LIFE-CYCLE IMPACTS OF FOREST RESOURCE ACTIVITIES IN THE PACIFIC NORTHWEST AND SOUTHEAST UNITED STATES

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ABSTRACT

Environmental impacts associated with the life-cycle of forest resource activities were assessed for the Southeastern U.S. and Pacific Northwest supply regions as a component of a broad analysis of life-cycle inventory data on wood products produced in these regions. The assessment included all of the inputs to establish a forest stand (seedlings, site preparation, and planting), to treat that stand through harvest maturity (thinning and fertilization) and to harvest the merchantable logs from the stand. To provide a region-wide representation under different management strategies, three forest management scenarios were structured for both the Southeastern U.S. and Pacific Northwest regions. Within each region, three combinations of management intensity and site productivity were allocated to acreages corresponding to the U.S. Forest Service RPA allocation and then merged into a single estimate of yield and the corresponding harvesting impacts. This allocation of acreage to management intensity/site productivity class provided a representative base case for each region.

A more intensive management alternative was created for each region by reallocating acres to higher management intensity classes. Harvesting activities were segmented into five stages to allow development of all inputs and outputs: (1) felling, (2) processing (bucking, limbing, cutting to length), (3) secondary transportation (skidding and yarding), (4) loading, and (5) hauling to a process point. The costs and consumption rates of energy and materials for these activities drove the log outputs, emissions, and carbon pools. Logs are allocated to wood product facilities, the primary product of the analysis, or pulp and paper mills as a co-product from the forest. Non-merchantable slash is generally left on site and is disposed of

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through site preparation activities. Transportation-related activities and the required diesel fuel produce by far the largest contribution to emission outputs. However, fertilizer use contributes to much of the change in emissions as acreage shifts to higher intensity management alternatives.

Keywords: Life-cycle inventory, forest management impacts, CORRIM, timber harvesting costs, timber harvesting fuel consumption.

BACKGROUND

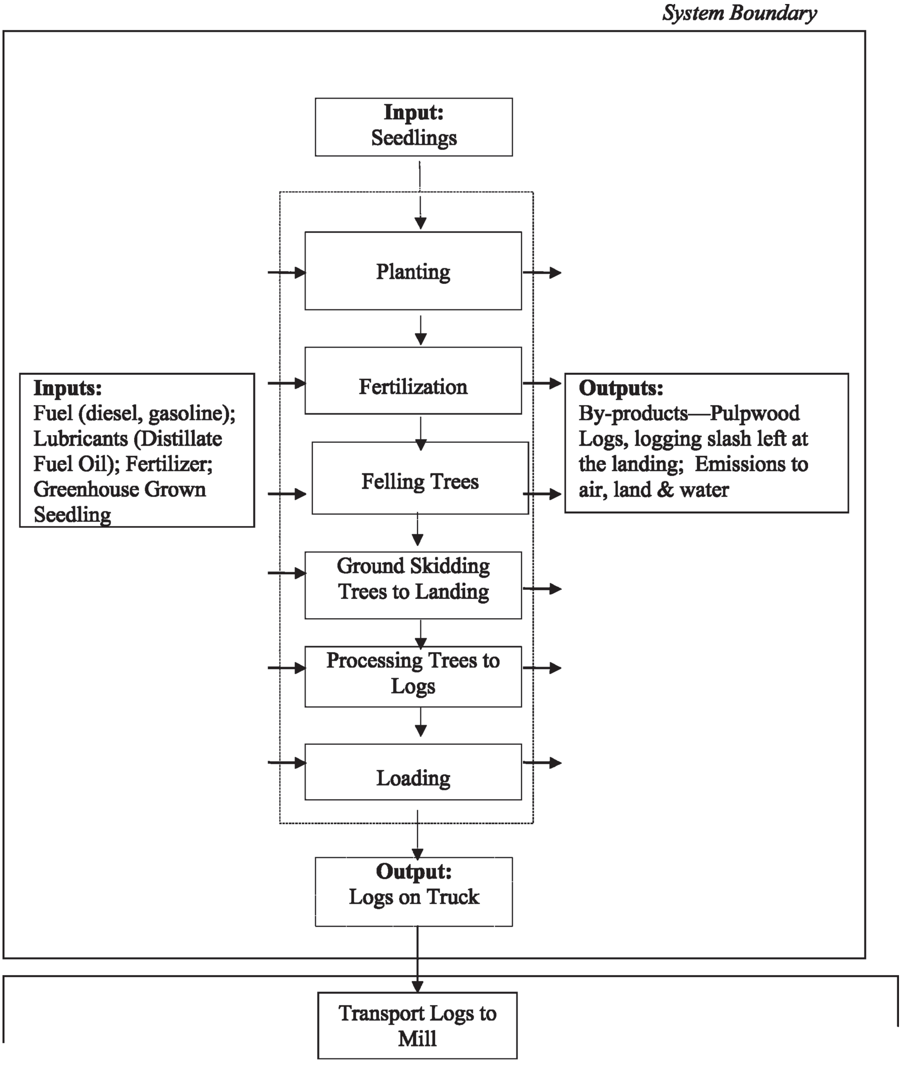
Removal of wood biomass from the forest and the activities associated with growth, removal, and reestablishment of trees require careful analysis to determine the total environmental impacts and to assess sustainability associated with the use of biomass-based products. Life-cycle inventories (LCIs) and analyses of impacts are not stationary and will change based on both past and prospective technologies, evolving forest management procedures, and market demands. Time becomes a critical element of this analysis since the period from initial planting or forest establishment to removal can range from five years for short rotation intensive culture to 100 years or more for selectively managed forests. Inputs and outputs of the life-cycle process include quantitative measures that can be used to interpret costs, production and environmental results, and qualitative measures that describe other aspects of the forest environment. Understanding the time-dependent linkages between technology changes and management practices and their effects on these factors is essential to identification of forest management alternatives that enhance the critical environmental features and are also cost-effective.

The forest resource module of the comprehensive CORRIM analysis includes the efforts required to establish a forest stand, to treat that stand through harvest maturity, and to harvest the merchantable logs from the stand. Stand establishment involves preparation of the site for planting and planting of seedlings on the prepared site. Intermediate stand treatments enhance growth and productivity while the stand is growing and frequently involve thinning, fertilization, or both.

In a fully developed scenario, two classes of output would be developed. One represents costs, quantities of product, measures of consumed resources, and the emission factors associated with those resources. This information is developed across the acres being managed for timber production and passed on to the next stage of processing. The second class of output involves measures unique to the forest resources stage that provide an indication of the environmental impact of the management activity on the forest. The life-cycle analysis presented here does not develop forest indicators of other impacts and co-products associated with the management activity, but a case study developing sustainability indicators for the Pacific Northwest is presented in a related article. Timber harvesting activities generally include five components: felling (severing the standing tree from the stump), processing (often called bucking, limbing and/or topping and involving removal of non-merchantable limbs and tops and cutting of the tree into merchantable and transportable log lengths), secondary transportation (often called skidding on gentle slopes and yarding on steep slopes, this transportation step moves trees or logs from the point of felling to a loading point near a haul road), loading (moving logs from decks to haul vehicles), and primary transportation (generally hauling of logs from the woods to a process point). Although all functions are required to remove logs from the woods, the specific order and location of the processing operation will vary by region and by harvesting system within a region. Transportation of logs from the woods to the process point is often considered part of the harvesting operation. The costs and consumption rates for primary transportation are included in the summary statistics of this analysis, but emission factors associated with primary transportation are included with the manufacturing modules for the subsequent product, in this case, lumber, plywood, or oriented strandboard (OSB).

System boundaries for forest resource activities in the Southeast United States are illustrated in Fig. 1. Inputs to the system include site preparation activities required to prepare a site for planting, the human effort required to hand plant seedlings, fertilizer used during stand growth, and the fuel and lubricants needed to power and maintain the harvesting system. The primary output product for this analysis is a log destined for a sawmill, plywood, or OSB plant. A primary co-product in the Southeast is pulpwood logs, used in the manufacture of pulp and paper. The other co-product, non-merchantable slash, is generally left at a landing and disposed of through mechanical activities or prescribed fire.

Factors involved in growth of the seedlings were modeled as input to the system, but were not considered to be within the system boundary. These factors include the fertilizer used in seedling growth and the electrical energy required to operate forest nursery pumps and to keep seedlings cool for planting.



Transportation emission factors included in Life Cycle Analysis of Final Wood Product

FIG. 1. System boundaries and process flow for forest stand establishment and harvesting for Southeast region.

In the Pacific Northwest, very little pulpwood is produced in the woods. Most of the feedstock for pulp and paper mills comes from the residual material generated during the manufacture of the primary wood product. The non-merchantable slash is generally left on site and is disposed of through a variety of site preparation techniques.

METHODOLOGY

Biomass volume yields per unit area

Regional scenarios were structured to describe conditions associated with the growth, removal, and reestablishment of trees in the forest resource module. One of the scenarios reflects conditions in the Pacific Northwest, specifically the west side of Oregon and Washington, and the other reflects conditions for the southeastern United States, with data centered in North Carolina. These regions represent predominant timber-producing regions within the United States.

The scenarios were structured from three general combinations of management intensity and site productivity for each region. Management intensities ranged from little intervention on low site productivity lands to higher management intensities involving combinations of fertilization and thinning on high productivity lands. Associated with each combination of management intensity and site productivity was an estimated yield of biomass. Management options were focused on private forest lands that generally involved planting, intermediate forest management activities such as fertilization and thinning, and a final harvest at the rotation age of the forest. Vegetation growth for the scenarios was simulated through established growth and yield vegetation simulators developed for each respective region. The simulation models produced estimates of standing and harvested biomass along with other stand attributes at selected points in time through the rotation age of the forest stand. Volumes of harvested biomass in the form of logs were passed on as resources to the manufacturing segments for lumber, plywood, or oriented strandboard (OSB). Volumes of logs destined for pulp and paper manufacture were treated as co-products of the forest resource module.

A single estimate of the average volume harvested per unit area for a region was developed by weighting each of the three combinations of site productivity and management intensity. The weighting factor for each combination was determined from acreage distributions of management intensity and site class that were established through expert opinion and subsequent analysis of U.S. Forest Service data available from the Resource Planning Assessment (RPA) database (USDA 2000, Mills 2001). The Forest Service information categorizes the number of private forest acres in each region by site classification and management intensity. Each of the management intensity and site classes used in the Forest Service analysis were associated with, and were represented by, one of the three general management intensity combinations described above.

The allocation of acreage to management intensity/site productivity class represented a base case for each region. In the Southeast, 37% of industrial and non-industrial private forestlands were classified in the lowest productivity class, 58% in the middle productivity class, and 5% in the highest class. In the Pacific Northwest, 42% of the lands were classified in the lowest productivity/management class, 46% in the middle class, and 12% in the highest productivity class.

Sensitivity of the results to management changes was assessed by considering the impacts of introducing higher levels of management intensity to private forest lands. This was simulated by shifting acreage in each region to a higher level of management intensity. In the Southeast, all lands in one class of management intensity were shifted to the next higher level. This alternate case resulted in a distribution in the Southeast of 0% in the lowest productivity class, 37% in the middle class, and 63% in the highest classification. In the Pacific Northwest, the shift of lands to a higher classification was based on analysis of the RPA data that indicated the potential to shift some, but not all acres to a higher management intensity. This resulted in

24% of the lands in the lowest productivity class, 40% in the middle class, and 36% in the highest class. These shifts resulted in higher volume production of biomass volume from the forested sites as a result of increased inputs (fertilization and thinning) throughout the life of the forest stand.

Vegetation simulators common to the respective regions were used in conjunction with established research to estimate the units of biomass by tree component—stem, roots, branches, and foliage. Estimates of tree biomass by component were then used to estimate the standing and removed carbon pool over time.

Site preparation and stand establishment

Forest stand establishment and timber harvesting activities include site preparation for planting after harvest, planting of seedlings, forest management activities, including fertilization and thinning, over the life of the stand, and harvesting of the mature stand. Cost, production, and emission factors associated with site preparation and forest stand establishment were developed from information in existing studies and were integrated with information on subsequent stand treatments and final harvesting to develop overall factors associated with the log delivered to a lumber mill, plywood plant, or OSB mill.

Site preparation and planting factors for the Southeast were developed from published studies on forest nursery operations (South and Zwolinski 1996) and site preparation production and fuel consumption rates (Frazier et al. 1981). Cost and fuel consumption factors were calculated per seedling and were then multiplied by the number of planted seedlings per unit area specified for each of the three management scenarios to determine costs and fuel consumption rates per unit area. Total costs and fuel consumption per unit area were divided by the final harvested volume per unit area to establish the contribution of site preparation, seedlings, and planting to the costs and consumption factors per unit of harvested volume.

Factors for the Pacific Northwest were developed from personal communication with forest nursery managers (Wenny 2003) and a manuscript on greenhouse operations for containerized seedlings (Schlosser et al. 2002). Seedlings in both regions were assumed to be planted by hand. The only energy factors associated with planting were related to travel to and from the planting site.

In the Southeast region, fertilization regimes were developed for the mid-intensity and high-intensity scenarios, but not for the low-intensity option. Fertilization differences between the mid- and high-intensity options were primarily associated with the frequency of application. The high intensity option involved fertilization every four years over the 25-year life of the stand. The mid-intensity option involved fertilization at years two and sixteen. The fertilizer mixture included nitrogen, potassium, and phosphorus. Stand treatment options for the Southeast were developed by Lee Allen of the North Carolina Tree Nutrition Cooperative (Allen 2001).

Intermediate stand treatments in the Pacific Northwest included less fertilization, but added pre-commercial thinning. Fertilization was done in years 20, 30, and 40 only in the high-intensity option. Pre-commercial thinning was done in both the mid- and high-intensity options at year 15. These management scenarios were developed at the University of Washington from growth and yield information available to their stand modeling researchers (Lippke and Comnick 2002).

Rates of fuel consumption for stand establishment and management activities and the per-acre rates of fertilization are shown in Table 1.

Timber harvesting

Harvesting costs, production, and fuel and oil consumption rates were developed for each equipment component within the harvesting system and were assimilated from existing studies of the types of harvesting equipment used in the two regions. These studies included both published information and personal interviews with timber harvesting contractors (Biltonen 2002; Hochrein and Kellogg 1988; Jorgenson 2002;

TABLE 1. *Seedling, site preparation, planting, and fertilization consumption.*

	Southeast region			Pacific Northwest region		
	Low intensity	Medium intensity	High intensity	Low intensity	Medium intensity	High intensity
		Fuel consumption (gal/acre)			*Fuel consumption (gal/acre)*	
Greenhouse and seedling	5.46	5.46	5.46	2.62	3.93	3.93
Site preparation	2.16	7.86	14.18	0.00	0.00	0.00
Planting	0.71	0.71	0.71	0.41	0.41	0.41
Pre-commercial thin	0.00	0.00	0.00	0.96	0.96	0.96
Total	8.32	14.02	20.34	3.98	5.29	5.29
		Pounds/acre over rotation			*Pounds/acre over rotation*	
Nitrogen						
In seedlings	0.125	0.125	0.125	0.038	0.057	0.057
On site	0	236	636	0	0	354
Phosphate						
In seedlings	0.006	0.006	0.006	0.063	0.095	0.095
On site	0	40	115	0	0	60
Potassium						
In seedlings	0.075	0.075	0.075	0.154	0.232	0.232
On site	0	0	0	0	0	0

Keegan et al. 1995; Kellogg and Bettinger. 1995; Kellogg et al. 1996; Lawson 2002; Ledoux 1984; Reynolds 2002; Stevens and Clarke 1974). Cost, production, and consumption factors of the harvesting system were calculated through the addition of the component factors. This analysis assumes the use of the most common system for a region within the assumed slope classification of the harvested sites. In the Southeast region, this involves the use of mechanized harvesting systems operating on relatively gentle terrain. Mechanized felling utilizes a cutting device mounted on a woods tractor (feller-buncher) that travels through the stand to cut and bunch trees, transportation of those harvested trees to a landing (skidding), and the use of another machine that can delimb and process trees into logs at the landing. Two general systems were used. A smaller feller-buncher and grapple skidder were used for commercial thinning. A larger, more capital-intensive system was used for final harvest. The processing operation for this type of system generally takes place at the landing. Thus, whole trees are moved to the landing through the secondary transportation operation and are then processed into logs. Since whole trees are moved to the landing, the removed carbon from the site includes both the stem and the crown.

Although harvesting operations in the Pacific Northwest can be found on both gentle and steep terrain, they are more likely to involve steeper slope conditions than are operations in the Southeast. Steep slope harvesting will usually involve cable yarding as the method of secondary transportation. Cable yarders stay on haul roads and move logs to the landing through a series of cables stretched from the road to the end of a harvesting corridor. The steep slopes also limit the use of mechanized felling systems, so felling operations are generally done with a person operating a chainsaw—often called manual felling. Limited decking areas at a landing will dictate processing of the trees into log lengths near the stump of the felled tree, so processing operations (bucking, limbing, and topping) are also done by a person operating a chainsaw located in the woods. Processing in the woods changes the order of operations from those described for the Southeast. Processing follows immediately after felling. The secondary transportation step (yarding) will move logs rather than whole trees to the landing. Since limbs and tops of the trees are left on the site, removed carbon for Pacific Northwest systems includes only the carbon associated with the stem.

Cost, production, and fuel and lubrication consumption rates for the selected systems are shown in Table 2. The total cost and fuel con-

TABLE 2. *Timber harvesting system production, costs, and consumption.*

		Production rate CCF/SMHR	Production cost $/CCF	Diesel use gal/CCF	Lubricant use gal/CCF
System 1: Southeast Thinning System					
Felling:	Small feller buncher	17.28	$5.03	0.31	0.01
Skidding:	Small wheeled skidder	3.24	$16.98	0.95	0.02
Processing:	Stroke delimber	25.92	$3.86	0.22	0.00
Loading:		8.64	$6.94	0.58	0.01
Subtotal	Stump to truck		$32.81	2.06	0.04
Hauling:		2.59	$34.56	3.14	0.06
System total			$67.37	5.20	0.09
System 2: Southeast Final Harvest System					
Felling:	Large feller buncher	22.03	$4.40	0.27	0.00
Skidding:	Medium grapple skidder	4.05	$18.52	1.19	0.02
Processing:	Stroke delimber	25.92	$3.86	0.22	0.00
Loading		8.64	$6.94	0.58	0.01
Subtotal	Stump to truck		$33.72	2.26	0.04
Hauling		2.59	$34.56	3.14	0.06
System total			$68.28	5.40	0.10
System 3: Pacific Northwest—Cable Thinning					
Felling:	Hand felling	2.49	$11.22	0.08	0.00
Yarding:	Large yarder—partial	7.78	$16.72	1.80	0.03
Loading		8.64	$6.94	0.58	0.01
Subtotal	Stump to truck		$34.89	2.46	0.04
Hauling		2.59	$45.47	4.13	0.07
System total			$80.36	6.59	0.12
System 4: Pacific Northwest—Clearcut					
Felling:	Hand felling	2.49	$11.22	0.08	0.00
Yarding:	Large yarder—clearcut	10.79	$10.19	1.19	0.02
Loading		8.64	$6.94	0.58	0.01
Subtotal	Stump to truck		$28.36	1.84	0.03
Hauling		2.59	$45.47	4.13	0.07
System total			$73.83	5.98	0.11

SMHR = scheduled machine hour, includes productive time and delays.
CCF = 100 cubic feet of solid wood.

sumption over the life of the stand were calculated as the sum of all forest management activities, including commercial thinning and final harvest. The averaged costs and fuel consumption rates at each level of management intensity were then calculated as the total costs and consumption values divided by the total merchantable volume removed. The fuel consumption rates shown in Table 2 are also used in modeling the air emissions associated with the harvesting operations.

Carbon production and removal

In the Southeast, carbon estimates were developed through the NUTREM2 model (NCSFNC 2000) developed and used in the region. The annual production of carbon in the stem was estimated at 50% of the biomass of the stem. Carbon in the branches was estimated at 21% of stem biomass. Biomass and the related carbon in the foliage and roots were also developed from the NUTREM2 model. Standing carbon estimates were calculated from the estimate of total tree volume generated in the NUTREM2 model coupled with adjustments for the age of the stand. Carbon in branches and course roots were again estimated as a function of stem carbon. Carbon in foliage was set equal to amount of annual production of carbon. Carbon in fine roots was calculated as twice the annual carbon production in fine roots.

Carbon removed is calculated as the difference between carbon in the year before activity and carbon after the activity plus any carbon accumulation during the year of activity. As noted in the harvesting section, removed carbon includes carbon in both the stem and crown.

In the Northwest, carbon budgets were constructed from tree lists describing standard inventory data for individual trees, e.g., species, diameter, and crown ratio. These tree lists were derived from the FVS growth model (Wykoff 1986). They include tree characteristics at five-year intervals as predicted by the model. From these data, timber volume and the biomass of leaves, roots, and stem are estimated using published allometric equations (Gholz et al. 1979). The equations take the following form:

$$y = ae^{b*dbh}$$

where y is the mass or volume being predicted, dbh is the diameter at breast height, and a and b are species-specific parameters. Stem volume is multiplied by specific gravity of each species to estimate stem mass. Masses of carbon in each tissue are estimated by multiplying tissue mass by species-specific carbon concentrations. The need for species-specificity in these parameters is obvious from the substantial species differences in allometric equations (Gholz et al. 1979), specific gravity (Panshin and de Zeeuw 1970), and carbon concentrations (Vertregt and Penning de Vries 1987). The carbon amounts are then summed over the several parts of the tree. Per-tree estimates are expanded to a per-acre basis using standard forest inventory techniques (Marshall and Waring 1986; Monserud and Marshall 1999). Carbon accumulation in biomass is estimated by the changes in carbon standing stocks as estimated by the above procedure.

The model also predicts tree mortality, which releases carbon from the canopy and other above-ground pools. It also describes the mortality of tree parts as biomass of a particular part declines during the subsequent time steps. Finally, the model estimates the mass of parts of the tree not hauled off-site during harvesting. All of these dying tissues are assigned to pools of decomposing material. Species-specific estimates of decomposition rate are used to estimate losses of carbon to the atmosphere. The equations take the following form:

$$x_t = x_0(1 - k * t)$$

where x_t is the weight at time t, x_0 is initial weight, k is a species and tissue-specific constant describing proportional weight loss per year, and t is time in years (Aber and Melillo 1991). The mass of decomposing material is estimated as the sum of mortality in the most recent time interval and the residual mass of decomposing material (x_t) from previous time steps. The masses of decaying material are summed over all species and tissue types.

While standing carbon represents an estimate of carbon in the standing tree based on the estimates of biomass, the rates of decomposition of down material, down foliage, or roots from harvested trees are not well documented for either the Southeast or Northwest. The general assumption in both the Southeast and Northwest is that fine roots grow and decompose at about the same rate. This means they do not add net carbon to the system. What is not known, however, is the degree of carbon release from the decomposed fine roots in the soil and whether the net release of fine root carbon over the 30- or 100-year rotation of a managed forest will be different from the carbon released in a non-managed stand. Carbon information for both regions includes the standing carbon inventory just prior to harvest at the rotation age and an estimate of removed carbon through forest management activities, both intermediate thinning and the final harvest.

Environmental impacts

Environmental impacts were assessed using an established method built into the SimaPro 5.09 software (Goedkoop and de Gelder 2001; Goedkoop and Oele 2001). SimaPro was used to perform the life-cycle analysis, to generate emission factors, and to analyze the relative contribution of the various site preparation and harvesting processes to emissions. SimaPro was developed in the Netherlands by PRé Consultants B.V., SimaPro5 contains a U.S. database for a number of materials, including paper products, fuels, and chemicals. Franklin Associates (FAL) provides an additional U.S. database that is incorporated within SimaPro.

The SimaPro software allows selection of the assessment method used to evaluate overall life-cycle impacts. Briefly, the assessment method quantifies the impacts of the process on a set of environmental indicators including, for example, carcinogens, climate change or greenhouse impacts, the ozone layer, and acidification or eutrophication. The indices associated with a particular assessment method can be summarized into a single value that represents a weighted average of the environmental effects per cubic meter of wood produced. Although the selected measures and the weighting values are arbitrary, the method provides a means of objectively comparing the environmental impacts of various alternatives.

The assessment method selected for the modules analyzed in the comprehensive CORRIM analysis was Eco-indicator 99 (E)/Europe EI 99 E/E. This method incorporates measures of impact of the total process on developed measures such as fossil fuels, respiratory inorganics, climate change, and carcinogens. Contribution to these factors is measured in method-derived indices that assess the impact on human health, plant species, and energy replacement needs. While each of these impact areas has direct measurements, the method also combines these factors into a single dimensionless index reflecting the total impact of the process. The single factor is a direct result of the assumptions used in developing and weighting the indicator, but can be used to illustrate the relative differences between the various forest management treatment options.

SOUTHEAST EXAMPLE

Scenarios developed for the Southeast represent a composite of stands from the extensive database managed by the Forest Nutrition Cooperative at North Carolina State University (Hafley et al. 1982; Buford 1991). The corresponding carbon analysis was done with a related NUTREM2 model (NCSFNC 2000) with carbon factors based on data in the SETRES database common to the Southeastern United States.

The three scenarios represent combinations of the site index and corresponding level of management intensity. The first reflects non-industrial private forests (NIPF) with low-intensity management that might be implemented by the small private landowner. The second reflects high-intensity management on NIPF lands and/or low intensity management on industrial lands. The third scenario reflects high intensity management on industry lands. Specific assumptions associated with these three scenarios are outlined in Table 3.

The increasing levels of site productivity and management intensity result in an increase in the volume of wood fiber produced per acre, but also reflect a change in the type of product produced. Three product categories were identified for the Southeast: pulpwood, chip-and-saw, and sawtimber. Chip-and-saw material consists of smaller diameter trees processed through a specific type of sawmill that produces both lumber and pulpwood chips. Sawtimber represents a higher value product with more of the material eventually ending up as lumber. In the summary tables for this analysis, chip-and-saw material was considered to be part of the lumber component of production. The production from the low intensity areas is divided between pulpwood and chip-and-saw material. In the medium management intensity option, the percentage of volume in pulpwood remains about the same, but more of the lumber component is shifted from chip-and-saw to sawtimber. With higher intensity management, even more of the volume is shifted to the sawtimber category.

These three site/management scenarios were averaged to develop a composite average for the region. Weighting for the composite average was determined through analysis of a general Resources Planning Act (RPA) survey of the region conducted by the U.S. Forest Service (USDA 2000; Mills 2001). This survey deter-

TABLE 3. *Southeastern (SE) U.S. scenarios: specific assumptions for three management scenarios applied to private forest lands in the Southeastern U.S.*

Ownership/prescription	Low NIPF/low intensity	Medium NIPF/high intensity or industrial/low intensity	High Industrial/high intensity
Site index	58	67	80
Planting density (trees per acre)	726	726	726
Fertilization	None	Years 2, 16	Years 2, 5, 9, 13, 17, 21
First thinning—cubic meters	0	63	59
at year		*17*	*13*
Second thinning—cubic meters	0	0	58
at year			*19*
Final harvest—cubic meters	220	175	295
at year	*30*	*25*	*25*
Total yield/hectare—cubic meters	220	238	323
Rotation age	30 years	25 years	25 years
Percent sawlog	3.2%	20.2%	42.7%
Percent chip-n-saw	34.9%	11.2%	8.9%
Percent pulpwood	61.9%	68.6%	48.4%
Percent area in class for base case	37%	58%	5%
Percent area in class for alternative case	0%	37%	63%

mined the number of acres within each combination of site index and management intensity. The numbers of combinations of site index/management intensity were larger than the three specific scenarios created for this analysis so the acreages specified in the RPA analysis were matched to one of the scenarios and totaled. Two cases were structured. One emulates the current conditions as determined by the analysis of RPA information for current conditions. The second considers the impact of shifting to a higher intensity level of management sufficient to achieve timber production similar to that for lands with the higher site indices.

The resulting analysis for both the Base and Alternate cases for the Southeast and the Pacific Northwest are shown in Tables 4A, 4B, and 4C. The one-way hauling distance represents the average surveyed distance for the region from harvest site to lumber mill. The shift to the higher intensity scenario increased the production of merchantable volume from 222 cubic meters/hectare (3174 cubic feet/acre) to 291 cubic meters/hectare (4163 cubic feet/acre). The percent of the volume categorized for lumber increased from 35% to 44%. In addition, more of the lumber volume produced in the higher intensity scenario was categorized in the sawtimber category rather than in a chip-and-saw category.

The increased cost and fuel consumption required to produce the additional sawlog volume in the higher intensity scenario are generally offset by the increased volume. Costs and consumption rates per unit of sawlog volume are very close for the two scenarios. The exception is the requirement for fertilizer, illustrated in Table 4C by the requirement for nitrogen. A high requirement for fertilization is required in the Southeast to obtain the additional growth over the relative short rotation age (25 years) of the forest.

Table 4C also shows estimates of the standing and removed carbon at the end of the rotation age, an average of annual amounts of standing carbon over the rotation of the stand, and the carbon removed through thinning and harvesting activities. The values are expressed as units of carbon weight per unit of area.

PACIFIC NORTHWEST EXAMPLE

The scenarios developed for the western United States were structured in a manner similar to those for the Southeast. Three general combinations of site index and management intensity were developed to reflect conditions and

TABLE 4A. *Cost and energy consumption—base and alternate case representing a weighted average of the three management intensity levels for the Southeast and Pacific Northwest regions.*

	Southeastern U.S. and Pacific Northwest scenarios				
	Southeast U.S.		Pacific Northwest		
Rotation age	25		45		Year of rotation
	Percent of private land area in site/management category				
	Southeast U.S.		Pacific Northwest		
	Base case	Alternate case	Base case	Alternate case	
Low: NIPF low intensity	37%	0%	42%	24%	
Medium: Industrial low intensity	58%	37%	46%	40%	
High: Industrial high intensity	5%	63%	12%	36%	
Average one way haul distance		92		121	Kilometers
Harvesting systems:					
Low intensity	Small feller buncher/skidder/processor		Hand fell and buck/cable yard		
Medium intensity	Large feller buncher/medium skidder/large processor		Hand fell and buck/cable yard		
High intensity	Large feller buncher/medium skidder/large processor		Hand fell and buck/cable yard		
	Volume removed in thinning and final harvest				
Volume	222	291	501	581	Cubic meters/hectare
% Lumber	35%	44%	100%	100%	
% Pulpwood	65%	56%	0%	0%	

Note: Lumber includes both Sawtimber and Chip and Saw Volumes

management intensity ranging from the low intensities common to NIPF lands to higher intensities of management more common to high site index lands managed by the forest industry. Specific assumptions associated with these three combinations are outlined in Table 5.

Two cases were developed for western forests, one reflecting current conditions and one estimating the impact of higher intensities of management on lands with higher site indices. In Northwest operations, the merchantable volume is first delivered to sawmills, and residual chips are generated from the lumber or plywood manufacturing process. Direct delivery of pulpwood from the woods was not assumed to represent a significant part of the volume. This affects the commercial volume removed from the woods and the volume left on site after harvest. Results for the Base and Alternate cases are shown in Tables 4A, 4B, and 4C. The average one-way hauling distance in both cases reflects the average surveyed distance from harvest site to lumber mill. Average yield for the base case was 501 cubic meters/hectare (7159 cubic feet/acre). This volume increased to 581 cubic meters per hectare (8301 cubic feet/acre) under the higher intensity alternative.

As was the case for the Southeast region, the increased cost and fuel consumption required to produce the sawlog volume in the higher intensity scenario was generally offset by the increased volume produced. Costs and consumption rates per unit of sawlog volume are very close for the two scenarios. The requirement for nitrogen shown in Table 4C is higher for the alternate scenario than for the base scenario, but the amounts are significantly lower than for the Southeast region.

Carbon pools for the two alternatives, shown at the end of Table 4C, illustrate standing and removed carbon at the end of the rotation age, an average of annual amounts standing carbon over the rotation of the stand, and the carbon removed through thinning and harvesting activities.

TABLE 4B. *Cost and energy consumption—base and alternate case: system costs and fuel consumption.*

	Southeast U.S.		Pacific Northwest		
	Base case	Alternate case	Base case	Alternate case	
System costs					
Prep, plant, precom. thin.	553	1,010	630	639	Dollars per hectare
	2.49	3.48	1.26	1.10	Dollars/cubic meter
Stump to truck	2,620	3,470	5,700	6,720	Dollars per hectare
	11.81	11.91	11.38	11.56	Dollars/cubic meter
Hauling	92	92	121	121	Kilometers
Truck to mill	2,710	3,550	8,040	9,330	Dollars per hectare
	12.20	12.20	16.06	16.06	Dollars/cubic meter
Total cost	5,890	8,040	14,400	16,700	Dollars per hectare
	26.50	27.59	28.69	28.71	Dollars/cubic meter
Electric, fuel and lubricant consumption					
Seedling, site prep, plant, precom. thin.					
Fuel	114	168	44.3	46.5	Liters/hectare
	0.515	0.578	0.088	0.080	Liters/cubic meter
Lubricants	2.06	3.03	0.798	0.838	Liters/hectare
	0.009	0.010	0.002	0.001	Liters/cubic meter
Electric	101	101	193	206	MJ/hectare
	0.455	0.347	0.385	0.355	MJ/cubic meter
Stump to truck					
Fuel (diesel)	652	878	1,430	1,690	Liters/hectare
	2.93	3.02	2.85	2.90	Liters/cubic meter
Lubricants	11.7	15.8	25.7	30.3	Liters/hectare
	0.053	0.054	0.051	0.052	Liters/cubic meter
Hauling	92	92	121	121	Kilometers
Fuel (diesel)	933	1,220	2,770	3,210	Liters/hectare
	4.20	4.20	5.53	5.53	Liters/cubic meter
Lubricants	16.8	22.0	49.8	57.8	Liters/hectare
	0.076	0.076	0.099	0.099	Liters/cubic meter
Total planting and harvest operation					
Fuel	1,700	2,270	4,240	4,940	Liters/hectare
	7.65	7.79	8.46	8.50	Liters/cubic meter
Lubricants	30.6	40.9	76.3	89.0	Liters/hectare
	0.138	0.140	0.152	0.153	Liters/cubic meter

There is consistency between the results developed for the Southeast and those developed for the Pacific Northwest. Costs of logs onboard trucks in the Southeast are $11.81 per cubic meter for the base case and $11.91 per cubic meter for the alternate case. Comparable costs in the Pacific Northwest are 11.38 and 11.56, respectively. Production of sawlogs per unit of area is higher in the Pacific Northwest, but harvesting system costs are also higher because of the use of cable systems. Diesel consumption to the truck in the Southeast is 2.93 liters per cubic meter for the base case and 3.02 liters per cubic meter in the alternate case. This compares to 2.85 liters per cubic meter for the base case in the Pacific Northwest and 2.90 liters per cubic meter for the alternate case.

EMISSIONS FROM FOREST MANAGEMENT ACTIVITIES

Emission factors for fertilizers used in seedling development and in forest management were derived from existing database factors within the FAL database. Potassium fertilizer was considered as an input from nature. Nitrogen and phosphate fertilizers were considered as inputs from what SimaPro labels as the “tech-

TABLE 4C. *Cost and energy consumption—base and alternate case: fertilizer consumption and carbon pools.*

	Southeast U.S.		Pacific Northwest		
	Base case	Alternate case	Base case	Alternate case	
Fertilizer					
Nitrogen	189	547	47.7	143	Kilograms/hectare
	0.852	1.878	0.095	0.246	Kilograms/cubic meter
Phosphate	32.5	97.8	8.16	24.3	Kilograms/hectare
	0.146	0.336	0.016	0.042	Kilograms/cubic meter
Potassium	0.084	0.084	0.223	0.239	Kilograms/hectare
	0.000	0.000	0.000	0.000	Kilograms/cubic meter
Carbon pools at end of rotation					
Average of standing carbon pools over rotation					
Stem	25,400	26,200	65,100	70,600	Kilograms/hectare
Crown	8,340	8,940	12,500	12,800	Kilograms/hectare
Roots	9,120	9,200	14,700	16,200	Kilograms/hectare
Total	42,900	44,400	92,300	99,600	Kilograms/hectare
Standing carbon prior to harvest					
Stem	44,500	45,600	139,000	156,000	Kilograms/hectare
Crown	13,400	14,100	22,300	23,600	Kilograms/hectare
Roots	15,100	15,500	32,400	37,000	Kilograms/hectare
Total	73,000	75,100	193,000	217,000	Kilograms/hectare
Removed through thinnings and final harvest					
Stem	56,500	71,800	156,000	178,000	Kilograms/hectare
Crown	16,000	20,600	0	0	Kilograms/hectare
Roots	0	0	0	0	Kilograms/hectare
Total	72,500	92,400	156,000	178,000	Kilograms/hectare
	255	247	312	307	Kilograms/cubic meter

Pounds/cu ft based on stem volume divided by merchantable cubic feet.
Stem carbon: carbon in stem + bark.
Crown carbon: carbon in branches + foliage − litter.
Roots: carbon in course and fine roots.

nosphere," reflecting a manufacturing process to produce these fertilizers.

Assumptions relative to diesel fuel and gasoline were consistent with those used in the analysis of the primary wood products of lumber, plywood, and oriented strandboard. They were derived from the FAL database. Diesel fuel was the primary power source for all site preparation and harvesting equipment except chainsaws and the vehicles used to transport crews to and from the forest stand. Lubricant consumption in harvesting equipment generally consists of hydraulic oils and general lubricants required for the hydraulic systems and moving parts of the harvesting equipment. Lubricants are not consumed through combustion, but are replaced through regular maintenance activities. Used lubricating fluids were assumed to be recycled.

The primary direct emissions from forest management activities will be through the air emissions created through the combustion of diesel and gasoline engines. Air emissions for all operations required to produce logs loaded on trucks are shown for base and alternate cases studied for both regions in Table 6. Emissions from seedling growth and planting represented a very small portion of the total for the forest management activity, and the total emissions for the forest management activities were a small component of the overall emission factors associated with the primary wood products.

The factors shown in the tables represent the combined effect of fuel combustion and fertilization. The non-fossil CO_2 emissions shown in the table are assumed to be derived from biomass and therefore have a neutral impact in the overall life-cycle analysis.

The single factor analysis for each of the pro-

TABLE 5. *Pacific Northwest (PNW) scenarios: specific assumptions for three levels of management intensity in the Pacific Northwest.*

Management intensity class prescription	Low intensity	Medium intensity	High intensity
Site index	86	114	130
Planting density (trees per acre)	400	600	600
Genetics and fertilization	None	None	Years 20, 30, 40
Pre-commercial thinning	None	Year 15	Year 15
(Trees per acre)		*300*	*275*
Commercial thinning—cubic meters	0	81	81
at year		*30*	*25*
Final harvest—cubic meters	433	409	701
at year	*45*	*45*	*45*
Total yield/hectare—cubic meters	433	490	782
Percent sawlogs	100%	100%	100%
Rotation age	45 years	45 years	45 years
Percent area in class for base case	42%	46%	12%
Percent area in class for alternative case	24%	40%	36%

cesses in the planting, site preparation, intermediate site treatments, and final harvesting activity to overall emission factors is shown for the high intensity levels for both of the harvest regions in Figs. 2 and 3.

The primary contributor to the overall impact factor for all scenarios is the combustion of diesel equipment. Within that category, the largest individual contributor is the equipment used for the secondary transportation of the cut logs or trees from the woods to the landing. This is followed closely by the diesel consumption used in the loading logs on trucks. Factors associated with hauling the harvested logs to the final processing point are included in the analysis for the manufactured lumber or plywood product.

TABLE 6. *Projected emissions to the air for both regions and both the base and alternate case—using SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E.*

	SE base	SE alternate	PNW base	PNW alternate
	Kilograms/cubic meter of harvested log			
Aldehydes	1.69E – 04	1.77E – 04	1.49E – 04	1.51E – 04
Ammonia	3.19E – 04	7.38E – 04	3.74E – 05	8.69E – 05
CO	7.70E – 02	7.45E – 02	1.03E – 01	1.02E – 01
CO_2	3.99E – 01	9.50E – 01	3.24E – 02	9.71E – 02
CO_2 (fossil)	9.25E + 00	9.71E + 00	8.02E + 00	8.12E + 00
CO_2 (non-fossil)	2.51E – 03	3.00E – 03	1.96E – 03	2.03E – 03
Dust (SPM)	2.11E – 04	5.01E – 04	1.71E – 05	5.12E – 05
Formaldehyde	2.44E – 03	2.47E – 03	2.18E – 03	2.20E – 03
Methane	6.29E – 03	1.27E – 02	1.71E – 03	2.47E – 03
N_2O	2.34E – 03	5.54E – 03	1.90E – 04	5.69E – 04
NO_2	7.63E – 04	1.88E – 03	6.21E – 05	1.84E – 04
Non-methane VOC	3.78E – 02	4.66E – 02	3.00E – 02	3.12E – 02
NO_x	1.67E – 01	1.71E – 01	1.46E – 01	1.47E – 01
Organic substances	1.16E – 04	1.31E – 04	9.57E – 05	9.82E – 05
Particulates (PM10)	1.15E – 02	1.18E – 02	1.02E – 02	1.03E – 02
Particulates (unspecified)	7.38E – 04	8.72E – 04	5.19E – 04	5.40E – 04
SO_2	1.94E – 03	4.80E – 03	1.57E – 04	4.66E – 04
SO_x	4.38E – 02	7.56E – 02	1.97E – 02	2.36E – 05
VOC	3.22E – 05	7.63E – 05	2.61E – 06	7.80E – 06

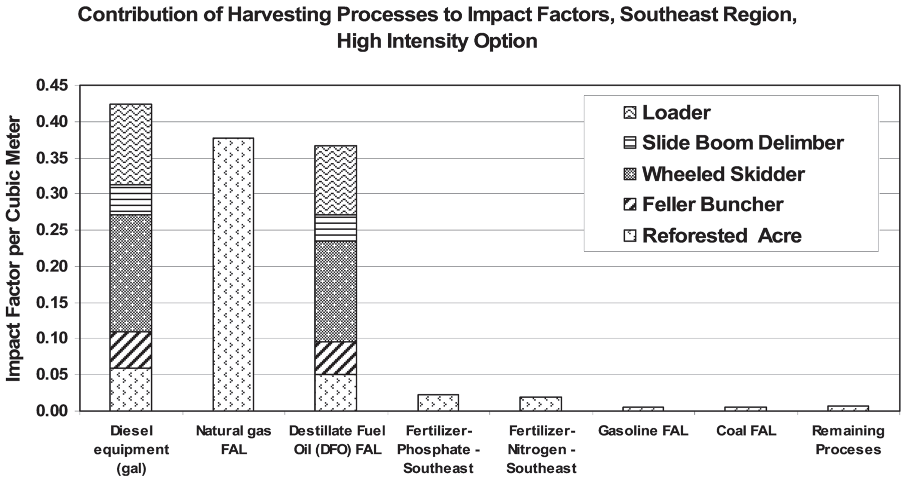


FIG. 2. Contribution of forest management processes to impact factors as generated by SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E for the Southeast region with high intensity management.

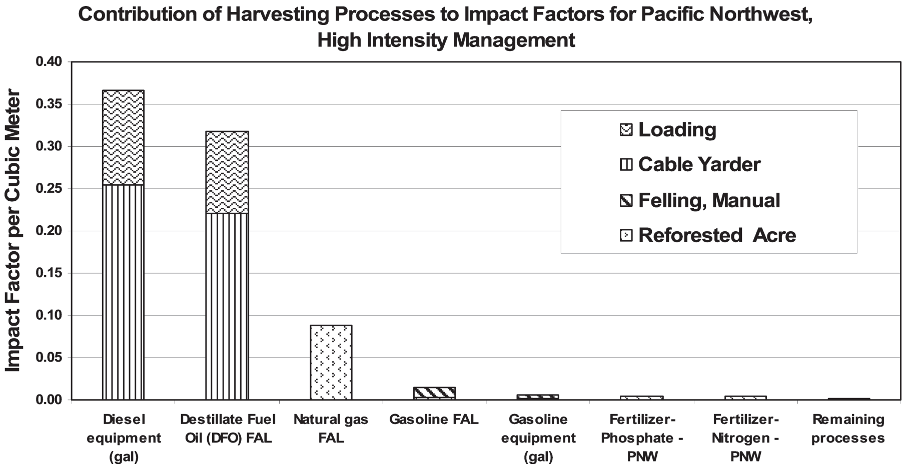


FIG. 3. Contribution of forest management processes to impact factors as generated by SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E for the Pacific Northwest with high intensity management.

Graphs for the high intensity scenarios show a significant contribution from natural gas related to the process called the reforested acre. This reflects the contribution that the fertilizer applications make to the final product.

Summaries of the total impact factor for each of the management intensities and regions and for the weighted averages by region for the base and alternate cases are shown in Table 7. The higher factors for the Southeast region generally reflect the increased use of mechanized site preparation and the higher levels of fertilization intensity.

FUTURE WORK

The approach used to reduce the multiple site index/management intensity classifications of each region listed in the RPA to the three scenarios developed for each region requires additional review and assessment to ensure valid categorization of the forest lands of the respective

TABLE 7. *Comparison of overall impact factor by management scenario and region as developed through the Eco-indicator 99 (E)/Europe EI 99 E/E method of SimaPro.*

	Impact factor per cubic meter of harvested log		
Single factor measurement	Southeast	Percent difference	Pacific Northwest
High intensity	1.227	53%	0.802
Medium intensity	1.002	37%	0.734
Low intensity	0.785	19%	0.661
Average for base case	0.932	31%	0.713
Average for alternate case	1.144	54%	0.742
Percent increase for alternate	19%		4%

SimaPro, Eco-indicator 99 (E)/Europe EI 99 E/E.

regions. The three management scenarios within each region could be benchmarked against other known data for the region and perhaps calibrated to be more representative of the region. This process should consider both the allocation of acreage to the three categories and the harvested volumes generated from these classifications.

Indices for other co-products and impacts associated with forest management activities developed for the Pacific Northwest were addressed in another module of the CORRIM project. That analysis accounts for reserved acreage adjacent to the managed stands that could impact the resulting site indices. However, analysis of these co-products could be more directly integrated into the forest resource analysis and extended to cover the Southeast.

Fuel consumption data for the selected harvesting systems are generally based on the horsepower of the machines used within those systems. The fuel consumption calculations show consistency across the range of equipment used and should have a fairly high degree of reliability. Lubricant consumption was calculated as a percent of fuel consumption. This assumption generalizes the consumption rate and fails to distinguish between individual equipment characteristics.

The assumption of steep slope settings in the Pacific Northwest dictated the use of cable logging systems, but this added to costs associated with Northwest harvesting operations. There are sites in the Northwest that are harvested with mechanized, ground-based harvesting systems and these sites could be categorized and analyzed in a manner similar to that used for the Southeast.

Region-specific data on the consumption of resources during seedling growth, site preparation, and stand establishment are limited. Estimates for these values were developed using a limited set of published data and through direct inquiries of forest nursery managers. Stand establishment requirements were based on planting rates for seedlings and the distance of the stands from the mill. Additional base information would be useful for this segment, but when seedling growth and planting are combined with the timber harvesting operation, emission flows are dominated by the fuel consumption required for harvesting the timber.

Carbon models should be reviewed for consistency between regions and for consistent application of both production and decomposition functions. Other data issues related to carbon production, decomposition, and release were noted in the general discussion of the methods for estimating carbon.

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