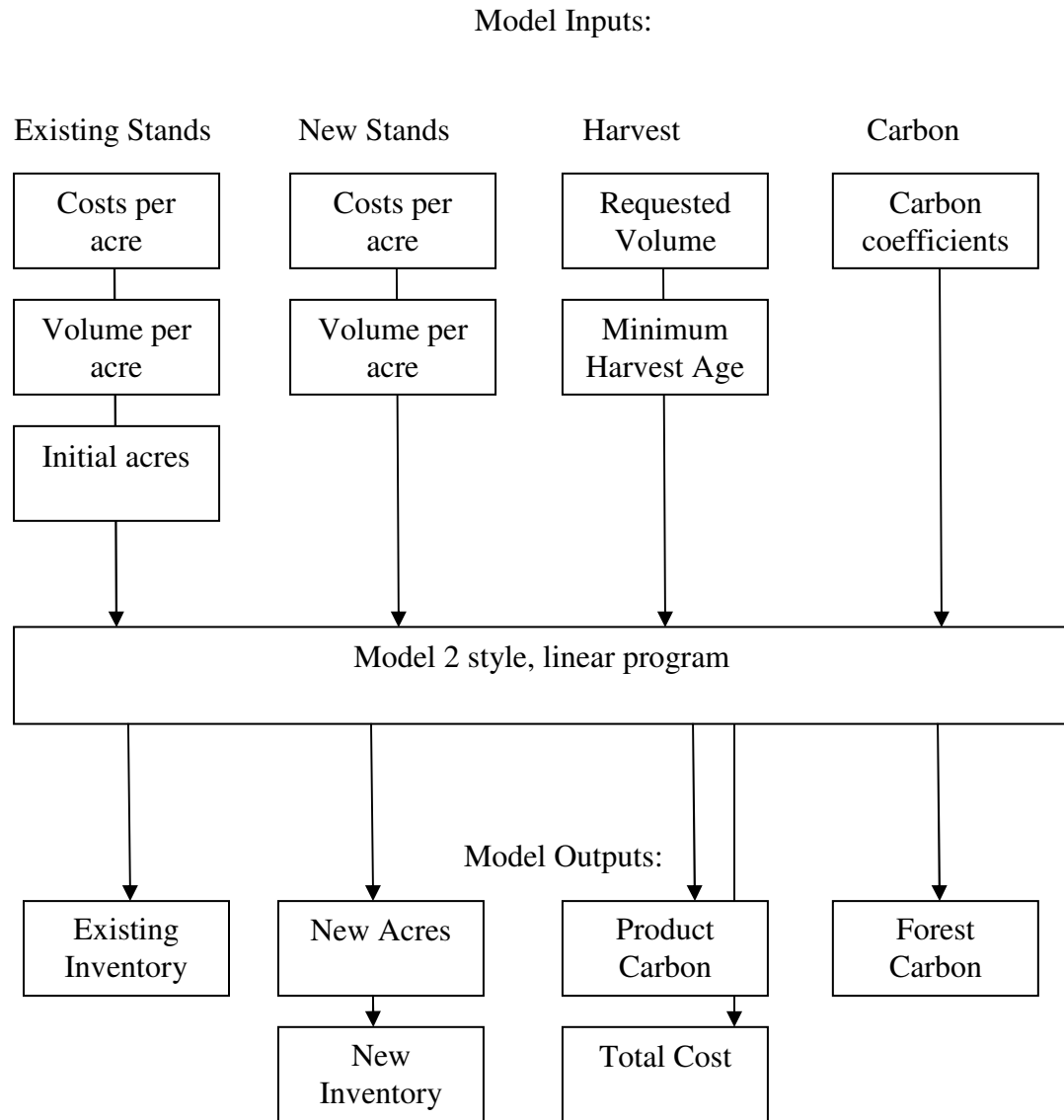
Figure 2. Model Flow Chart for Current harvest model

Model Inputs:

Existing Stands	New Stands	Harvest	Carbon
Initial acres	Volume per acre	Minimum Harvest Age	Carbon coefficients
Volume per acre			

Model 2 style, linear program

Model Outputs:

Existing Inventory	New Acres	Product Carbon	Forest Carbon
	New Inventory	Maximum First Period Harvest	
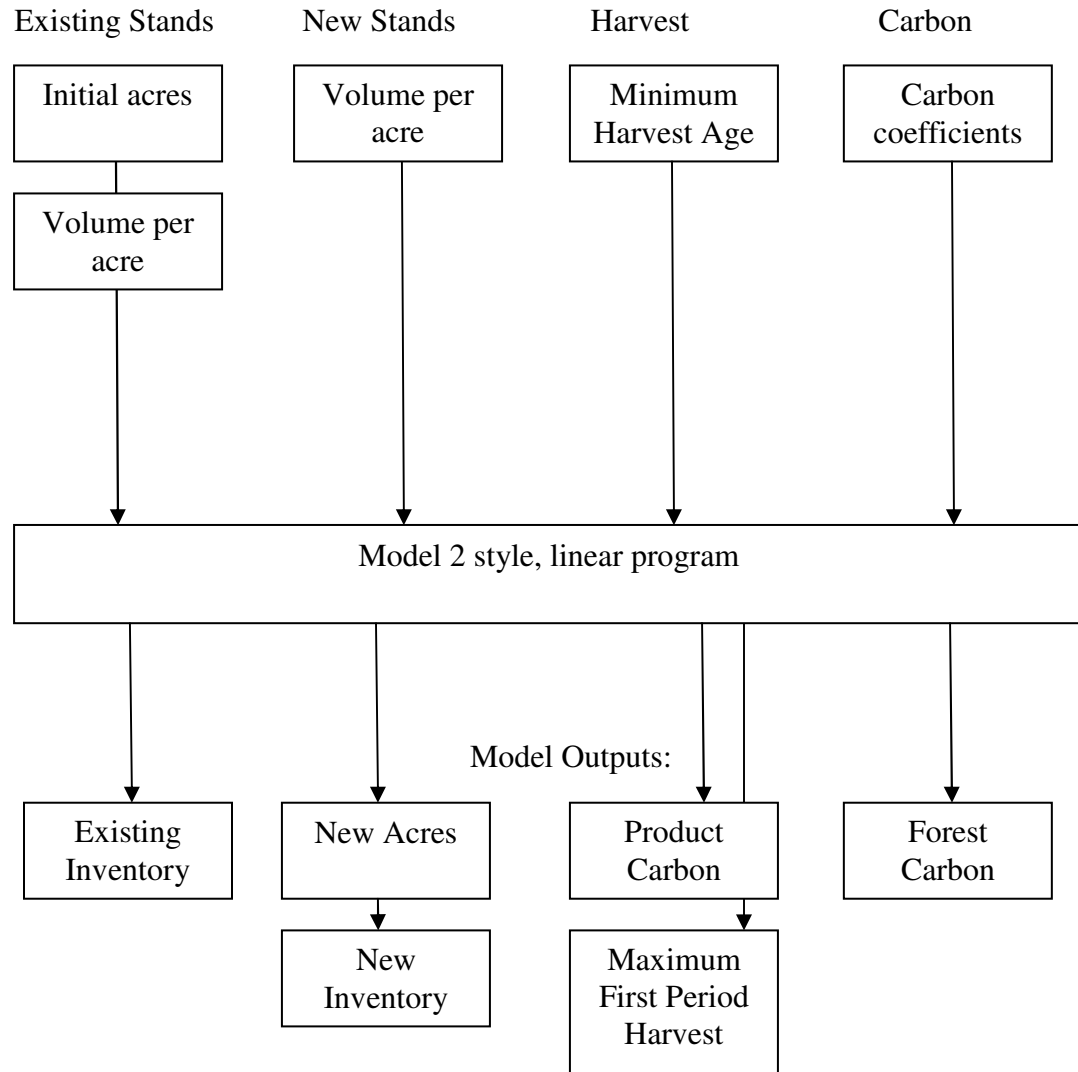
Figure 3. Model Flow Chart for Maximum Strict Even-Flow Model

Atmosphere

Emissions

Products in Landfills

Sequestration

Products in Use

Products as Energy

Harvest

Emission

Coarse Woody Debris and Reforestation

Standing Live Tree

Standing Dead Tree

Understory

Forest Floor

Coarse Woody Debris

Soil
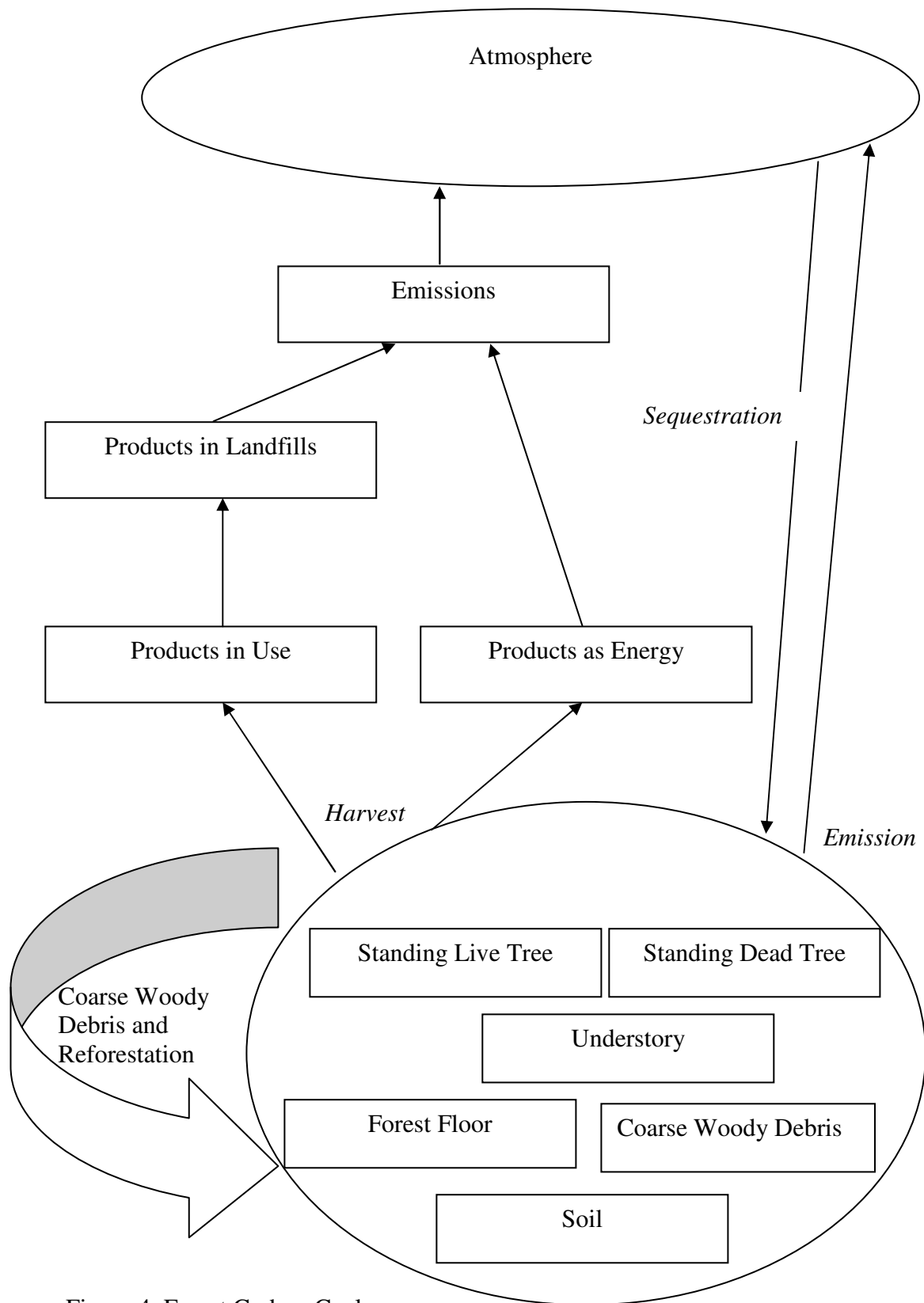
Figure 4. Forest Carbon Cycle

Table 1. Product proportions for standing volume per acre on National Forest and other public timberlands

	softwood saw timber	softwood pulp	softwood fuelwood	hardwood saw timber	hardwood pulp	hardwood fuelwood
CB	0.500000	0.469990	0.030010	0.986000	0.005000	0.009000
LS	0.225000	0.751740	0.023260	0.050000	0.826500	0.123500
NE	0.475000	0.509250	0.015750	0.350000	0.565500	0.084500
PNWE	0.950000	0.035000	0.015000	0.000000	0.000000	0.000000
PNWW	0.930000	0.030000	0.040000	0.842550	0.014180	0.143270
PSW	0.950000	0.020000	0.030000	0.798000	0.010000	0.192000
RMN	0.952020	0.026090	0.021890	0.892850	0.094540	0.012610
RMS	0.952020	0.026090	0.021890	0.892850	0.094540	0.012610
SC	0.900000	0.095000	0.005000	0.550000	0.405000	0.045000
SE	0.950000	0.045000	0.005000	0.700000	0.270000	0.030000

Table 2. Coefficients for Carbon Calculations from Smith et al. (2004) and Turner et al. (1995)

Region	Forest Type		Coarse Woody Debris		Standing Dead Tree		
		Understory	Decomposition	Mortality	A	B	C
Northeast	aspen-birch	2.7	0.0670	0.0147	0.044	704.783	3.506
Pacific Northwest, westside	western hemlock	2.0	0.0290	0.0060	0.284	848.735	0.379
Southeast	oak-pine	5.2	0.0520	0.0097	0.051	826.837	1.353

Region	Forest Type	Standing Live Tree		
		F	G	H
Northeast	aspen-birch	73.332	0.018	38.263
Pacific Northwest, westside	western hemlock	362.826	0.001	469.212
Southeast	oak-pine	337.113	0.015	456.362

Region	Forest Type	Forest Floor			
		I	J	K	L
Northeast	aspen-birch	18.400	53.700	10.200	9.200
Pacific Northwest, westside	western hemlock	87.500	116.700	27.500	16.000
Southeast	oak-pine	15.400	20.100	10.000	3.800

Table 3. Carbon Dispositions for harvested wood products by years after harvest.

Carbon in products		Years Since Harvest										
		0	10	20	30	40	50	60	70	80	90	100
Northeast	hardwood saw timber	0.220	0.090	0.060	0.050	0.050	0.040	0.040	0.030	0.030	0.030	0.030
Pacific Northwest, westside	softwood saw timber	0.500	0.370	0.330	0.300	0.260	0.240	0.220	0.200	0.180	0.170	0.160
Southeast	softwood pulp	0.301	0.067	0.047	0.039	0.034	0.031	0.029	0.028	0.026	0.025	0.024

Carbon in landfills		Years Since Harvest										
		0	10	20	30	40	50	60	70	80	90	100
Northeast	hardwood saw timber	0.000	0.090	0.110	0.110	0.110	0.110	0.110	0.110	0.100	0.100	0.100
Pacific Northwest, westside	softwood saw timber	0.000	0.090	0.120	0.130	0.150	0.160	0.170	0.180	0.190	0.190	0.190
Southeast	softwood pulp	0.000	0.161	0.164	0.157	0.100	0.143	0.135	0.127	0.121	0.114	0.109

Table 3 (Continued). Carbon Dispositions for harvested wood products by years after harvest.

Carbon as energy

		Years Since Harvest										
		0	10	20	30	40	50	60	70	80	90	100
Northeast	hardwood saw timber	0.480	0.490	0.490	0.490	0.500	0.500	0.500	0.500	0.500	0.500	0.500
Pacific Northwest, westside	softwood saw timber	0.240	0.250	0.260	0.260	0.260	0.260	0.260	0.270	0.270	0.270	0.270
Southeast	softwood pulp	0.436	0.453	0.454	0.455	0.455	0.455	0.455	0.455	0.456	0.456	0.456

Carbon in emissions

		Years Since Harvest										
		0	10	20	30	40	50	60	70	80	90	100
Northeast	hardwood saw timber	0.300	0.330	0.340	0.350	0.340	0.350	0.350	0.360	0.370	0.370	0.370
Pacific Northwest, westside	softwood saw timber	0.260	0.290	0.290	0.310	0.330	0.340	0.350	0.350	0.360	0.370	0.380
Southeast	softwood pulp	0.263	0.319	0.335	0.349	0.411	0.371	0.381	0.390	0.397	0.405	0.411

RESULTS:

Current Harvest:

The current harvest scenario yields harvest results that minimize costs given a harvest request in each period and region. The stands chosen were predominately young existing stands with lower management costs and the regenerated or new stands. The costs per acre are lower because the costs are associated with management and young and "non-stocked" stands have had only planting and little management. "Non-stocked" stands, stands without enough volume to be classified as any particular forest type, were also favored because of their low costs. The low cost stands were favored to the extent that they could fulfill the harvest request; once these stands were harvested, other forest types began to be harvested in order of increasing silvicultural costs. Deferring costs into the future makes their discounted value less than it would have been if the stands were harvested earlier in the projection period.

In the current harvest model, average annual net carbon sequestration over the planning horizon for U.S. public lands was approximately 35 Teragrams. Net carbon sequestration in the beginning was positive, showing a net sink (more carbon was sequestered than was released). The net sequestration shrank in the periods nearing 2100 as more carbon was lost to harvest and wood products, but the forest did not become a net source of carbon. (See figure 5.) This is unlike the maximum sustainable harvest model that had negative net sequestration in some periods when energy was treated as a source. In comparison to the recent results described by Depro et al. (2008), 16 less Teragrams of carbon are sequestered on an average annual basis.

The Depro et al. study did not minimize costs and harvested from stands based on proportional volume available in each stand. The differences in modeling harvest may result in differences in sequestration rates. Although all stands are assumed to be of medium site class, different forest types have different growth rates and the types with slower growth tended to coincide with lower management costs. The lower cost stands in some cases such as the "non-stocked" stands have slower growth rates. Net sequestration on these stands would be slower, reducing the average rate of net carbon sequestration.

The harvest levels that approximate current public lands management policy in this scenario were significantly lower than the maximum sustainable harvest in the second model (Haynes et al. 2007). (See figure 6.) The total discounted cost for the harvests across the U.S. were estimated to be $106.5 billion dollars, in 2007 dollars. This cost is an approximation of planting and management costs. On average 10-percent of the annual net carbon sequestration was in postharvest wood and paper products. The distribution of net carbon sequestration was not equal over the U.S.; western forests held over 70-percent of the net carbon sequestered. (See figure 7.) Net carbon sequestration in understory, forest floor and downed woody debris carbon was nearly 13-percent of the total western net carbon sequestration and 13-percent nationwide. After the western states, the next largest sources of net carbon sequestration were the South central (9.3-percent), the Lake States (8.4-percent) and the Southeast regions (5.4-percent). Similarly to Depro et al., most of the carbon stock was held in standing live and standing dead trees, an equally impressive amount of carbon was held in non-timber forest carbon.

The national inventory levels for the current harvest and no-harvest scenarios are different despite the low harvest levels under the current harvest scenario. (See figure 8.) The current harvest inventory shows steeper growth from 2000- 2060 because younger stands with more rapid growth are replacing older, more slowly growing stands. This results in the current harvest scenario accumulating 41,000,000 million cubic feet more in carbon stores. These inventories show stark contrasts to the national inventory of the maximum strict even-flow model that shows heavy harvest of younger age classes; by harvesting older stands and replacing them with fast growing stands the average growth rate remains high. (See figure 8.) When older stands are slowly replaced or not replaced at all, as in the current harvest and no harvest scenarios, the average growth rate slows as the majority of the timberlands approach culmination age, the age at which the rate of growth for forests as a whole reaches its maximum and begins to decline.

Maximum Strict Even-Flow:

The maximum even-flow harvest model does not consider cost. The purpose of the model is to understand the maximum amount of timber that can sustainably be removed from public lands and the carbon sequestration that would result. The 113 billion cubic feet harvested annually above current harvest levels resulted in a substantial decrease in average net carbon sequestration to 19 Teragrams annually. This would imply that for every additional billion cubic feet of harvest above current harvest levels approximately 7 Teragrams of carbon is released. Net carbon sequestration by region varied from an average loss of 1.24 Teragrams to net

sequestration of 12 Teragrams annually. (See figure 9.) This level of net carbon

sequestration is even lower than the 27 to 35 Teragrams of net carbon sequestration

reported by Depro et al. (2008) when estimating the net carbon sequestration

associated with pre-1989 public harvest levels. The maximum sustainable harvest

modeled here is much higher than the pre-1989 levels, and these increased harvest

levels led to increased losses of carbon from harvest and forest product decay.

The vast majority of the timber came from the western regions of the Pacific

Northwest west, Pacific Southwest, and the Rocky Mountain regions, and the percent

of national average annual net carbon sequestration in these regions increased

approximately 12-percent over the current harvest scenario. (See figure 10.) The

portion of net carbon sequestration from post harvest wood and paper products was

approximately 10-percent with the energy credit, and 7-percent without the credit.

Postharvest wood product, landfill, energy and emissions net carbon sequestration was

on average 3.8 Teragrams with the energy credit and 1.5 Teragrams without the credit.

Recall that the energy credit treats energy carbon as a sink because it serves as an

offset to carbon from fossil fuel energies that would be released if fossil fuel energy

sources were used instead of a renewable wood product. With the higher harvest, net

carbon sequestration in non-timber forest carbon decreased to 11-percent of all forest

net carbon sequestration.

When the two energy credit methods are averaged, as stands aged, they

initially sequestered more carbon, but later reduced their levels of net sequestration as

they were harvested and wood products began to decay. The younger stands that

replaced these older stands, despite their faster rates of growth, are able to sequester

less carbon per acre in the younger portion of their rotation. In the maximum strict even-flow scenario, all regions accrued timber volume by 2100, but non-timber carbon, due to more frequent site disturbance, was unable to reach 2000 levels. Percent of carbon held in forests was greatest in the Southern and Rocky Mountain regions. (See figure 11.) Southern regions would have more carbon in forests due to lower harvest levels in the maximum strict even-flow model.

Harvest volumes from National Forest lands were considerably higher than those on other public lands, as National Forest lands hold more volume. Maximum first period harvest was 5,731 mmcf across the U.S., over five times the 1,270 mmcf harvested by public forests in 2001 (Smith et al., 2002).

No-Harvest Comparison:

The final model scenario assumes no public harvest. This scenario sequesters the largest amount of carbon, 46 additional Teragrams of carbon annually above the maximum sustainable harvest case. (See figure 12.) At the end of the planning horizon, total carbon held in public forests equals 164 petagrams. (See figure 13.) This is far more than the other scenarios even with product carbon accounted for in the other models, because carbon is lost into the atmosphere during and after harvest as slash left on-site quickly decays. (See figures 14 and 15.) There are also losses of carbon that occur during the creation of forest products. These losses to decay and wood products make carbon sequestration slower when harvesting is allowed. The young timberlands that replace older harvested lands grow quickly, but hold less in total carbon stores than their older counterparts; the net sequestration from forest

products adds to total carbon stores, but does not come close to the vast amounts of carbon stored in non-harvested older timberlands.

This finding differs from other papers that have shown that the highest carbon mitigation can be reached when high productivity lands are used exclusively for wood products creation (Marland and Marland, 1992). The wood products considered in these studies were either long lasting or used for fuel purposes. Allowing harvested timber to be allocated to all types of wood products increases carbon emissions and results in no harvest regimes sequestering more carbon.
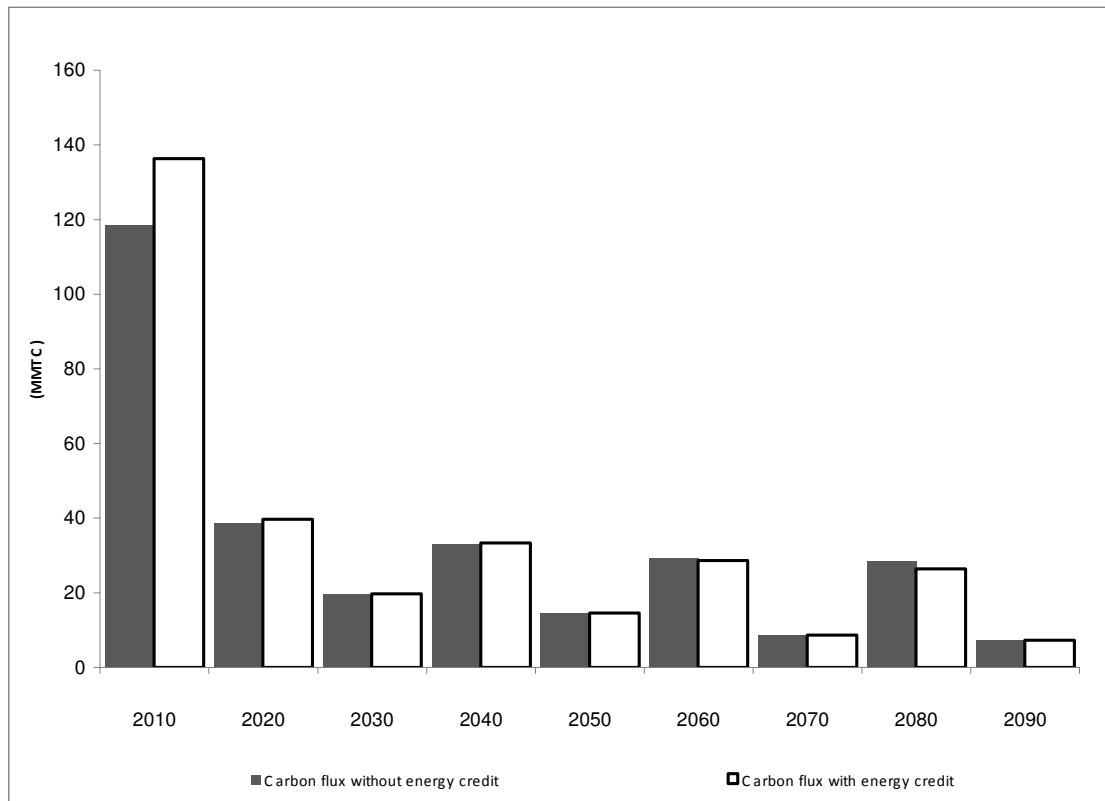
Figure 5. U.S. net carbon sequestration with and without energy credit under the

current harvest scenario 2010-2090.
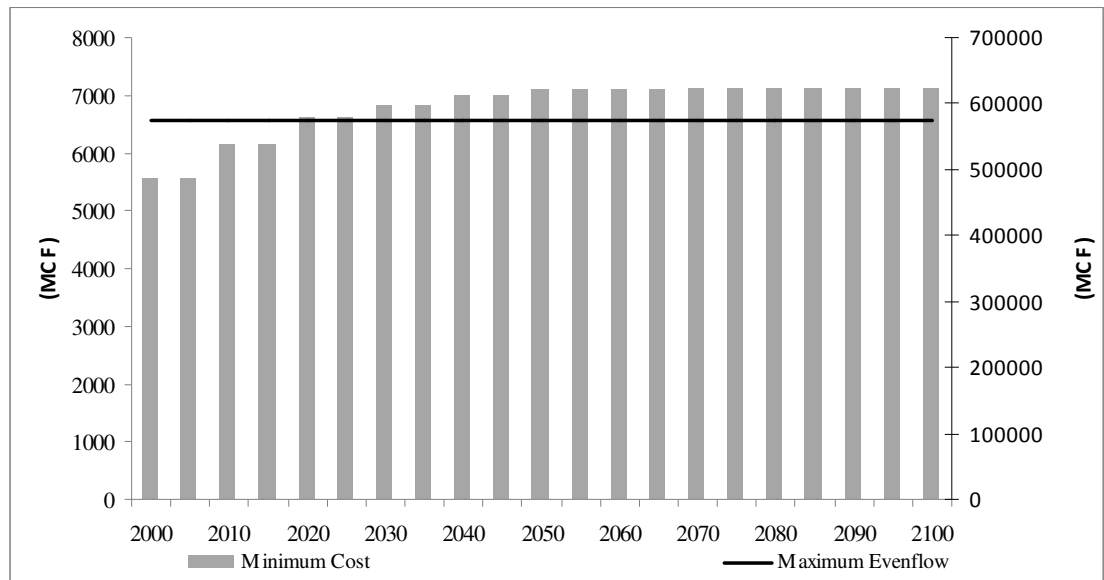
Figure 6. Harvest volumes by period for current harvest (bars) and maximum strict even-flow (line) scenarios with current harvest on the left axis and maximum strict even-flow harvest on the right axis.
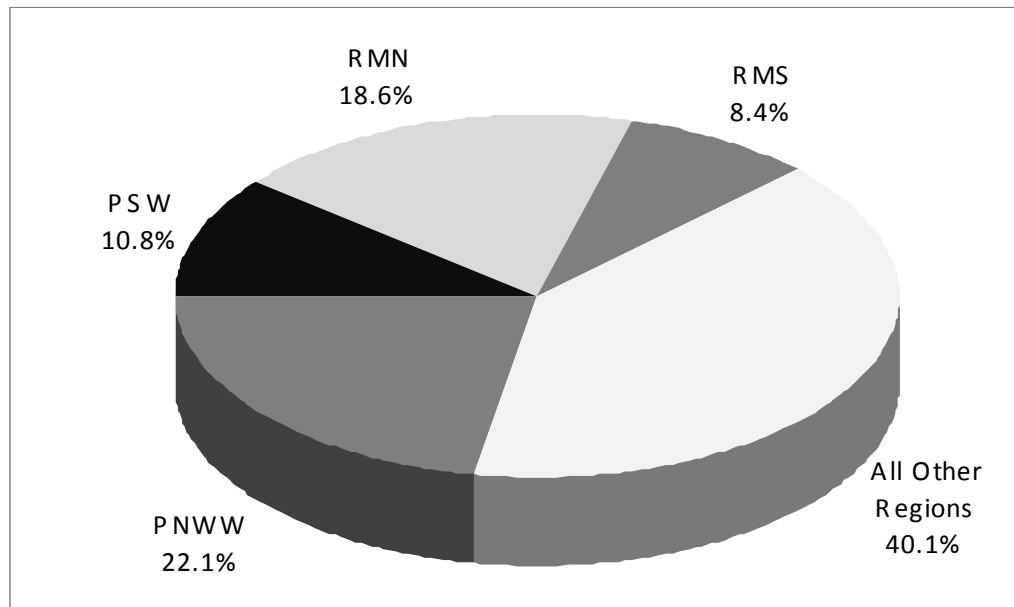
Figure 7. Average annual distribution of net carbon sequestration by region under the current harvest scenario without energy credit.
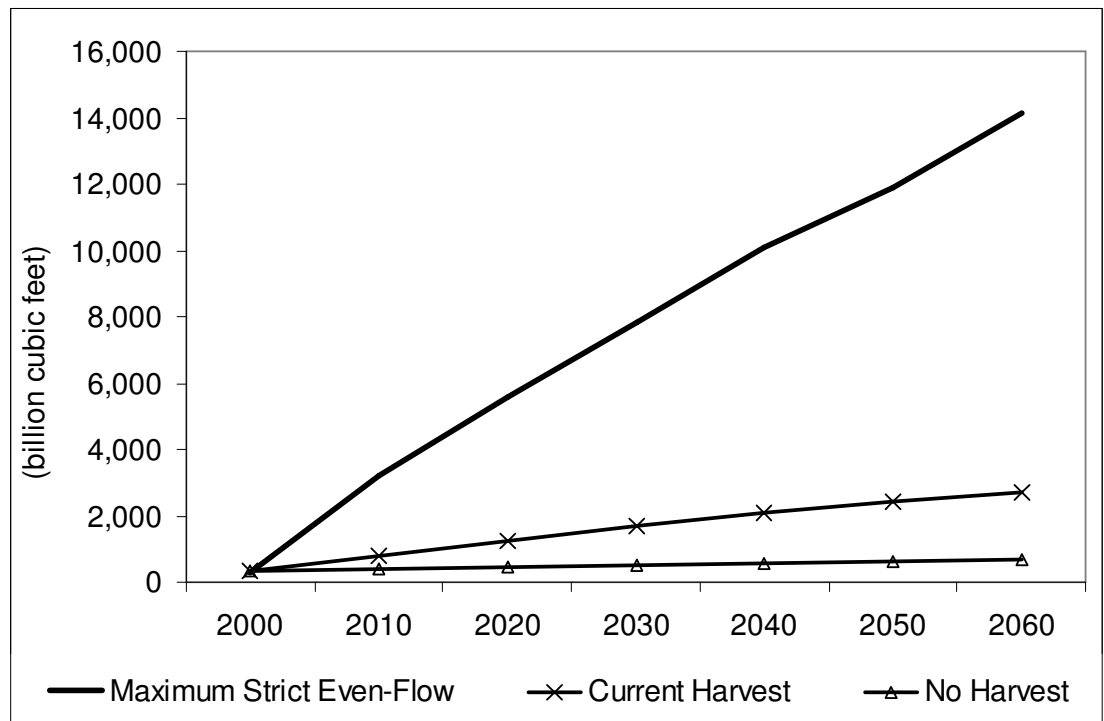
Figure 8. National inventory of growing stock on public lands under the maximum strict even-flow, current harvest, and no-harvest scenario 2000 -2060 in billions of cubic feet.
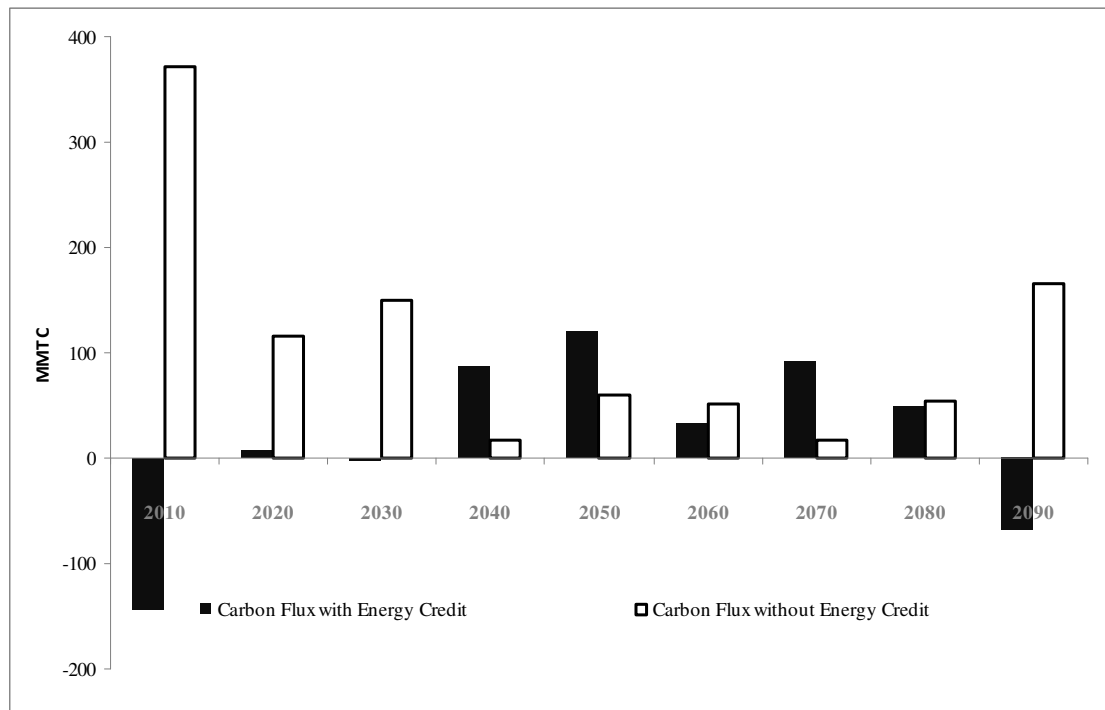
Figure 9. U.S. net carbon sequestration with and without energy credit under the maximum strict even-flow scenario.
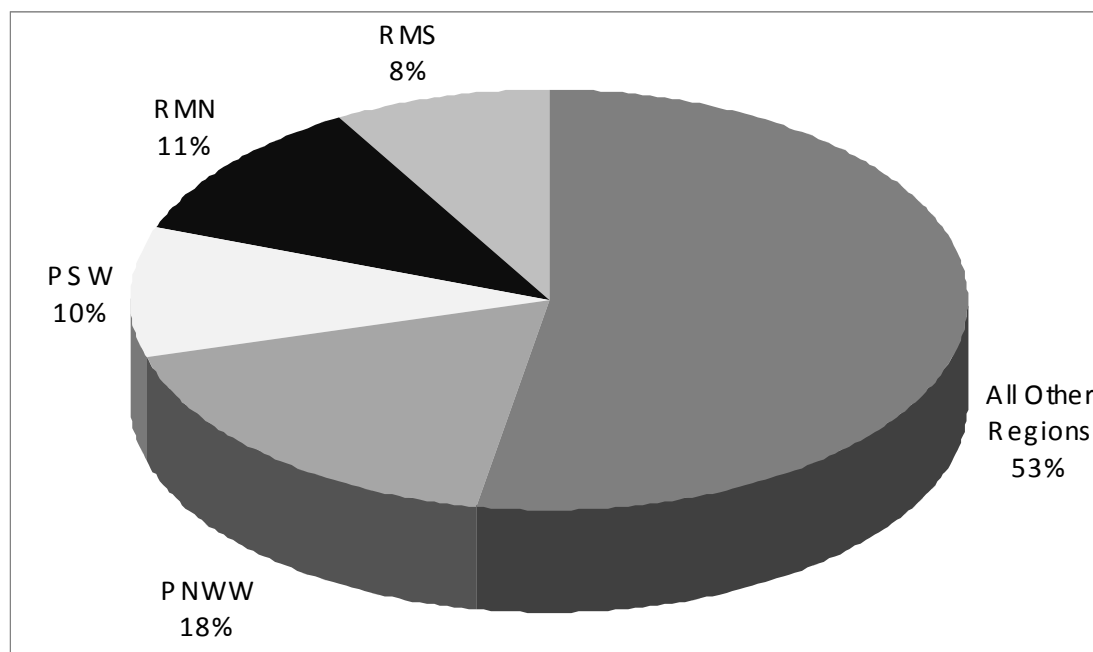
Figure 10. Average annual distribution of net carbon sequestration by region under the maximum strict even-flow scenario without energy credit.
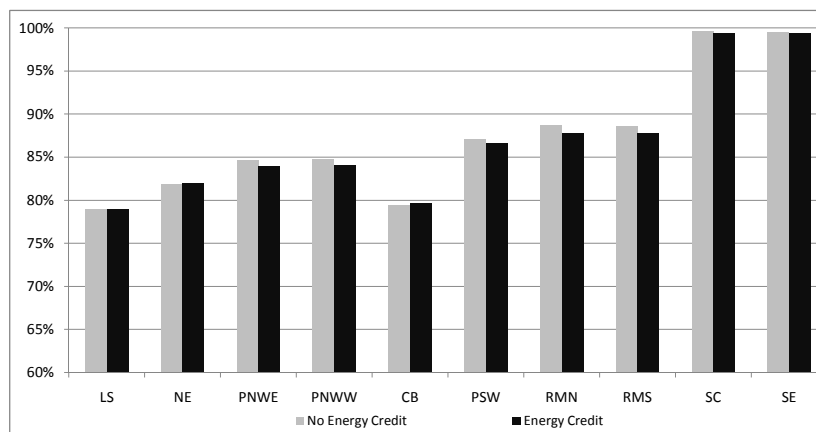
Figure 11. Average annual carbon held in forests as a percent of under the maximum strict even-flow scenario.
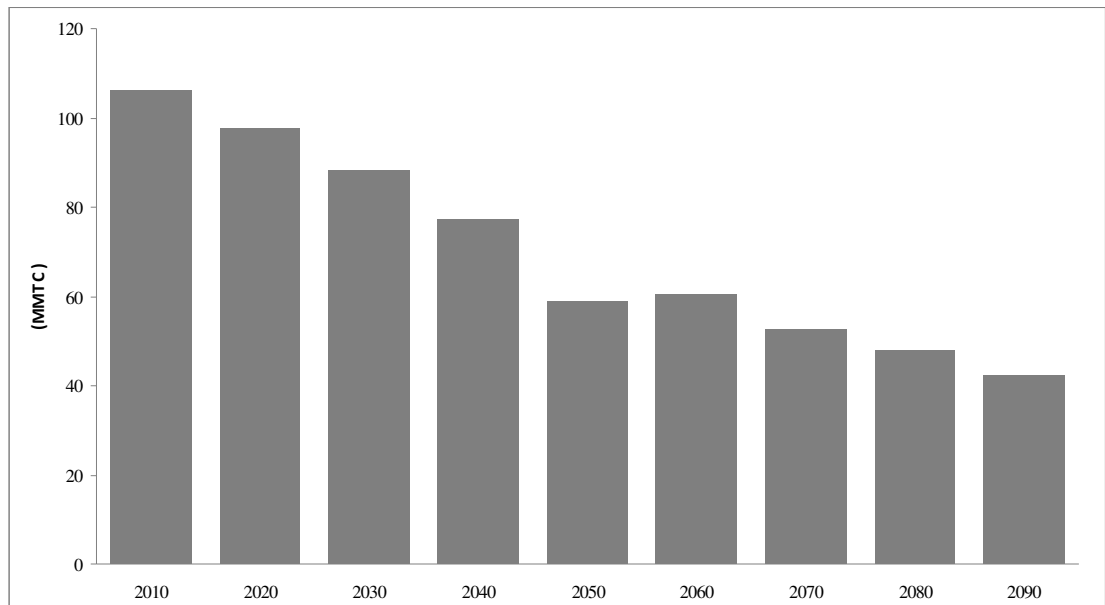
Figure 12. U.S. net carbon sequestration under the no-harvest scenario.
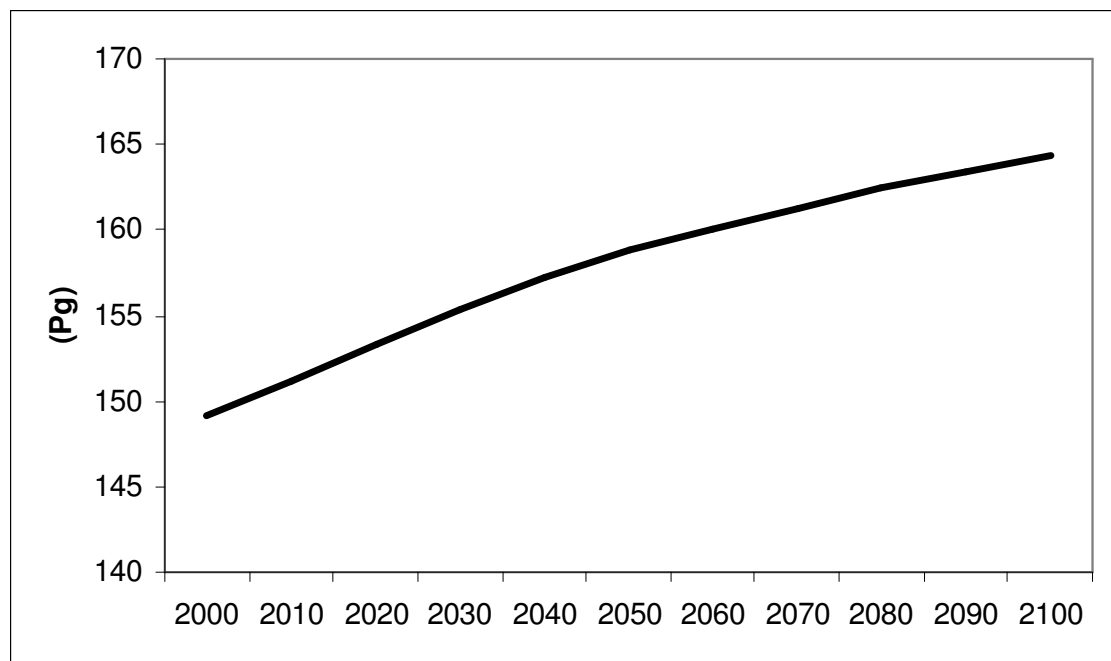
Figure 13. National net carbon inventory in all pools on public timberlands under no-harvest scenario, 2000-2100.
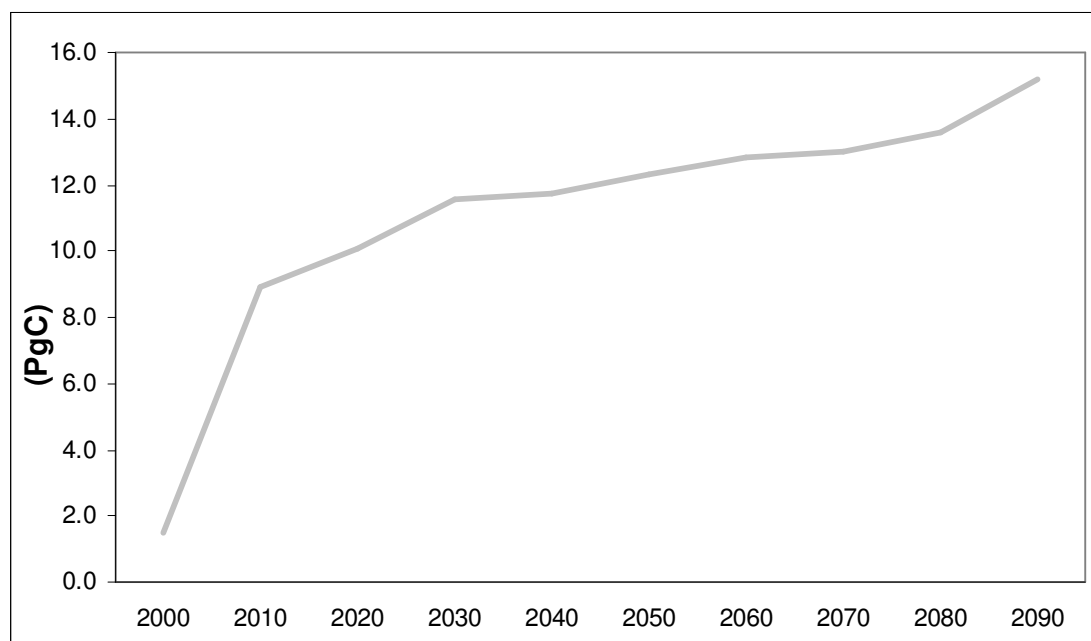
Figure 14. National net carbon stored in all pools under maximum strict even-flow scenario, 2000-2100.
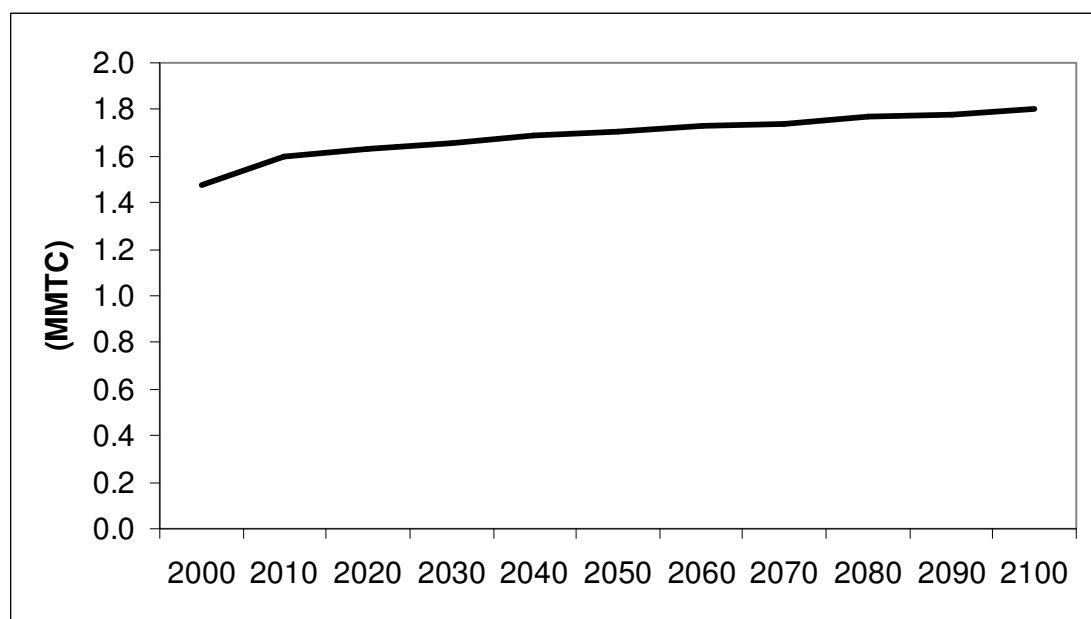
Figure 15. National net carbon stored in all pools under current harvest scenario 2000-

2100.

CONCLUSIONS:

To date little research has been directed at the carbon sequestration potentials

of public lands relative to research on the many other uses of public lands such as

habitat, watershed uses, timber, and recreation. This paper expands the body of

knowledge pertaining to public lands as sources of carbon sequestration to offset U.S.

greenhouse gas emissions through the analysis of varied, although limited, harvest

scenarios and the development of an explicit, contemporaneous accounting process for

carbon. The scenarios investigated offer estimates of carbon sequestration potential at

the extremes of public forest management – zero cut and maximum strict even-flow yield of volume – and at approximately their current management.

The results of this study indicate that, if maximum net carbon sequestration is the objective, a no-harvest option would be preferable over the current harvest and to maximum strict even-flow harvest levels. Forest product decay contributes significantly to lower net sequestration rates in under current harvest and maximum strict even-flow harvests. Increasing the product life of forest products could substantial impacts on net sequestration of the harvest scenarios.

All forests in this study are assumed to be regenerated to the same forest type. It may be possible to increase net carbon sequestration rates if forests are regenerated to faster growing forest types. Reduced rates of net carbon sequestration are also possible if forests are left to natural regeneration. Net sequestration with natural regeneration could be much slower due to less dense regeneration or the natural regeneration of slower growing forest types.

The results of this study indicate that for every additional one billion cubic feet of harvested volume above current harvest levels approximately 7 Teragrams of carbon is released. The wood products generated from this harvest off-set carbon emissions from man-made products that would be used as alternatives for forest products, plastics or metals instead of wood. The reduced carbon emissions from using forest products as an alternative to man-made products is not taken into consideration; net carbon sequestration under both harvest scenarios would increase if these additional carbon off-sets were taken into account.

A useful research extension would be to expand upon current models to create a model where carbon is a variable that can be optimized. Carbon can then be integrated into the objective function; this would allow for researchers to determine the necessary price per ton of carbon needed to produce management changes. Creating the program in an optimization framework would allow for profit maximization, cost minimization, harvest maximization, and carbon storage and net sequestration maximization when carbon is integrated as a variable. A model with carbon tons as a variable would also allow the institution and changing of prices for carbon tonnage; with prices on carbon tonnage it will be possible to vary the prices of carbon and observe sequestration levels as timber and carbon tonnage trade off. With carbon as a variable the interactions between potential carbon markets, timber markets, and agriculture markets can be analyzed.

One further important research extension would be to model the connections between timber harvests and fire occurrences. Historical fire patterns can be used to create burn frequencies for a stochastic model that can run contemporaneously with this model. This could help researchers and policy makers understand the differences and tradeoffs between carbon losses due to timber harvest and carbon losses due to catastrophic fire and the interactions between fire susceptibility and timber harvests.

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APPENDICES

Appendix A. Mathematical Representation of All Models

Current Harvest Scenario:

Minimize Z= $\Sigma(t=1\text{-}100)$ $\{\frac{1}{(1+.04)^t}* (C_{\beta it}*\alpha_{\beta it})\}+\{\frac{1}{(1+.04)^t}* (Cn_{\beta jt}*\alpha n_{\beta jt})\}$

s.t.
$\Sigma(t=1\text{-}100)$ $\alpha_{\beta it} - \alpha_{\beta i0} =0$
$\Sigma(i=1\text{-m})$ $\alpha_{\beta it} - \Sigma(j=1\text{-n})$, $\alpha n_{\beta jt}=0$
$\Sigma(i=1\text{-m})$ $(v_{\beta it} * \alpha_{\beta it})+ \Sigma(j=1\text{-n})$ $(vn_{\beta jt} * \alpha n_{\beta jt}) - H_{\beta t}= 0$,
$H_{\beta t}, C_{\beta it}, Cn_{\beta jt}, \alpha_{\beta it}, \alpha n_{\beta jt}, vn_{\beta jt}, v_{\beta it} >=0$

Maximum Strict Even-Flow Scenario:

Maximize Z= H_1
s.t.

$\Sigma(t=1\text{-}100)$ $\alpha_{\beta it} - \alpha_{\beta i0} =0$
$\Sigma(i=1\text{-m})$ $\alpha_{\beta it} - \Sigma(j=1\text{-n})$, $\alpha n_{\beta jt}=0$
$\Sigma(i=1\text{-m})$ $(v_{it} * \alpha_{it})+ \Sigma(j=1\text{-n})$ $(vn_{jt} * \alpha n_{jt}) - H_t= 0$,
$H_1 = H_2 = H_3 = \ldots = H_{20}$
$\alpha_{it}, \alpha n_{jt}, vn_{jt}, v_{it} >=0$

where j=1-n, new stand strata
i=1-m, existing stand strata
β= 1-r, regions
t=1-100, years since 2000
$C_{\beta it}$ = cost of management of existing stand i at time t
$\alpha_{\beta it}$= existing acres of stand i harvested at time t
$v_{\beta it}$ = volume per acre on stand i at time t
$Cn_{\beta jt}$ = cost of management of new stand j at time t
$\alpha n_{\beta jt}$= new acres of stand j harvested at time t
$vn_{\beta jt}$ = volume per acre on new stand j at time t
$H_{\beta t}$= harvest in region β at time t
H_t= total U.S. harvest at time t

Appendix B. GAMS code for Maximum Strict Even-Flow Model

```
sets   T     /0,5,10,15,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90,95,100/

 cohort     /0TO4, 5TO9,10TO14, 15TO19, 20TO24,25TO29, 30TO34, 35TO39,
        40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79,
        80TO84, 85TO89, 90TO94, 95TO99, 100TO104,105TO109, 110TO114,
        115TO119,120TO124,125TO129,130TO134, 135TO139, 140TO144,
        145TO149, 150TO154, 155TO159, 160TO164, 165TO169, 170TO174,
        175TO179, 180TO184,185TO189,190TO194,195TO199,200TO204,
        205TO209,210TO214,215TO219,220TO224,225TO229,230TO234,
        235TO239, 240TO244,245TO249,250PLUS,90PLUS/


      vol                /SFT,HWD/

      YearAge            /2000,2005,2010,2015,2020,2025,2030,2035,2040,
                2045,2050,2055,2060,2065,2070,2075,2080
                ,2085,2090,2095,2100,PLUS0, PLUS5, PLUS10,
                PLUS15, PLUS20, PLUS25, PLUS30,
                PLUS35, PLUS40, PLUS45, PLUS50, PLUS55, PLUS60,
PLUS65,
                PLUS70, PLUS75, PLUS80, PLUS85, PLUS90, PLUS95,
PLUS100,NEVER/
      Year(yearage)        /2000,2005,2010,2015,2020,2025,2030,2035,2040,
                2045,2050,2055,2060,2065,2070,2075,2080
                ,2085,2090,2095,2100,NEVER/


      YEARS(year)
/2000,2005,2010,2015,2020,2025,2030,2035,2040,2045,2050,2055,2060,2065,2070,2
075,2080
                ,2085,2090,2095,2100, NEVER/


  age(yearage)      /PLUS0, PLUS5, PLUS10, PLUS15, PLUS20, PLUS25, PLUS30,
        PLUS35, PLUS40, PLUS45, PLUS50, PLUS55, PLUS60, PLUS65,
        PLUS70, PLUS75, PLUS80, PLUS85, PLUS90, PLUS95, PLUS100,NEVER/




      Type   ATLAS forest types
/1,2,3,4,5,6,7,8,9,10,20,21,23,25,27,28,30,40,41,43,44,45,46,49,50/
      owner               /NF, OP/
      owners(owner)        /NF,op/
      MI management intensity   /LO, LO_PART_CUT, RESERVED/
      MIH(mi) harvestable mi's   /LO,LO_PART_CUT/
```

```
    si    site              /ME/
    pp product proportions     /ssaw, spulp,sfuel,hsaw,hpulp,hfuel/


    sp(pp)                 /ssaw,spulp,sfuel/
    hp(pp)                 /hsaw,hpulp,hfuel/
    Reg                 /ls, ne, pnwe, pnww, cb, psw, rmn, rms, sc, se/
    REGS(REG)            /ls, ne, pnwe, pnww, cb, psw, rmn, rms, sc, se/
    CReg                 /NE, NLS, NPS, SC, SE, PSW, PWE, PWW, RMN, RMS/
    CRegs(creg)          /NE, NLS, NPS, SC, SE, PSW, PWE, PWW, RMN, RMS/
    CType             /aspenbirch,
mbbotherhw,oakhickory,oakpine,otherpine,sprucefir,WRJpine,
                Nonstocked, lowlandhw,
mbb,pine,conifer,bottomlandhw,naturalpine,otherconifer,
                plantedpine,uplandhw,douglasfir,
firspruce,hardwoods,pinyonjuniper,redwood,

lodgepolepine,ponderosapine,otherhardwoods,redalder,westernhemlock,miscconifer/
    dm                 /decomp,mort/
ctypes(ctype)
/aspenbirch, mbbotherhw,oakhickory,oakpine,otherpine,sprucefir,WRJpine,
                Nonstocked, lowlandhw,
mbb,pine,conifer,bottomlandhw,naturalpine,otherconifer,
                plantedpine,uplandhw,douglasfir,
firspruce,hardwoods,pinyonjuniper,redwood,

lodgepolepine,ponderosapine,otherhardwoods,redalder,westernhemlock,miscconifer/


    prod_disp product carbon disposition /products, landfills,energy, emissions/
    csfthwd sft and hwd in carbon     /sw,hw,all/
    LiveCoeff  live tree biomass coefficients         /f,g,h/
    deadcoeff  dead tree biomass coefficients          /a,b,c/
    ffcoeff    forest floor coef                 /i,j,k,l/;

*************acres in existing
stands*****************************************
table existing_acre(reg, owner, type, mi, cohort, si)
$INCLUDE "existing_acres_2000.prn"

PARAMETER exist_acre(reg, owner, type, mi, cohort, SI) all stands all ages all
owners all periods (ac);
```

exist_acre(reg, owner, type, mi, cohort, SI) = existing_acre(reg, owner, type, mi, cohort, SI);

*************volume in all existing stands by product
proportions***************
table existing_volume_pp(reg, owner, type, mi, cohort, year, pp)   XISTVOLPP.TXT
IS IN CF PER AC
$INCLUDE "xistvolpp.txt"

ALIAS (PP,PP3);
parameter existvolpp(reg, owner, type, mi, cohort, year, pp) volume in pp's by mcf per
ac;
     existvolpp(reg, owner, type, mi, cohort, year, pp)
    =existing_volume_pp(reg, owner, type, mi, cohort, year, pp)/1000;

**************************volume pp in all new
stands***************************
table NEW_volume_pp(reg, owner, type, mi, age, pp)
$INCLUDE "NEW_vol_nf_op.prn"

ALIAS (PP,PP2);

PARAMETER NEW_vol_pp(reg, owner, type, mi, age, pp) NEW VOLUMES all
stands all ages all owners all periods (mcf per acre);
    NEW_vol_pp(reg, owner, type, mi, age, pp) $
    (SUM(PP2, NEW_volume_pp(reg, owner, type, mi, age, pp2)) GT 0) =
(NEW_volume_pp(reg, owner, type, 'lo', age, pp)/1000);

*-------------------
$INCLUDE "MAPPINGS.TXT"

**************************HARVEST*********************************
****
** IGNORE HARVEST COSTS AND PAYMENTS TO PUBLIC AGENCIES

*COSTS/REGION for existing stands
table pub_exist_costs(reg,type,mi,cohort,year,si)
$INCLUDE "exist_cost.prn"

PARAMETER exist_cost(reg,type,mi,cohort,year,sI) harvesting costs per ac by region
type mi cohort and year;
    exist_cost(reg,type,mi,cohort,year,sI) =
pub_exist_costs(reg,type,mi,cohort,year,sI)*1000;

*costs for new stands
table pub_new_costs(age,reg,type,mi,sI)
$INCLUDE "new_cost.prn"

PARAMETER new_cost(age,reg,type,mi,sI) harvesting costs per ac by region type mi
cohort and year;
    new_cost(age,reg,type,mi,sI) = pub_new_costs(age,reg,type,mi,sI)*1000;

*Harvest Volume Table
table harvest_request(year,reg,owner)
$INCLUDE "harvest_requests.prn"

PARAMETER harv_req(year,reg,owner) harvest requests for NF and OP lands by
year and region (mcf);
    harv_req(year,reg,owner) = harvest_request(year,reg,owner)*1000;

***************************Carbon
Coefficients********************************

table SnagCoef(creg, ctype, owner,csfthwd,deadcoeff)
$INCLUDE "StDeadCoef.prn"

PARAMETER StDeadCoef(creg,ctype,owner,csfthwd,deadcoeff) dead tree biomass
coefficients a b c;
    StDeadCoef(creg, ctype,owner,csfthwd,deadcoeff) = SnagCoef(creg,ctype,
owner,csfthwd,deadcoeff);

table LvTrCoef(creg, ctype, owner,csfthwd,livecoeff)
$INCLUDE "LvTrCoef.prn"

PARAMETER LvTreeCoef(creg,ctype,owner,csfthwd,livecoeff) live tree biomass
coefficients f g h;
    LvTreeCoef(creg, ctype,owner,csfthwd,livecoeff) = LvTrCoef(creg,ctype,
owner,csfthwd,livecoeff);

table ForestFloorCoef(reg, ctype,ffcoeff)
$INCLUDE "ForestFloorCoef.prn"

PARAMETER ForFloorCoef(reg,ctype,ffcoeff) live tree biomass coefficients f g h;
    ForFloorCoef(reg, ctype,ffcoeff) = ForestFloorCoef(reg,ctype,ffcoeff);

table data_carbonunder(reg, ctype)
$INCLUDE "data_carbonunder.prn"

```
PARAMETER undercarbon(reg,ctype) understory carbon ratios percents of live tree
carbon;
    undercarbon(reg, ctype) = data_carbonunder(reg,ctype);

table prod_acct_1(reg,pp, prod_disp,T)
$include "prod_acct_1.prn"

parameter prod_acct(reg,pp, prod_disp,T) percentage product dispostion;
      prod_acct(reg,pp,prod_disp,T)=prod_acct_1(reg,pp,prod_disp,T);



table data_carboncwd(reg, ctype)
$INCLUDE "data_carbon_cwd_3.prn"

PARAMETER carboncwd(reg,ctype) understory carbon ratios percents of live tree
carbon;
    carboncwd(reg, ctype) = data_carboncwd(reg, ctype);

table decomposition_mortality(ctype, dm)
$INCLUDE "decomp_mort.prn"

PARAMETER decompmort(ctype,dm) decay rates and mortality rates for downed
woody debris;
    decompmort(ctype,dm) =decomposition_mortality(ctype,dm);



********************Acres in each
region*************************************

Parameter reg_acre(reg)   calculates the number of acres in each region (ac);
reg_acre(reg)=sum((owner, type, mi, cohort, SI),exist_acre(reg, owner, type, mi,
cohort, SI));

alias (year,year2), (age,age2), (yearS,yearS2), (cohort,cohort2);

parameter date(year)/
 2000 2000,
 2005 2005,
 2010 2010,
 2015 2015,
 2020 2020,
 2025 2025,
 2030 2030,
 2035 2035,
```

```
  2040 2040,
  2045 2045,
  2050 2050,
  2055 2055,
  2060 2060,
  2065 2065,
  2070 2070,
  2075 2075,
  2080 2080,
  2085 2085,
  2090 2090,
  2095 2095,
  2100 2100,
  NEVER 2105/

parameter elapsed(age)/
  PLUS0 0,
  PLUS5 5,
  PLUS10 10,
  PLUS15 15,
  PLUS20 20,
  PLUS25 25,
  PLUS30 30,
  PLUS35 35,
  PLUS40 40,
  PLUS45 45,
  PLUS50 50,
  PLUS55 55,
  PLUS60 60,
  PLUS65 65,
  PLUS70 70,
  PLUS75 75,
  PLUS80 80,
  PLUS85 85,
  PLUS90 90,
  PLUS95 95,
  PLUS100 100,
  NEVER   105/

parameter time(T)/
0 0,
5 5,
10 10,
15 15,
20 20,
```

```
25 25,
30 30,
35 35,
40 40,
45 45,
50 50,
55 55,
60 60,
65 65,
70 70,
75 75,
80 80,
85 85,
90 90,
95 95,
100 100/

parameter floorcoeff(reg)
/ls 0.1339167,
ne 0.1339167,
pnwe 0.2604615,
pnww 0.2604615,
psw  0.2604615,
cb  0.1339167
rmn  0.2604615,
rms  0.2604615,
sc   0.2604615,
se  0.1339167/

parameter meanage(cohort)/
0TO4  2,
5TO9  7,
10TO14  12,
15TO19  17,
20TO24  22,
25TO29  27,
30TO34  32,
35TO39  37,
40TO44  42,
45TO49  47,
50TO54  52,
55TO59  57,
60TO64  62,
65TO69  67,
70TO74  72,
```

```
75TO79  77,
80TO84  82,
85TO89  87,
90TO94  92,
95TO99  97,
100TO104 102,
105TO109 107,
110TO114 112,
115TO119 117,
120TO124 122,
125TO129 127,
130TO134 132,
135TO139 137,
140TO144 142,
145TO149 147,
150TO154 152,
155TO159 157,
160TO164 162,
165TO169 167,
170TO174 172,
175TO179 177,
180TO184 182,
185TO189 187,
190TO194 192,
195TO199 197,
200TO204 202,
205TO209 207,
210TO214 212,
215TO219 217,
220TO224 222,
225TO229 227,
230TO234 232,
235TO239 237,
240TO244 242,
245TO249 247,
250PLUS  250,
90PLUS   90/;
*/////////////////////////////////////////////\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*////////////// Greg Adding sets to limit new variable  \\\\\\\\\\\\\\\\\\\\\
*//////////////  also resetting date of never           \\\\\\\\\\\\\\\\\\\\\
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\V/////////////////////////////////
date('never')=0;
date('never')=sum(years$(ord(years) eq card(years)-1),date(years)+5);
* date of never is next to last year in years + 5
set use_age(year,age);
```

use_age(years,age)$((date(years)+elapsed(age) lt date('never') or ord(age) eq card(age))
    and (ord(age) gt 1))=yes;
* sets allowable year,age pairs for times less than never
*///\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*\\\/////////////////////////////////

scalar disc the discount rate
/.04/

parameter MHA(REG) set minimum harvest ages by region
/ls 50, ne 50, pnwe 50, pnww 50, cb 50, psw 50, rmn 50, rms 50, sc 30, se 30/;
******************Model
Formulation***

Variables
       z   objective function discounted value of timber management costs
       exist(reg, owners, type, mi, cohort, years,SI) existing acres harvested
       new(reg, owners, type, mih, years, age, SI) new acres harvested
       V(reg,years,owners,type,pp) volume harvested in year and region on given ownership (mcf per acre)
       checkvol(years,regs) check volume
       inven_new(years,regs,owners) start of period new inventory (all types sis and mihs)
       inven_exst(years,regs,owners) start of period exst inventory (all types sis and mihs)
       inven(regs,years,owners,type) start of period total inventory (all types sis and mihs)
       maxEF maximum even flow harvest
 ;

positive variables exist, new, v, a_exist, a_new,maxef ;
equations
obj objective function
E_acre(regs, owners, type, mih, cohort,SI) existing acres constraints
N_acre(regs, owners, type, mih, years, SI) new acre constraints
perharv(regs,years) harvest in first period
harv_vol(REGS,YEARs,owners,type,pp) harvested volume in year (mcf per acre x acres = mcf)
checkharv(years,regs) check harvest volume
invent_new(years,regs,owner)
invent_exst(years,regs,owner)
invent_comp(regs,years,owner,type)
 ;

```
*#######################################################
*########  OBJECTIVE FUNCTION      #################
*#######################################################

obj..  z =e= -maxef;

***********************acreage
constraints***********************************
**** NOTE CURRENT YEAR = YEARS, YEAR PLANTED = YEARS2
**** NOTE CURRENT AGE = AGE, AGE WHEN CUT = AGE2

*****EXISTING ACRES CONSTRAINTS--ALLOCATE NO MORE TO A
HARVESTS OVER PROJECTION
* THAN AVAILABLE IN ORIGINAL (2000) INVENTORY---UNITS AC's
 E_acre(REGS, owners, type, miH,cohort,SI)$(exist_acre(REGS, owners, type, mih,
cohort, SI) gt 0)..
 sum(years$(meanage(cohort)+(date(years)-2000) ge mha(regs)),exist(REGS, owners,
type, mih, cohort,years, SI)) =e=
 exist_acre(REGS, owners, type, mih, cohort, SI);
*set as equality so that all existing acres will be alloctaed to some harvest year
*may be largely NEVER for short runs

********NEW ACRES CONSTRAINTS--PLANT NO MORE IN A YEAR THAN
WAS HARVESTED---UNITS AC's
 n_acre(REGS, owners, type, 'lo', YEARS, SI)$((sum((cohort,mih),exist_acre(REGS,
owners, type, mih, cohort,SI)) gt 0) and
   (ord(years) lt card(years)))..

 SUM(use_age(years,age)$(elapsed(age) ge MHA(regs)),new(REGS, owners, type,
'lo', YEARS, age, SI)) =e=
* NEW ACRES HARVESTED IN YEARS
 (sum(YEARS2$(ord(YEARS2) lt ord(YEARS)),

  sum(use_age(years2,age2)$((date(YEARS)-date(YEARS2) eq elapsed(age2)) and
(elapsed(age2) ge MHA(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI))))+
* EXISTING ACRES HARVESTED IN YEARS
  (sum((cohort,mih)$((exist_acre(REGS, owners, type, mih, cohort, SI) gt 0) and
(meanage(cohort)+(date(years)-2000) ge mha(regs))),exist(REGS, owners, type, mih,
cohort, years,SI)));

******VOLUME HARVESTED IN YEARS (mcf)
 harv_vol(REGS,YEARS,owners,type,pp)$(ord(years) lt card(years))..
```

V(regs,years,owners,type,pp)=e= sum((si)$(sum((cohort,mih),exist_acre(REGS, owners, type, mih, cohort,SI)) gt 0),
 (sum(YEARS2$(ord(YEARS2) lt ord(YEARS)),

  sum(use_age(years2,age2)$((date(YEARS)-date(YEARS2) eq elapsed(age2)) and (elapsed(age2) ge mha(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners, type, 'lo', age2,pp))))+

  sum((cohort,mih)$(meanage(cohort)+(date(years)-2000) ge mha(regs)),exist(REGS,owners,type,mih,cohort,years,si)*existvolpp(REGS, owners, type, mih, cohort, YEARS, pp)));

perharv(regs,years)$(ord(years) lt card(years))..
 sum((type,pp,owners),(1.2*v(regs,years,owners,type,pp)))=e= maxef;

* recompute the harvest to check
 checkharv(years,regs)$(ord(years) lt card(years))..
  checkvol(years,regs) =e= sum((owners,type,pp), V(regs,years,owners,type,pp));

*compute start of period new inventory
invent_new(years,regs,owners)$(sum((cohort,type,mih,si),exist_acre(REGS, owners, type, mih, cohort,SI)) gt 0)..
 inven_new(years,regs,owners) =e=
  sum((type,si,pp),
  sum(use_age(years2,age2)$(ord(YEARS2) lt ord(YEARS)),

  sum(age$((date(YEARS)-date(YEARS2) eq elapsed(age)) and (elapsed(age2) ge mha(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners, type, 'lo', age,pp)))
  );
*compute start of period existing inventory
invent_exst(years,regs,owners)$(sum((cohort,type,mih,si),exist_acre(REGS, owners, type, mih, cohort,SI) gt 0))..
 inven_exst(years,regs,owners) =e=
  sum((type,mih,si,pp),
  sum((cohort,years2)$(ord(years2) ge ord(years)),
  exist(REGS,owners,type,mih,cohort,years2,si)*(
    existvolpp(REGS, owners, type, mih, cohort, YEARs, pp)$(ord(years) lt card(years))
    +

```
    (sum(year$(date(year) eq date(years) and (meanage(cohort)-(date(years)-2000) ge
mha(regs))),existvolpp(REGS, owners, type, mih, cohort, YEAR, pp))
    $(ord(years) eq card(years)))
    ))
  );

*compute start of period total inventory
invent_comp(regs,years,owners,type)$(sum((cohort,mih,si),exist_acre(REGS, owners,
type, mih, cohort,SI)) gt 0)..
 inven(regs,years,owners,type) =e=
  sum((si,pp),
  sum(use_age(years2,age2)$(ord(YEARS2) lt ord(YEARS)),

  sum(age$((date(YEARS)-date(YEARS2) eq elapsed(age)) and (elapsed(age2) ge
mha(regs)) ),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners,
type, 'lo', age,pp)))+
  sum((cohort,mih,years2)$(ord(years2) ge ord(years)),
  exist(REGS,owners,type,mih,cohort,years2,si)*(
    existvolpp(REGS, owners, type, mih, cohort, YEARs, pp)$(ord(years) lt
card(years))
    +
    (sum(year$(date(year) eq date(years) and (meanage(cohort)+(date(years)-2000) ge
mha(regs))),existvolpp(REGS, owners, type, mih, cohort, YEAR, pp))
    $(ord(years) eq card(years)))
    ))
  );

model harvest /all/;

solve harvest using LP minimizing Z;

parameter v_simple(regs,owners,years) calculates summed volume;
v_simple(regs,owners,years) = sum((type, pp),
V.l(regs,years,owners,type,pp));

parameter new_simple(regs,years2) calculates summed acres;
new_simple(regs,years2) = sum((owners,type,age2,si),
new.l(REGS, owners, type, 'lo', YEARS2, age2, SI));

parameter exist_simple(regs,years) calculates summed acres;
exist_simple(regs,years) = sum((owners,type,mih,cohort,si),
exist.l(REGS,owners,type,mih,cohort,years,si));

parameter inventory_simple(regs,owners,years) calculates summed volume;
```

inventory_simple (regs,owners,years)= sum(type,
inven.l(regs,years,owners,type));

*==
==================
*====   Beginning of Carbon Equations   ========
*====   ========
*==
==================
****
****
****
****
******Standing Tree Carbon Sequestered IN YEARS and region
******Standing Tree Carbon Sequestered IN YEARS and region

parameter Tcarb(regs,owners,years) calculates tree carbon;
Tcarb(regs,owners,years)= ((sum((cregs,ctypes,type,csfthwd),
lvtrcoef(cregs,ctypes,owners,csfthwd,"f")*
(lvtrcoef(cregs,ctypes,owners,csfthwd,"g")+
(1-exp(-
inven.l(regs,years,owners,type)/lvtrcoef(cregs,ctypes,owners,csfthwd,"h"))))))/2.471)*
0.5;

parameter snagcarb(regs,owners,years) calculates carbon in snags or standing dead
trees;
snagcarb(regs,owners,years)=
(sum((cregs,ctypes,type,csfthwd),((tcarb(regs,owners,years)*2))*
stdeadcoef(cregs,ctypes,owners,csfthwd,"a")*
exp(-((inven.l(regs,years,owners,type)/
stdeadcoef(cregs,ctypes,owners,csfthwd,"b"))**
stdeadcoef(cregs,ctypes,owners,csfthwd,"c"))))/2.471)*0.5;

parameter floorcarb(regs,owners) calculates average forest floor carbon;
floorcarb(regs,owners) =
(sum((type,mih,cohort,si)$(exist_acre(REGS, owners, type, mih, cohort, SI) gt 0),
(exist_acre(REGS, owners, type, mih, cohort, SI)* floorcoeff(regs))));

parameter tree_carb(regs,years) carbon just by reg and year;
tree_carb(regs,years) = sum((owners,csfthwd,cohort),
Tcarb(regs,owners,years));

```
parameter snag_carb(regs,years) carbon just by reg and year;
snag_carb(regs,years) = sum((owners,csfthwd,cohort),
snagcarb(regs,owners,years));

parameter floor_carb(regs) carbon just by reg and year;
floor_carb(regs) = sum((owners),
floorcarb(regs,owners));

parameter prod_carb(regs,years,prod_disp) calculates carbon in products and landfills;
prod_carb(regs,years,prod_disp)=
sum((owners,type,pp,t,years2)$(date(years)-date(years2) eq time(T)),
(v.l(regs,years2,owners,type,pp))*prod_acct(regs,pp,prod_disp,T));

parameter understory_carbon(years,regs) calculates carbon in understory vegetation;
understory_carbon(years,regs)=
sum((owners,ctype,type),
inven.l(regs,years,owners,type)*undercarbon(regs,ctype));

parameter dwd_carbon(years,regs) calculates carbon in downed woody debris;
dwd_carbon(years,regs)=
(sum((owners,ctype,type,pp),0.5*
((0.2*v.l(regs,years,owners,type,pp))+(inven.l(regs,years,owners,type)*decompmort(c
type,'mort')))+
(0.2*v.l(regs,years-1,owners,type,pp)*(1-(5*decompmort(ctype,'decomp'))))));



parameter xcut(years);
parameter ncut(years);
parameter tcut(years);
parameter nplant(years);
xcut(years)=sum((REGS,owners,type,mih,cohort,si),exist.l(REGS,owners,type,mih,co
hort,years,si));
ncut(years)=sum((REGS, owners, type, mih, use_age(years2,age), SI)
  $((date(years) eq date(years2)+elapsed(age)) or (sameas(years,'never') and
sameas(age,'never'))),
  new.l(REGS, owners, type, mih, YEARS2, age, SI) );
tcut(years)=xcut(years)+ncut(years);
nplant(years)=sum((REGS, owners, type, mih, use_age(years,age), SI),new.l(REGS,
owners, type, mih, YEARS, age, SI) );
display
tcarb,tree_carb,snagcarb,understory_carbon,prod_carb,dwd_carbon,floorcarb,floor_ca
rb, v_simple,inventory_simple;
```

Appendix C. GAMS code for Current harvest model

```
sets   T    /0,5,10,15,20,25,30,35,40,45,50,55,60,65,70,75,80,85,90,95,100/

 cohort    /0TO4, 5TO9,10TO14, 15TO19, 20TO24,25TO29, 30TO34, 35TO39,
       40TO44, 45TO49, 50TO54, 55TO59, 60TO64, 65TO69, 70TO74, 75TO79,
       80TO84, 85TO89, 90TO94, 95TO99, 100TO104,105TO109, 110TO114,
       115TO119,120TO124,125TO129,130TO134, 135TO139, 140TO144,
       145TO149, 150TO154, 155TO159, 160TO164, 165TO169, 170TO174,
       175TO179, 180TO184,185TO189,190TO194,195TO199,200TO204,
       205TO209,210TO214,215TO219,220TO224,225TO229,230TO234,
       235TO239, 240TO244,245TO249,250PLUS,90PLUS/


     vol                /SFT,HWD/


     YearAge             /2000,2005,2010,2015,2020,2025,2030,2035,2040,
                2045,2050,2055,2060,2065,2070,2075,2080
                ,2085,2090,2095,2100,PLUS0, PLUS5, PLUS10,
                PLUS15, PLUS20, PLUS25, PLUS30,
                PLUS35, PLUS40, PLUS45, PLUS50, PLUS55, PLUS60,
PLUS65,
                PLUS70, PLUS75, PLUS80, PLUS85, PLUS90, PLUS95,
PLUS100,NEVER/
     Year(yearage)          /2000,2005,2010,2015,2020,2025,2030,2035,2040,
                2045,2050,2055,2060,2065,2070,2075,2080
                ,2085,2090,2095,2100,NEVER/


     YEARS(year)
/2000,2005,2010,2015,2020,2025,2030,2035,2040,2045,2050,2055,2060,2065,2070,2
075,2080
                ,2085,2090,2095,2100, NEVER/



 age(yearage)     /PLUS0, PLUS5, PLUS10, PLUS15, PLUS20, PLUS25, PLUS30,
       PLUS35, PLUS40, PLUS45, PLUS50, PLUS55, PLUS60, PLUS65,
       PLUS70, PLUS75, PLUS80, PLUS85, PLUS90, PLUS95, PLUS100,NEVER/



     Type  ATLAS forest types
/1,2,3,4,5,6,7,8,9,10,20,21,23,25,27,28,30,40,41,43,44,45,46,49,50/
     owner              /NF, OP/
     owners(owner)         /NF,op/
     MI management intensity    /LO, LO_PART_CUT, RESERVED/
```

MIH(mi) harvestable mi's   /LO,LO_PART_CUT/

si   site   /ME/
pp product proportions   /ssaw, spulp,sfuel,hsaw,hpulp,hfuel/

sp(pp)   /ssaw,spulp,sfuel/
hp(pp)   /hsaw,hpulp,hfuel/
Reg   /ls, ne, pnwe, pnww, cb, psw, rmn, rms, sc, se/
REGS(REG)   /ls,ne, pnwe, pnww, cb, psw, rmn, rms, sc, se/
CReg   /ne,NLS, NPS, SC, SE, PSW, PWE, PWW, RMN, RMS/
CRegs(creg)   /NE,NLS, NPS, SC, SE, PSW, PWE, PWW, RMN, RMS/
CType   /aspenbirch,
mbbotherhw,oakhickory,oakpine,otherpine,sprucefir,WRJpine,
                 Nonstocked, lowlandhw,
mbb,pine,conifer,bottomlandhw,naturalpine,otherconifer,
                 plantedpine,uplandhw,douglasfir,
firspruce,hardwoods,pinyonjuniper,redwood,

lodgepolepine,ponderosapine,otherhardwoods,redalder,westernhemlock,miscconifer/
    dm   /decomp,mort/
ctypes(ctype)
                 /aspenbirch,
mbbotherhw,oakhickory,oakpine,otherpine,sprucefir,WRJpine,
                 Nonstocked, lowlandhw,
mbb,pine,conifer,bottomlandhw,naturalpine,otherconifer,
                 plantedpine,uplandhw,douglasfir,
firspruce,hardwoods,pinyonjuniper,redwood,

lodgepolepine,ponderosapine,otherhardwoods,redalder,westernhemlock,miscconifer/

    prod_disp product carbon disposition /products, landfills,energy, emissions/
    csfthwd sft and hwd in carbon   /sw,hw,all/
    LiveCoeff live tree biomass coefficients   /f,g,h/
    deadcoeff dead tree biomass coefficients   /a,b,c/
    ffcoeff   forest floor coef   /i,j,k,l/;

*************acres in existing
stands***
table existing_acre(reg, owner, type, mi, cohort, si)
$INCLUDE "existing_acres_2000.prn"

PARAMETER exist_acre(reg, owner, type, mi, cohort, SI) all stands all ages all
owners all periods (ac);

exist_acre(reg, owner, type, mi, cohort, SI) = existing_acre(reg, owner, type, mi, cohort, SI);

************volume in all existing stands by product proportions***************
table existing_volume_pp(reg, owner, type, mi, cohort, year, pp)   XISTVOLPP.TXT IS IN CF PER AC
$INCLUDE "xistvolpp.txt"

ALIAS (PP,PP3);
parameter existvolpp(reg, owner, type, mi, cohort, year, pp) volume in pp's by mcf per ac;
     existvolpp(reg, owner, type, mi, cohort, year, pp)
     =existing_volume_pp(reg, owner, type, mi, cohort, year, pp)/1000;
$INCLUDE "MAPPINGS.TXT"
**************************HARVEST*******************************
****
** IGNORE HARVEST COSTS AND PAYMENTS TO PUBLIC AGENCIES

*COSTS/REGION for existing stands
table pub_exist_costs(reg,type,mi,cohort,year,si)
$INCLUDE "exist_cost.prn"

PARAMETER exist_cost(reg,type,mi,cohort,year,sI) harvesting costs per ac by region type mi cohort and year;
     exist_cost(reg,type,mi,cohort,year,sI) =
pub_exist_costs(reg,type,mi,cohort,year,sI)/1000;

*costs for new stands
table pub_new_costs(age,reg,type,mi,sI)
$INCLUDE "new_cost.prn"

PARAMETER new_cost(age,reg,type,mi,sI) harvesting costs per ac by region type mi cohort and year;
     new_cost(age,reg,type,mi,sI) = pub_new_costs(age,reg,type,mi,sI)*1000;

*Harvest Volume Table
table harvest_request(year,reg,owner)
$INCLUDE "harvest_requests.prn"

PARAMETER harv_req(year,reg,owner) harvest requests for NF and OP lands by year and region (mcf);
     harv_req(year,reg,owner) = harvest_request(year,reg,owner)*1000;

```
***************************Carbon
Coefficients********************************

table SnagCoef(creg, ctype, owner,csfthwd,deadcoeff)
$INCLUDE "StDeadCoef.prn"

PARAMETER StDeadCoef(creg,ctype,owner,csfthwd,deadcoeff) dead tree biomass
coefficients a b c;
    StDeadCoef(creg, ctype,owner,csfthwd,deadcoeff) = SnagCoef(creg,ctype,
owner,csfthwd,deadcoeff);

table LvTrCoef(creg, ctype, owner,csfthwd,livecoeff)
$INCLUDE "LvTrCoef.prn"

PARAMETER LvTreeCoef(creg,ctype,owner,csfthwd,livecoeff) live tree biomass
coefficients f g h;
    LvTreeCoef(creg, ctype,owner,csfthwd,livecoeff) = LvTrCoef(creg,ctype,
owner,csfthwd,livecoeff);

table ForestFloorCoef(reg, ctype,ffcoeff)
$INCLUDE "ForestFloorCoef.prn"

PARAMETER ForFloorCoef(reg,ctype,ffcoeff) live tree biomass coefficients f g h;
    ForFloorCoef(reg, ctype,ffcoeff) = ForestFloorCoef(reg,ctype,ffcoeff);

table data_carbonunder(reg, ctype)
$INCLUDE "data_carbonunder.prn"

PARAMETER undercarbon(reg,ctype) understory carbon ratios percents of live tree
carbon;
    undercarbon(reg, ctype) = data_carbonunder(reg,ctype);

table prod_acct_1(reg,pp, prod_disp,T)
$include "prod_acct_1.prn"

parameter prod_acct(reg,pp, prod_disp,T) percentage product dispostion;
      prod_acct(reg,pp,prod_disp,T)=prod_acct_1(reg,pp,prod_disp,T);


table data_carboncwd(reg, ctype)
$INCLUDE "data_carbon_cwd_3.prn"

PARAMETER carboncwd(reg,ctype) understory carbon ratios percents of live tree
carbon;
    carboncwd(reg, ctype) = data_carboncwd(reg, ctype);
```

```
table decomposition_mortality(ctype, dm)
$INCLUDE "decomp_mort.prn"

PARAMETER decompmort(ctype,dm) decay rates and mortality rates for downed
woody debris;
    decompmort(ctype,dm) =decomposition_mortality(ctype,dm);



********************Acres in each
region**************************************

Parameter reg_acre(reg)   calculates the number of acres in each region (ac);
reg_acre(reg)=sum((owner, type, mi, cohort, SI),exist_acre(reg, owner, type, mi,
cohort, SI));

alias (year,year2), (age,age2), (yearS,yearS2), (cohort,cohort2);

parameter date(year)/
 2000 2000,
 2005 2005,
 2010 2010,
 2015 2015,
 2020 2020,
 2025 2025,
 2030 2030,
 2035 2035,
 2040 2040,
 2045 2045,
 2050 2050,
 2055 2055,
 2060 2060,
 2065 2065,
 2070 2070,
 2075 2075,
 2080 2080,
 2085 2085,
 2090 2090,
 2095 2095,
 2100 2100,
 NEVER 2105/

parameter elapsed(age)/
 PLUS0 0,
 PLUS5 5,
```

```
      PLUS10 10,
      PLUS15 15,
      PLUS20 20,
      PLUS25 25,
      PLUS30 30,
      PLUS35 35,
      PLUS40 40,
      PLUS45 45,
      PLUS50 50,
      PLUS55 55,
      PLUS60 60,
      PLUS65 65,
      PLUS70 70,
      PLUS75 75,
      PLUS80 80,
      PLUS85 85,
      PLUS90 90,
      PLUS95 95,
      PLUS100 100,
      NEVER   105/

parameter time(T)/
0 0,
5 5,
10 10,
15 15,
20 20,
25 25,
30 30,
35 35,
40 40,
45 45,
50 50,
55 55,
60 60,
65 65,
70 70,
75 75,
80 80,
85 85,
90 90,
95 95,
100 100/

parameter meanage(cohort)/
```

```
0TO4  2,
5TO9  7,
10TO14  12,
15TO19  17,
20TO24  22,
25TO29  27,
30TO34  32,
35TO39  37,
40TO44  42,
45TO49  47,
50TO54  52,
55TO59  57,
60TO64  62,
65TO69  67,
70TO74  72,
75TO79  77,
80TO84  82,
85TO89  87,
90TO94  92,
95TO99  97,
100TO104 102,
105TO109 107,
110TO114 112,
115TO119 117,
120TO124 122,
125TO129 127,
130TO134 132,
135TO139 137,
140TO144 142,
145TO149 147,
150TO154 152,
155TO159 157,
160TO164 162,
165TO169 167,
170TO174 172,
175TO179 177,
180TO184 182,
185TO189 187,
190TO194 192,
195TO199 197,
200TO204 202,
205TO209 207,
210TO214 212,
215TO219 217,
220TO224 222,
```

```
225TO229 227,
230TO234 232,
235TO239 237,
240TO244 242,
245TO249 247,
250PLUS  250,
90PLUS   90/;

parameter floorcoeff(reg)
/ls 0.1339167,
ne 0.1339167,
pnwe 0.1339167,
pnww 0.2604615,
psw  0.2604615,
cb  0.1339167
rmn  0.2604615,
rms  0.2604615,
sc   0.2604615,
se  0.1339167/;




*////////////////////////////////////////////////\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*////////////// Greg Adding sets to limit new variable \\\\\\\\\\\\\\\\\\\\\
*//////////////  also resetting date of never         \\\\\\\\\\\\\\\\\\\\\
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\//////////////////////////////
date('never')=0;
date('never')=sum(years$(ord(years) eq card(years)-1),date(years)+5);
* date of never is next to last year in years + 5
set use_age(year,age);
use_age(years,age)$((date(years)+elapsed(age) lt date('never') or ord(age) eq
card(age))
    and (ord(age) gt 1))=yes;
* sets allowable year,age pairs for times less than never
*////////////////////////////////////////////////\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\//////////////////////////////

scalar disc the discount rate
/.04/

parameter MHA(REG)  set minimum harvest ages by region
/ls 50, ne 50, pnwe 50, pnww 50, cb 50, psw 50, rmn 50, rms 50, sc 30, se 30/;
*****************Model
Formulation*****************************************
```

Variables
        z   objective function discounted value of timber management costs
        exist(reg, owners, type, mi, cohort, years,SI) existing acres harvested

        new(reg, owners, type, mih, years, age, SI) new acres harvested
        V(reg,years,owners,type,pp) volume harvested in year and region on given
ownership (mmcf per acre)
        checkvol(years,regs) check volume
        inven_new(years,regs,owners) start of period new inventory (all types sis and
mihs)
        inven_exst(years,regs,owners) start of period exst inventory (all types sis and
mihs)
        inven(regs,years,owners,type) start of period total inventory (all types sis and
mihs)

  ;

positive variables exist, new, v, a_exist, a_new ;
equations
obj objective function
E_acre(regs, owners, type, mih, cohort,SI) existing acres constraints
N_acre(regs, owners, type, mih, years, SI) new acre constraints
perharv(regs,years,owners) harvest in first period
harv_vol(REGS,YEARs,owners,type,pp) harvested volume in year (mcf per acre x
acres = mcf)
checkharv(years,regs) check harvest volume
invent_new(years,regs,owner)
invent_exst(years,regs,owner)
invent_comp(regs,years,owners,type)
 ;

*###
*######## OBJECTIVE FUNCTION   ################
*###

obj.. z =e= (sum((regS,yearS,type,mih,cohort,si,owners)$(ord(years) lt card(years)) ,

(exist_cost(regs,type,mih,cohort,years,si)*exist(REGS,owners,type,mih,cohort,years,si
))/
        (1+disc)**(date(years)-2000))+
       sum((regs,use_age(years,age),type,mih,si,owners)$((ord(years) lt card(years))
        and (sum(cohort,exist_acre(REGS, owners, type, mih, cohort,SI)) gt 0)),
       (new_cost(age,regs,type,'lo',si) * new(regs,owners,type,'lo',years,age,si))/
        (1+disc)**(date(years)-2000)));

************************acreage
constraints*************************************
**** NOTE CURRENT YEAR = YEARS, YEAR PLANTED = YEARS2
**** NOTE CURRENT AGE = AGE, AGE WHEN CUT = AGE2

*****EXISTING ACRES CONSTRAINTS--ALLOCATE NO MORE TO A
HARVESTS OVER PROJECTION
* THAN AVAILABLE IN ORIGINAL (2000) INVENTORY---UNITS AC's
 E_acre(REGS, owners, type, miH,cohort,SI)$(exist_acre(REGS, owners, type, mih, cohort, SI) gt 0)..
 sum(years$(meanage(cohort)+(date(years)-2000) ge mha(regs)),exist(REGS, owners, type, mih, cohort,years, SI)) =e=
 exist_acre(REGS, owners, type, mih, cohort, SI);
*set as equality so that all existing acres will be alloctaed to some harvest year
*may be largely NEVER for short runs

********NEW ACRES CONSTRAINTS--PLANT NO MORE IN A YEAR THAN
WAS HARVESTED---UNITS AC's
 n_acre(REGS, owners, type, 'lo', YEARS, SI)$((sum((cohort,mih),exist_acre(REGS, owners, type, mih, cohort,SI)) gt 0) and
   (ord(years) lt card(years)))..

 SUM(use_age(years,age)$(elapsed(age) ge MHA(regs)),new(REGS, owners, type, 'lo', YEARS, age, SI)) =e=
* NEW ACRES HARVESTED IN YEARS
 (sum(YEARS2$(ord(YEARS2) lt ord(YEARS)),

  sum(use_age(years2,age2)$((date(YEARS)-date(YEARS2) eq elapsed(age2)) and (elapsed(age2) ge MHA(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI))))+
* EXISTING ACRES HARVESTED IN YEARS
  (sum((cohort,mih)$((exist_acre(REGS, owners, type, mih, cohort, SI) gt 0) and (meanage(cohort)+(date(years)-2000) ge mha(regs))),exist(REGS, owners, type, mih, cohort, years,SI)));

******VOLUME HARVESTED IN YEARS (mcf)
 harv_vol(REGS,YEARS,owners,type,pp)$(ord(years) lt card(years))..
 V(regs,years,owners,type,pp)=e= sum((si)$(sum((cohort,mih),exist_acre(REGS, owners, type, mih, cohort,SI)) gt 0),
 (sum(YEARS2$(ord(YEARS2) lt ord(YEARS)),

  sum(use_age(years2,age2)$((date(YEARS)-date(YEARS2) eq elapsed(age2)) and (elapsed(age2) ge mha(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners, type, 'lo', age2,pp))))+

sum((cohort,mih)$(meanage(cohort)+(date(years)-2000) ge
mha(regs)),exist(REGS,owners,type,mih,cohort,years,si)*existvolpp(REGS, owners,
type, mih, cohort, YEARS, pp)));

2000 harvest constraint***************
***UNITS MCF
 perharv(regs,years,owners)$(ord(years) lt card(years))..
 sum((type,pp),(1.2*v(regs,years,owners,type,pp)))=e= (harv_req(years,regs,owners));

* recompute the harvest to check
 checkharv(years,regs)$(ord(years) lt card(years))..
  checkvol(years,regs) =e= sum((owners,type,pp), V(regs,years,owners,type,pp));

*compute start of period new inventory
invent_new(years,regs,owners)$(sum((cohort,type,mih,si),exist_acre(REGS, owners,
type, mih, cohort,SI)) gt 0)..
 inven_new(years,regs,owners) =e=
  sum((type,si,pp),
  sum(use_age(years2,age2)$(ord(YEARS2) lt ord(YEARS)),

  sum(age$((date(YEARS)-date(YEARS2) eq elapsed(age)) and (elapsed(age2) ge
mha(regs))),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners,
type, 'lo', age,pp)))
  );
*compute start of period existing inventory
invent_exst(years,regs,owners)$(sum((cohort,type,mih,si),exist_acre(REGS, owners,
type, mih, cohort,SI) gt 0))..
 inven_exst(years,regs,owners) =e=
  sum((type,mih,si,pp),
  sum((cohort,years2)$(ord(years2) ge ord(years)),
  exist(REGS,owners,type,mih,cohort,years2,si)*(
    existvolpp(REGS, owners, type, mih, cohort, YEARs, pp)$(ord(years) lt
card(years))
    +
    (sum(year$(date(year) eq date(years) and (meanage(cohort)-(date(years)-2000) ge
mha(regs))),existvolpp(REGS, owners, type, mih, cohort, YEAR, pp))
    $(ord(years) eq card(years)))
    ))
  );

*compute start of period total inventory
invent_comp(regs,years,owners,type)$(sum((cohort,mih,si),exist_acre(REGS, owners,
type, mih, cohort,SI)) gt 0)..

```
 inven(regs,years,owners,type) =e=
  sum((si,pp),
  sum(use_age(years2,age2)$(ord(YEARS2) lt ord(YEARS)),

  sum(age$((date(YEARS)-date(YEARS2) eq elapsed(age)) and (elapsed(age2) ge
mha(regs)) ),
  new(REGS, owners, type, 'lo', YEARS2, age2, SI)*NEW_vol_pp(REGS, owners,
type, 'lo', age,pp)))+
  sum((cohort,mih,years2)$(ord(years2) ge ord(years)),
  exist(REGS,owners,type,mih,cohort,years2,si)*(
    existvolpp(REGS, owners, type, mih, cohort, YEARs, pp)$(ord(years) lt
card(years))
    +
    (sum(year$(date(year) eq date(years) and (meanage(cohort)+(date(years)-2000) ge
mha(regs))),existvolpp(REGS, owners, type, mih, cohort, YEAR, pp))
    $(ord(years) eq card(years)))
    ))
  );

model harvest /all/;

solve harvest using LP minimizing Z;

parameter v_simple(regs,years) calculates summed volume;
v_simple(regs,years) = sum((owners,type, pp),
V.l(regs,years,owners,type,pp));

parameter new_simple(regs,years2) calculates summed acres;
new_simple(regs,years2) = sum((owners,type,age2,si),
new.l(REGS, owners, type, 'lo', YEARS2, age2, SI));

parameter exist_simple(regs,years) calculates summed acres;
exist_simple(regs,years) = sum((owners,type,mih,cohort,si),
exist.l(REGS,owners,type,mih,cohort,years,si));

parameter inventory_simple(regs,years) calculates summed volume;
inventory_simple (regs,years)= sum((owners,type),
inven.l(regs,years,owners,type));




*================================================================
==================
*====    Beginning of Carbon Equations                     ========
*====                                                  ========
```

```
*==============================================================
==================
*****************************************************************
********

*****************************************************************
*********
******Standing Tree Carbon Sequestered IN YEARS and region

parameter Tcarb(regs,owners,years) calculates tree carbon;
Tcarb(regs,owners,years)= ((sum((cregs,ctypes,type,csfthwd),
lvtrcoef(cregs,ctypes,owners,csfthwd,"f")*
(lvtrcoef(cregs,ctypes,owners,csfthwd,"g")+
(1-exp(-
inven.l(regs,years,owners,type)/lvtrcoef(cregs,ctypes,owners,csfthwd,"h"))))))/2.471)*
0.5;

parameter snagcarb(regs,owners,years) calculates carbon in snags or standing dead
trees;
snagcarb(regs,owners,years)=
(sum((cregs,ctypes,csfthwd,type),((tcarb(regs,owners,years)*2))*
stdeadcoef(cregs,ctypes,owners,csfthwd,"a")*
exp(-((inven.l(regs,years,owners,type)/
stdeadcoef(cregs,ctypes,owners,csfthwd,"b"))**
stdeadcoef(cregs,ctypes,owners,csfthwd,"c"))))/2.471)*0.5;

parameter floorcarb(regs,owners,years,cohort) calculates forest floor carbon;
 floorcarb(regs,owners,years,cohort)=
 (sum((cohort2,years2,type,mih,si)$((exist.l(regs,owners,type,mih,cohort,years,si) gt
0)),
*and (meanage(cohort) gt 20)),
 (sum((ctypes),(exist.l(regs,owners,type,mih,cohort2,years,si))*

(((meanage(cohort2)*forfloorcoef(regs,ctypes,'I'))/(forfloorcoef(regs,ctypes,'J')+meana
ge(cohort2)))))))-
*+++++++++++++++++++++++++++++
(sum((cohort2,years2,type,ctypes,mih,si)$((ord(years) ge ord(years2)) and
(exist.l(regs,owners,type,mih,cohort,years,si) gt 0)),
((exist.l(regs,owners,type,mih,cohort2,years,si))*
( (forfloorcoef(regs,ctypes,'K')*(exp(((date(YEARS)-
date(YEARS2))/forfloorcoef(regs,ctypes,'L')))))$(forfloorcoef(regs,ctypes,'L') gt 0.01)
  +(forfloorcoef(regs,ctypes,'K'))$(forfloorcoef(regs,ctypes,'L') lt 0.01)))))
*+++)+++++++++++++++++++++++++
 /2.471);
```

parameter tree_carb(regs,years) carbon just by reg and year;
tree_carb(regs,years) = sum((owners,csfthwd),
Tcarb(regs,owners,years));

parameter snag_carb(regs,years) carbon just by reg and year;
snag_carb(regs,years) = sum((owners,csfthwd),
snagcarb(regs,owners,years));

parameter floor_carb(regs) carbon just by reg and year;
floor_carb(regs) = sum((owners),
floorcarb(regs,owners));

parameter understory_carbon(years,regs) calculates carbon in understory vegetation;
understory_carbon(years,regs)=
sum((owners,ctype,type),
inven.l(regs,years,owners,type)*undercarbon(regs,ctype));

parameter prod_carb(regs,years,prod_disp) calculates carbon in products and landfills;
prod_carb(regs,years,prod_disp)=
sum((owners,type,pp,t,years2)$(date(years)-date(years2) eq time(T)),
(v.l(regs,years2,owners,type,pp))*prod_acct(regs,pp,prod_disp,T));

parameter dwd_carbon(years,regs) calculates carbon in downed woody debris;
dwd_carbon(years,regs)=
(sum((owners,ctype,type,pp),0.5*
*left on site this period
((0.2*v.l(regs,years,owners,type,pp))+
*natural mortality and decay
(inven.l(regs,years,owners,type)*decompmort(ctype,'mort')))+
*decomposition from last period of logging slash
(0.2*v.l(regs,years-1,owners,type,pp)*(1-(5*decompmort(ctype,'decomp'))))))));

parameter xcut(years);
parameter ncut(years);
parameter tcut(years);
parameter nplant(years);
xcut(years)=sum((REGS,owners,type,mih,cohort,si),exist.l(REGS,owners,type,mih,cohort,years,si));
ncut(years)=sum((REGS, owners, type, mih, use_age(years2,age), SI)

```
   $((date(years) eq date(years2)+elapsed(age)) or (sameas(years,'never') and
sameas(age,'never'))),
   new.l(REGS, owners, type, mih, YEARS2, age, SI) );
tcut(years)=xcut(years)+ncut(years);
nplant(years)=sum((REGS, owners, type, mih, use_age(years,age), SI),new.l(REGS,
owners, type, mih, YEARS, age, SI) );
display
tcarb,tree_carb,snagcarb,understory_carbon,prod_carb,dwd_carbon,floorcarb,floor_ca
rb,v_simple, inventory_simple;
```