LIFE-CYCLE IMPACTS OF INLAND NORTHWEST AND NORTHEAST/NORTH CENTRAL FOREST RESOURCES

*Elaine E. Oneil**
Research Scientist
School of Forestry
College of Environment
University of Washington
PO Box 352100
Seattle, WA 98195-2100

Leonard R. Johnson†
Professor Emeritus
1205 Kamiaken
University of Idaho
Moscow, ID 83843

Bruce R. Lippke†
Professor Emeritus
School of Forestry
College of Environment
University of Washington,
PO Box 352100
Seattle, WA 98195-2100

James B. McCarter
Research Scientist
School of Forestry
College of Environment
University of Washington
PO Box 352100
Seattle, WA 98195-2100

Marc E. McDill
Associate Professor of Forest Management
School of Forest Resources
310 Forest Resources Building
The Pennsylvania State University
University Park, PA 16802

Paul A. Roth
Program Manager
Resource Inventory & Analysis
Bureau of Forestry
137 Penn Nursery Road
Spring Mills, PA 16875

---

* Corresponding author: eoneil@u.washington.edu
† SWST member

Wood and Fiber Science, 42(CORRIM Special Issue), 2010, pp. 29–51

James C. Finley
Professor of Forest Resources
302 Forest Resources Building
The Pennsylvania State University
University Park, PA 16802

(Received March 2009)

Abstract. Determining the life-cycle inventory (LCI) and impact of forest harvest, regeneration, and growth is necessary in conducting a life-cycle assessment of wood products. This publication provides quantitative assessments of the economic and environmental impacts of forest management activities covering portions of the Inland Northwest (INW), including Montana, Idaho, and eastern Washington, and of the Northeastern and North Central (NE/NC) forests from Minnesota to Maine and south as far as Missouri, West Virginia, and Pennsylvania. The management scenarios provide the inputs needed to develop an LCI on all the inputs and outputs for wood products as impacted by forest treatments and the harvesting of logs in the region. Productive timberlands were grouped according to forest type, productivity, management intensity, and ownership into three broad forest types in the west: cold, dry, and moist; and four in the east: spruce/fir, northern hardwoods, oak/hickory, and aspen/birch. Spruce/fir represented the feedstock to softwood lumber and a composite of northern hardwoods and oak/hickory the feedstock to hardwood lumber. Simulations used the US Forest Service Forest Vegetation Simulator to estimate standing and harvested biomass and log volumes passed on as resources to the manufacturing segments for lumber, plywood, or oriented strandboard. The combinations of ownership, management intensity, and forest type were stratified and averaged to produce a single estimate of yield and the corresponding harvesting impacts. Both historic harvest rates and increased management intensity scenarios were simulated for each region. In the INW, the shift to the higher intensity scenario increased the average production of merchantable volume at harvest to 249 – 399 m^3/ha when averaged across the forested land in each ownership class. For the NE/NC region, the production of merchantable volume averaged 263 m^3/ha for softwood and 328 m^3/ha for hardwood forests with an insignificant volume response from shifting land into more intensive management. Average growth varied widely for INW forest categories from a low on federal land for the base case of 0.7 – 6.7 m^3/ha·yr for moist state and private land under the intensive management alternative. Current condition estimates of softwood log and bark carbon exported for mill processing in the INW and NE/NC regions were 751 and 988 kg/ha·yr, respectively.

Keywords: Inland Northwest, LCI, LCA, fire risk reduction, forest, wood products, forest carbon.

INTRODUCTION

The Consortium for Research on Renewable Industrial Material (CORRIM) research project was designed to 1) collect environmental and economic data on all life-cycle stages (life-cycle inventory [LCI]) from planting and growing the renewable raw material, progressing to the manufacturing of products, and for transport, design, and construction of buildings as well as activities associated with occupation, use, and final demolition; 2) ensure that the data follow consistent definitions and collection procedures in keeping with ISO standards; and 3) develop analytical procedures that facilitate integration of results and assessments across alternatives for the full life cycle for all stages of processing to address environmental performance questions (life-cycle-assessment) (CORRIM 1998). The need for a LCI and assessment of log processing stages as inputs into solid wood products manufacturing has become increasingly important as we move into an era in which the carbon sequestration potential of forests, and the carbon storage inherent in solid wood products, has become a significant element in policy decisions surrounding greenhouse gas reductions by the forest sector.

Using CORRIM protocols, we developed an LCI for the forest resources stage of processing from regeneration to harvest and delivery of logs to the mill for two regions of the US: the Northeast/North Central (NE/NC) and the Inland Northwest (INW). These regional analyses provide estimates of the production rates, costs, and emissions associated with management of representative timber producing land for the NE/NC region from Minnesota to Maine and as far south as Missouri, West Virginia, and Pennsylvania; and for the INW covering Idaho, Montana, and the area east of the Cascade Mountains in Washington.

The collapse of the manufacturing infrastructure in many parts of the western US led us to limit the analysis to the timber producing land in Idaho, Montana, and the area east of the Cascade Mountains in Washington State where a relatively robust milling infrastructure still remains. Timber output from Idaho and Montana accounts for 91% of the roundwood production for the Rocky Mountain Region, whereas 10% of the roundwood production for the Pacific Coast Region comes from eastern Washington based on 2006 Resource Planning Act data (FIA 2009). The land within this three-state region, including national forest lands not specifically excluded from management, were considered as timber-producing land. The growth, yield, management, and harvest data from this region characterize the removals from the forest that become the log inputs for the ensuing transportation and processing LCI analyses for the INW softwood lumber manufacturing (Puettmann et al 2010).

A previous study referred to as CORRIM Phase I (Johnson et al 2005) provided a similar analysis for Pacific Northwest and Southeast forests, the two largest US supply regions. This study was designed to extend the geographic coverage to the four main supply regions. It evaluates log inputs for hardwood and softwood lumber production covering approximately 26% of the US production (FIA 2009). Together, this and the Johnson et al (2005) studies provide national coverage for the forest resource inputs of the dominant US softwood and hardwood lumber supply regions.

Developing estimators for logs and coproducts associated with lumber manufacturing production across such diverse regions requires a landscape approach that integrates both inputs and outputs by forest type, ownership, and management scenario. Two approaches were taken for this project. In the INW, all forest types covering more than 5% of the area were included in growth and yield simulations with the outputs aggregated to obtain a landscape-level estimate. In the NE/NC, the forest types were first aggregated into regionally significant forest type groups and a range of site class and management scenarios were simulated for each group. Both approaches considered alternative rotation ages and management scenarios, including alternatives without management or disturbance. Depending on the scenario, different proportions of the area in these forest types were allocated to different management intensity categories. The impacts from applying a range of management intensities across the broad spectrum of forest types in these two regions were weighted to be representative of the impact for the timber-producing land. The analysis does not include reserved forest land under any ownership category. In the INW, national forest lands within the dry and mixed conifer forests that are not explicitly reserved from harvest across the entire region are included. In the NE/NC, private and public lands that could be placed under active management are included.

The analysis identifies both carbon emissions and environmental toxicity implications associated with establishing a forest stand, treating that stand through maturity, and harvesting the merchantable logs that are exported to mills as the next stage of processing. Stand establishment involves site preparation for planting and planting the seedlings or allowing for natural regeneration or sprouting, depending on management intensity and region. Intermediate stand treatments designed to enhance growth and productivity can include fertilization, thinning, and species selection.

Timber harvesting includes five components: felling (cutting) the standing tree; processing (removing nonmerchantable limbs and tops and cutting of the tree into merchantable and transportable log lengths); secondary transportation (moving 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 (hauling of logs from the forest to a process point). The costs and consumption rates for primary transportation are included in our summary statistics, but consistent with the system boundary for the forest resources module (Fig 1), emission factors associated with primary transportation to processing mills are included with the manufacturing modules of the life-cycle analysis. Although all functions are performed in the forest setting, the specific order and location of the processing operation varies by harvesting system. Steep-slope harvesting will usually involve cable yarding as the method of secondary transportation, which changes the order of operations in the system in that processing follows immediately after felling. The secondary transportation step (yarding) typically moves logs rather than whole trees to the landing. All of the harvest in the NE/NC and most in the INW use ground-based skidding in which processing follows secondary transportation; therefore, this method is identified as a dominant factor in the system boundaries for forest resource activities illustrated in Fig 1.

Inputs to the system include site preparation activities for planting (if any), the human effort required to plant seedlings (if any), precommercial thinning activities scheduled during stand growth (if any), and the fuel and lubricants needed to operate the harvesting systems. Factors involved in growth of the seedlings were modeled as inputs to the system but were not considered to be within the system boundary. These factors included the fertilizer used in seedling growth and the electrical energy required to operate forest nursery pumps, to power the growing operations, and to keep seedlings cool until planting. No on-site fertilization was considered part of these management alternatives. Not all forest types and management

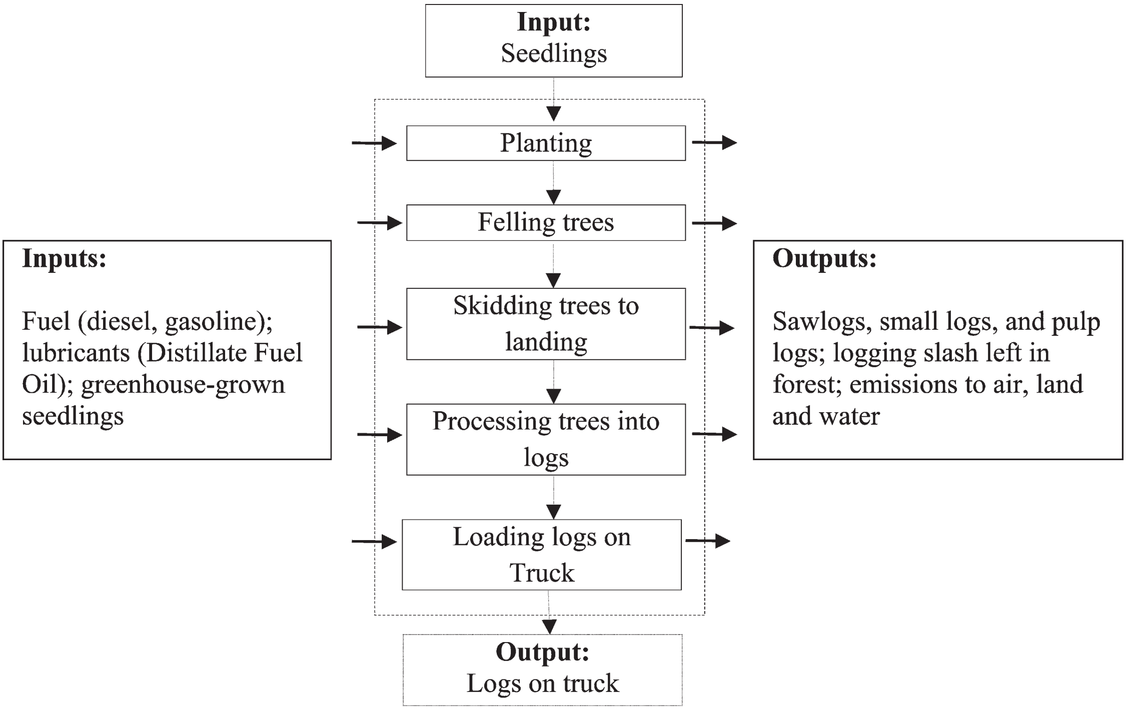

Figure 1. System boundaries and process flow for forest stand establishment and harvesting.

scenarios used planting and thinning treatments; therefore, these inputs were weighted to reflect their relative input values across all land by region and management intensity.

The primary output product for this analysis is a log destined for a sawmill, plywood mill, or oriented strandboard (OSB) plant. Pulpwood logs are only removed from the forest if markets are sufficiently strong to pay for their removal. In the INW, most of the feedstock for pulp and paper mills comes from the residual material from the manufacturing plants for the primary wood products (lumber, plywood, and OSB), but in the NE/NC region, much of the feedstock for pulp and paper mills comes directly from the forest. A primary coproduct, nonmerchantable slash, is generally left in the forest or at a landing. This material is left to decay (NE/NC) or is disposed of through mechanical activities and/or prescribed fire (INW). This slash may find future use as a bioenergy input, but that component of the LCI was not included in this analysis.

METHODS

Categorizing Management Intent

Following the protocol used in CORRIM Phase I (Johnson et al 2005), the life-cycle analysis includes two general cases, one reflecting current management conditions, called the base case, and the other reflecting an increase in management intensity within specific ownership classes called the alternate case. The base case represents estimates of current harvest activity by forest type, treatment regime, productivity level, and ownership class. The alternate case reflects assumptions regarding the distribution of an increased area to more intensive management regimes. Given the complexity of the forest types, sites, stocking levels, age class distribution, harvest regimes, and ownership patterns, it was necessary to develop a weighted average value for each case that incorporated the breadth of management intent, harvest rate, and prescriptions used by different owner groups in each region.

Volume and Biomass Yields per Unit Area

Timber production scenarios were developed to describe conditions associated with growth, removal, and re-establishment of trees based on common management regimes for each region. Tree growth for the scenarios was simulated using the Forest Vegetation Simulator (FVS) developed by the US Forest Service (USFS) (Wykoff et al 1982; Wykoff 1986). The simulation model produced estimates of standing and harvested biomass along with many other stand attributes at decadal intervals up to the rotation age of the forest stand. Log volume, biomass, and carbon estimations were generated with the Landscape Management System (LMS) (McCarter et al 1998) using the Northeast and Lake States FVS growth and yield models for the NE/NC analysis and the Inland Empire, Blue Mountains, and East Cascades FVS variants for the INW. Volumes of harvested biomass in the form of logs were passed on as resources to the manufacturing segments for lumber, plywood, or OSB. Volumes of logs destined for pulp and paper manufacture were treated as coproducts of the forest resource module. The LMS carbon module estimates biomass by tree component: stem, roots, branches, and foliage. Estimates of tree biomass by component were used to estimate the standing and removed carbon pools over time.

Forest Profiles

Inland Northwest. Scenarios developed for the INW used a subset of the USFS Forest Inventory and Analysis (FIA) data covering eastern Washington, Idaho, and Montana that included only plots classified as unreserved timberland. FIA plots were segregated into dominant habitat types by owner group, and the median stand by habitat type and owner group was chosen to represent the diversity of forest types in the region. The process identified 94 stands representing 30 unique habitat type/owner combinations that were further grouped into dry, moist, and cold forest types for assignment of relatively uniform treatment regimes and management intensities that were applied according to owner profile.

The three forest types and associated management scenarios were used to develop a weighted average representing a composite input value for the region. National forests comprise a substantial portion of the INW forest land base but presently contribute only a limited amount of timber volume. In calculating output variables, we weighted results by volume produced regionally in each of the management categories to account for the substantially different management intensity that is occurring on national forests relative to other timber-producing lands. Summaries from the aggregated average by volume harvested were forwarded to the manufacturing modules for incorporation into the life-cycle analysis.

For the INW, the base case reflects historical harvest rates by ownership and region applied across the forest types. Base case management intensities ranged from understory thinning for fire safety on national forest lands to clearcutting on the higher productivity lands of industrial forest owners. The alternate case applied more intensive management to private land by emphasizing species selection, enhancing thinning regimes, and actively managing more private land. Over the long term, these shifts in management activity produced more biomass volume from the private forests sites but assume that forest land investment is made on an ongoing basis. Increasing management intensity on national forests was obtained by treating more land under a restoration thinning approach emphasizing retention of dominant overstory trees and reducing wildfire hazard through removal of ladder fuels. An estimated yield of log volume, biomass, and carbon was determined for each owner group by habitat type and was then aggregated by forest group (dry, moist, cold) and management intensity. After the simulations were run, the similarities between removal volumes and effective harvest regimes permitted a further aggregation into three management scenarios and intensities: state and private (dry forests), state and private (moist and cold forests), and national forests.

Northeast/North Central. Forest growth and harvesting scenarios for the NE/NC region were derived using FIA data for the region. Data from Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, West Virginia, and Wisconsin were assessed. From the wide diversity of species mixes, productivity classes, habitat types, and ownerships, we identified four major forest types. The FIA databases for Wisconsin, Pennsylvania, New York, and Maine were chosen to represent the aspen/birch, oak/hickory, northern hardwood, and spruce/fir forest types, respectively. Each of the four state databases were queried to find plots of the target forest type that fell within a specific age range established for that type. Plots in very young stands were excluded. Plots in older stands were not selected because they would not provide adequate flexibility for modeling the proposed management scenarios. The age ranges used to select representative plots for each forest type were aspen/birch (15 – 25 yr), spruce/fir (30 – 40 yr), oak/hickory (40 – 60 yr), and northern hardwoods (40 – 50 yr).

A distance analysis was used to select a representative plot from the pool of candidate plots in the appropriate forest type and age range from each state database. The objective of the distance analysis was to select a single plot that was as similar as possible to the average species composition, basal area, quadratic mean diameter, and biomass volume of all the plots in the list.

The inventory data for the selected plots are tied to a specific site quality that influenced the development of the stand and reflects the history of the stand. To account for the different stand conditions across management intensities (ie different site quality), new inventory data were generated that matched the target plot but could be used to simulate the stand growth and development of the stand from an earlier time period. Data were aggregated into softwood and hardwood composite types for input into the life-cycle analysis of manufacturing models.

Because the aspen/birch type is primarily used for nonlumber products, it was not included in the hardwood composite summary.

Site Preparation and Stand Establishment

Postharvest and stand establishment activities vary substantially by owner group and region. These differences were recognized in the development of the site preparation and planting scenarios. For the NE/NC, no slash reduction activities are mandated for wildfire risk reduction and the analysis did not include slash disposal because it is assumed to decay in situ. Likewise, no planting is modeled for the NE/NC because natural regeneration is assumed to be sufficient on all sites. Precommercial thinning was modeled for specific forest types, management intensities, and owner groups.

In the INW, stand establishment activities often include measures to reduce wildfire hazard after harvest, site preparation for planting, planting of seedlings, and precommercial thinning, although treatments vary by owner group, management intensity, and forest type. Cost, production, and emission factors associated with site preparation and forest stand establishment were developed from information in existing studies. Wildfire hazard reduction and site preparation often involve broadcast burning of material on the ground of a harvested area or burning of mechanically created piles at either the landing or across the site. The predominant method for most private and state land managers is to pile and burn the material to permit more flexibility in meeting state limitations on open burning. National forest lands are more likely to be broadcast-burned, especially on slopes that require cable yarding. Site preparation for state and private lands was assumed to involve mechanized piling and burning using an excavator. On national forest lands, piling and burning was used on gentle slopes and broadcast burning was assumed on steep slopes. Fuel consumption rates and emission factors are based on this method of slash disposal. They were developed from published studies that document and model emission rates from both prescribed burns and wildfire (Battye and Battye 2002; Prichard et al 2006). Costs and consumption rates were determined per hectare and were then divided by the unit volume of the harvested log per unit area to determine contribution of this activity to the final product.

Factors covering seedling production and planting were developed from personal communication with forest nursery managers (Wenny 2003) and a developed manuscript on greenhouse operations (Schlosser et al 2003). The individual rates per seedling were multiplied by the number of seedlings planted per hectare to determine the total cost and fuel consumption rates associated with the final forest stand. Seedlings are hand-planted; therefore, the only fuel factors are related to travel to and from the planting site. Factors were divided by the final harvest volume to determine their contribution on the basis of unit volume of harvested log. Precommercial thinning was only applied as a treatment in the alternate case on state and private commercial forests in the INW. Although fertilization is used by a few large private landowners, it is not a common practice in either region. Management scenarios that were capable of increasing yield using thinning treatments were developed at the University of Washington based on growth and yield simulations developed specifically for this study. To develop overall factors associated with logs delivered to a lumber mill, plywood plant, or OSB plant, the weighted average contribution of site preparation, seedlings and planting, and precommercial thinning costs and consumption factors per unit of harvested volume were integrated with factors from final harvesting and divided by the final harvested volume per hectare to establish overall impact factors.

Timber Harvesting

Harvesting production, cost, and fuel consumption rates were drawn from existing studies of harvesting equipment typical of the systems used to harvest sites in each region. These studies included both personal interviews with timber harvesting contractors (Biltonen 2002; Jorgenson 2002; Lawson 2002; Reynolds 2002) and published information (for the INW, Stevens and Clarke 1974; Hochrein and Kellogg 1988; Keegan et al 1995; Kellogg and Bettinger 1994 Kellogg et al 1996; Ledoux 1984; and for the NE/NC: Miyata 1980; LeDoux 1985, 1987; Thompson et al 1995; Sturos et al 1996; Huyler and LeDoux 1999; LeDoux and Huyler 2001; Reiginger and Gasslgher 2001; Long 2003; Wang et al 2004a, 2004b, 2005; Grushecky et al 2005; Wang and McNeel; 2006). The costs, production, and consumption rates were developed for equipment options within each component of the system. Harvesting systems were developed as combinations of these harvesting components. Although there are many combinations of equipment and systems that can be used for harvesting timber, this analysis assumes the use of the most common systems operating on the range of slope classifications identified for the harvested sites.

For slopes less than 35% in the INW, mechanized harvesting systems are most commonly used. A mechanized system uses a feller-buncher, which fells and bunches trees for secondary transport to the landing. Its use implies the use of mechanized processor to delimb and process trees into logs at the landing. This leaves the majority of the slash for piling and disposal at the landing. The same general system was assumed for commercial thinning and final harvest operations. The system includes a large feller-buncher, a medium-sized grapple skidder, and a mechanized processor at the landing. Whole trees are moved to the landing, but only stem carbon is removed from the site because the crown is left for disposal by burning or to decompose in situ.

For those slopes greater than 35% in the INW, the assumed harvesting system involves hand felling and the movement of the material to the landing with cable-based systems, which keep the primary machinery on harvest roads. In cable systems, trees are typically felled and bucked into logs at the point of felling, leaving limbs, tops, and other unmerchantable materials in the forest. Because limbs and tops of the trees are left onsite, removed carbon for the percentage of the forest that is cable-yarded includes only the carbon associated with the stem.

For the NE/NC, all harvest and thinning operations were assumed to use ground-based systems and occur on slopes less than 35% (Wang and McNeel 2006). For the softwood forest types, a mechanized system was assumed, similar to that for the INW, including a large feller-buncher and grapple skidder but with chainsaw processing at the landing. For the hardwood forest types, hand felling and chainsaw delimbing at the stump with medium cable skidding of processed logs to the landing was assumed.

Carbon Production and Removal

Carbon budgets are constructed from tree lists describing standard inventory data for individual trees, including species, diameter, and crown ratio. These tree lists are grown inside the LMS using FVS growth models, which generate changes in tree characteristics according to the equations and criteria of the variants that are used in the INW and NE/NC. From these data, merchantable and total timber volumes were estimated using the default use standards for each FVS variant and species group. This analysis produces estimates of biomass of leaves, roots, and stem using the Jenkins et al (2003) allometric equations that are based on diameter at breast height and species group-specific coefficients. Carbon estimates are then computed by using a species-specific biomass-to-carbon conversion. The carbon amounts are then summed for the root, stem, bark, and crown parts and the per-tree estimates are expanded to a per-hectare basis using standard forest inventory techniques (Marshall and Waring 1986; Monserud and Marshall 1999). Carbon fluxes through time are driven by the changes in standing inventory as simulated by the growth model for each management scenario.

The carbon model uses FVS predictions of tree mortality to estimate releases of carbon from the canopy and other above-ground pools. The model 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 offsite during harvesting. All of these dying tissues are assigned to pools of decomposing material. Species-specific estimates of decomposition rates are used to estimate losses of carbon to the atmosphere using equations from Aber and Melillo (1991), which describe proportional weight loss per year. We calculate the mass of decomposing material as the sum of mortality in the most recent interval plus the residual mass of decomposing material from previous time steps summed over all species and tissue types. We assumed that fine roots grow and decompose at about the same rate so they add no 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 will be different over different time periods and under different treatment regimes. The results do not address soil carbon or the effect of forest management activities on total soil carbon because no reliable predictors were found that relate to the management treatments being considered.

In the INW, fire regulations decree that a substantial component of the tops and limbs that are left onsite must be burned to reduce fire risk. Carbon emissions from site preparation using fire assume that approximately 80% of the residual tops and limbs are disposed of in this manner. This assumption substantially affects the emission measures beyond what has been noted in any other regional analysis within the US. Emissions from burning residual piles are primarily an issue of timing, because residuals left unburned will still undergo decomposition and release about the same amount of carbon as the fire risk reduction treatments.

In addition to accounting for changes in annual production and decomposition of carbon from the forest pools across the landscape and through time, the analysis provides the inputs for the end uses of harvested carbon. In other articles within this Special Issue, stem carbon is distributed into long- and short-lived products based on mill use and are tracked for impact on displacement of fossil emissions such as the use of biofuel to displace fossil fuels and long-lived products substituting for fossil-intensive products such as steel and concrete. Short-lived products are permitted to decompose much like residuals that remain in the forest.

SimaPro Analysis

The SimaPro 7.0.2 software package (Goedkoop and deGelder 2001; Goedkoop and Oele 2001) was used to perform the life-cycle analysis, to generate emission factors, and to analyze the relative contribution of the various reforestation, site preparation, and harvesting processes to emissions. SimaPro7 contains a US database for a number of materials, including paper products, fuels, and chemicals, and Franklin Associates (FAL) provides an additional US database. The relative contribution of reforestation, site preparation, and harvesting processes to overall environmental impact uses the Eco-indicator 99 (E)/ Europe EI 99 E/E method incorporated within SimaPro. Models developed for SimaPro used the same protocol and energy assumptions as models developed for lumber and plywood manufacturing.

Factors for fertilizers used in seedling development were derived from existing database factors within the FAL database. Although potassium fertilizer is considered an input from nature, nitrogen and phosphate fertilizers include inputs from the required manufacturing processes. Assumptions relative to diesel fuel and gasoline were consistent with those used in the analysis of the primary wood products of lumber, plywood, and OSB and were derived from the FAL database. Diesel fuel was the primary power source for all site preparation and harvesting equipment except chainsaws and vehicles used to transport crews to and from the forest stand in planting operations. 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.

Individual models were developed for tree seedlings, slash disposal, and timber harvest. Models for tree seedlings served as a base for a process called a “reforested acre.” Input required to produce greenhouse-grown seedlings was included in the transportation resources required to plant seedlings in a reforested area. The “reforested acre” was developed as a SimaPro process for both management intensities and for each forest ownership/forest type category in the INW. For the NE/NC, natural regeneration was assumed across all forest type and management intensities. The “reforested acre” also included the input of the resources required in precommercial thinning.

Models for the disposal of slash after harvest were incorporated into a process called “site-prepared acre” in the INW. Separate process models were developed for each combination of forest ownership/forest type and management intensity. The processes incorporated emissions associated with the broadcast burning of slash and burning of slash piles. Slash disposal was required with each harvest entry, commercial thinning, or final harvest. The piling and burning processes also involved resources associated with the crew and equipment required to prepare the site and material for burning and to conduct the actual burn. INW was the only region where slash disposal through burning was modeled; therefore, environmental factors were also developed to represent the piling of slash without burning. This permits better comparison of environmental outputs from the INW with other regions. No slash disposal was conducted or modeled for the NE/NC.

Processes were developed for each piece of equipment used in thinning and harvest with fuel consumption and machine productivity generally related to the power of the equipment used and to the production rate of the equipment in units of harvested volume per scheduled machine hour. These processes included fuel and lubrication consumption rates. The processes developed for a “reforested acre” and “site-prepared acre” were combined with the processes associated with the harvesting systems used in commercial thinning and final harvest, resulting in an overall process for harvested sawlogs for each combination of forest ownership/forest type and management intensity. The weighted average of the forest ownerships/forest types were combined in “Product Assemblies” within SimaPro to permit average results weighted by volume harvested within each ownership category in the INW to more accurately reflect the base and alternate cases. The averaging was done by land in each category for the NE/NC.

For the forest resource module, we selected the Eco-indicator 99 (E)/Europe EI 99 E/E method from the potential suite of methods available in SimaPro that measure relative impacts of processes. This method measures the impact of the total process on fossil fuels, respiratory inorganics, climate change, and carcinogens among others. Contribution to these factors is measured in method-derived indices that assess the impact on human health, plant species, and energy replacement needs. Each factor is reported independently and they are also combined into a single dimensionless index reflecting the total impact of the process. The dimensionless index is a subjective measure that can be used to illustrate the relative differences among the various forest management options given the assumptions inherent in process development.

RESULTS

Table 1a and 1b give the expected output of product measured as total volume of logs destined for lumber, plywood, and OSB plants and total volume produced as pulpwood as a function of the specific modeling assumptions for the INW and NE/NC.

Table 1a. *Product output and management assumptions for timber-producing forests of the Inland Northwest (INW).*

Ownership/forest type/prescription scenarios	Base case			Alternate (maximum volume) case		
	State and private		National forest	State and private		National forest
Management intensity	Dry	Moist/cold	Dry/moist/cold	Dry	Moist/cold	Dry/moist/cold
Site class (lower number represents higher site class)	5.50	4.41	5.05	5.50	4.41	5.05
Rotation age	76	66	87	81	78	75
Planting density (trees/ha)	618	865	1082	618	865	1082
Fertilization	None	None	None	None	None	None
Precommercial thin	1	1	0	1	1	3
(trees/ha)	0	0	0	0	0	0
Commercial thin 1 (m^3/ha)	108	131	0	150	173	0
at yr	38	33	0	27	26	0
Commercial thin 2 (m^3/ha)	0	0	0	150	173	0
at yr	0	0	0	54	52	0
Commercial thin 3 (m^3/ha)	0	0	0	0	0	0
at yr	0	0	0	0	0	0
Final harvest (m^3/ha)	108	131	62	150	173	101
at yr	76	66	87	81	78	75
Total harvest (m^3/ha)	217	261	62	450	519	101
Sawlog (%)	48.5	48.5	25.1	52.9	52.9	25.1
Sawlog (m^3/ha)	105	127	16	238	275	25
Small sawlog[a] (%)	32.0	32.0	29.7	29.9	29.9	29.7
Small sawlog (m^3/ha)	69	84	18	135	155	30
Pulpwood (%)	19.5	19.5	45.2	17.2	17.2	45.2
Pulpwood (m^3/ha)	42	51	28	77	89	46
Thinned (%)	50.0	50.0	0.0	66.7	66.7	0.0
Average yield (m^3/yr·ha)	2.851	3.957	0.715	5.557	6.659	1.347
Ground based harvest (%)	90.0	70.0	50.0	90.0	70.0	50.0
Cable harvest (%)	10.0	30.0	50.0	10.0	30.0	50.0
Helicopter harvest (%)	0.0	0.0	0.0	0.0	0.0	0.0
Treated area in treatment category (%)	26.7	44.4	28.9	17.1	28.6	54.3
Total treated area in treatment category (1000 ha)	2345	3905	2537	2345	3909	7437
Total volume in treatment category (%)	30.1	60.5	9.4	27.5	52.9	19.6

[a] In INW, small sawlogs with large-end diameters typically less than 30 cm are scaled by weight rather than volume.

The total cost and fuel consumption were calculated for each forest management activity, including site preparation, planting, commercial thinning, and final harvest. Consumed resources include fuel, lubricants, and fertilizer. Averaged costs and fuel consumption rates were then calculated as the total divided by the total merchantable volume removed. Rates of fuel consumption for stand establishment and management activities are shown in Table 2 for the INW. Because the NE/NC had no site preparation or planting in simulations, these data were not generated. The product outputs from Table 1 and the consumption rates shown in Table 2 become inputs to the manufacturing life-cycle analysis used in SimaPro to determine the emissions associated with the management and harvesting operations. Comparisons of cost, fuel consumption, and fertilizer requirements for site preparation, seedling development, and planting are shown in Table 3 for the INW and NE/NC. The costs reflect differences in systems between the two regions and scenarios with a much more mechanized approach taken in the INW relative to the NE/NC generating lower \$/m^3 (Table 3). A minor efficiency gain was estimated for the higher production levels of the alternate scenario for the INW, but that gain was not found for NE/NC.

In INW, most of the harvested volume is first delivered to sawmill or plywood plants. Residual chips are generated from the lumber and plywood manufacturing process. Direct delivery of

Table 1b. *Product output and management assumptions for timber-producing forests of the Northeast/North Central forest types.*

Ownership/forest type/prescription scenarios	Northeast/North Central			Northeast/North Central		
	Softwood forests			Hardwood forest composite		
Management intensity	Low	Medium	High	Low	Medium	High
Site index	50	60	70	50	62	74
Rotation age	75	65	55	120	98	82
Planting density (trees/ha)	0	0	0	0	0	0
Fertilization	None	None	None	None	None	None
Precommercial thin	0	0	0	0	0	0
(trees/ha)	0	125	125	0	125	125
Commercial thin (m^3/ha)	0	0	3	0	39	93
at yr	0	40	35	0	70	72
Final harvest (m^3/ha)	302	282	191	339	215	125
at yr	75	65	55	120	98	82
Total harvest (m^3/ha)	302	282	194	339	254	218
Sawlog (%)	54.3	52.9	45.9	44.8	44.4	33.5
Sawlog (m^3/ha)	164	149	89	152	113	73
Chip n saw (%)	0.0	0.0	0.0	0.0	0.0	0.0
Chip n saw (m^3/ha)	0	0	0	0	0	0
Pulpwood (%)	45.7	47.1	54.1	55.2	55.6	66.5
Pulpwood (m^3/ha)	138	133	105	187	141	145
Thinned (%)	0.0	0.1	1.4	0.0	15.4	42.7
Average yield (m^3/ha·yr)	4.03	4.34	3.53	2.82	2.59	2.65
Ground-based harvest (%)	100	100	100	100	100	100
Land in category–base (%)	47.4	34.0	18.7	59.3	26.8	13.9
Percent land in category–alternate (%)	19.6	44.9	35.6	25.1	48.1	26.8

Table 2. *Seedling, site preparation, planting, and fertilization consumption for the Inland Northwest.*

	Inland Northwest base			Inland Northwest alternate		
	State/ private–dry	State/private– moist-cold	National forest–all	State/ private–dry	State/private– moist-cold	National forest–all
Planting and site preparation fuel consumption (L/ha)						
Greenhouse and seedling	4.043	5.661	7.084	4.043	5.661	7.084
Site preparation	52.176	66.356	16.884	75.374	113.060	23.656
Planting	3.464	4.850	6.070	3.464	4.850	6.070
Precommercial thin	11.107	11.107	0.000	11.107	11.107	33.321
Total	70.791	87.974	30.037	93.988	134.678	70.131
Slash disposal fuel consumption (L/ha)						
Gentle slopes	45.086	45.086	22.543	45.086	67.629	22.543
Pile at landing						
Steep slopes	115.988	115.988	11.225	115.988	173.982	11.225
Pile and burn in forest						
Fertilization (kg/ha) over the rotation						
Nitrogen						
In seedlings	0.026	0.037	0.046	0.026	0.037	0.046
Onsite	0.000	0.000	0.000	0.000	0.000	0.000
Phosphate						
In seedlings	0.044	0.062	0.078	0.044	0.062	0.078
Onsite	0.000	0.000	0.000	0.000	0.000	0.000
Potassium						
In seedlings	0.108	0.152	0.190	0.108	0.152	0.190
Onsite	0.000	0.000	0.000	0.000	0.000	0.000

Table 3. *Timber harvesting system production, costs, and consumption.*

		Production rate (m^3/h)[a]	Production cost (\$/m^3)	Diesel use (L/m^3)	Lubricant use (L/m^3)
System 1: Inland Northwest gentle–mechanized					
Felling	Large feller–buncher	62.39	1.55	0.365	0.007
Skidding	Medium skidder	12.23	5.07	1.126	0.020
Processing	Slide boom delimber	73.41	1.36	0.289	0.005
Loading	Large loader	24.47	2.45	0.774	0.014
Subtotal	Stump to truck		10.44	2.554	0.046
Hauling	Long log truck	16.78	17.13	5.894	0.106
System total	Stump to mill		27.56	8.447	0.152
System 2: Inland Northwest steep slope–cable yarding					
Felling	Hand felling	7.07	3.96	0.11	0.00
Skidding	Medium skyline	9.96	8.54	3.24	0.06
Processing					
Loading	Large loader	24.47	2.45	0.77	0.01
Subtotal	Stump to truck		14.95	4.12	0.07
Hauling	Long Log truck	16.78	17.13	5.89	0.11
System total	Stump to mill		32.08	10.01	0.18
System 3: NE/NC softwood forests					
Felling	Large feller-buncher	23.32	3.77	1.015	0.018
Skidding	Large grapple skidder	9.72	6.91	1.661	0.030
Processing	Chainsaw delimbing	10.28	3.46	0.023	0.000
Loading	Large loader	13.17	5.03	1.437	0.026
Subtotal	Stump to truck		19.17	4.137	0.074
Hauling	Long log truck	7.77	41.20	12.730	0.229
System total	Stump to mill		60.37	16.867	0.304
System 4: NE/NC hardwood composite					
Felling	Hand felling	5.15	6.27	0.073	0.001
Skidding	Medium cable skidder	5.49	11.68	2.734	0.049
Processing	Chainsaw delimbing	10.28	3.46	0.023	0.000
Loading	Large loader	13.17	5.03	1.437	0.026
Subtotal	Stump to truck		26.44	4.268	0.077
Hauling	Long log truck	7.77	41.20	12.730	0.229
System total	Stump to mill		67.64	16.998	0.306

[a] Scheduled machine hour including productive time and delays.
NE/NC, Northeast/North Central.

pulpwood from the forest, although not always commercially recovered, was calculated and treated as a coproduct in the analyses for both regions. Commercial recovery of pulpwood will affect the commercial volume removed from the forest and the volume left onsite after harvest.

Production volumes are presented for each of the management intensity/site options along with the regional average in Tables 4a and 4b. In the INW, the rotation age ranged 66 – 87 yr. The average yearly volumes were computed and 75 yr was selected as the base for comparison of the average volumes. In the NE/NC region, the rotation age for softwoods ranged 55 – 75 yr with 65 yr selected as the base for comparison. Hardwood rotation ages ranged 80 – 120 yr with the longest rotation age dominant; hence, 120 yr was selected as the base for comparison. The average volume production per hectare-year was calculated for each option and then expanded to the base year to develop a volume for each particular option.

For the INW, the shift to the higher intensity scenario increased the production of merchantable volume from 249 m^3/ha with 78% of the harvested volume going into sawlogs to

Table 4a. *Production volume for the Inland Northwest from each of the management/site options with weighted average regional production average weighted by volume and calculated at a base year of 75.*

Inland Northwest base case	66 – 87			yr in rotation
Base year for comparison	75			yr
	State and private		National forest	
	Dry	Moist/cold	Dry/moist/cold	Regional average by volume
Total volume (%)	30.1	60.5	9.4	100.0
Volume (m^3/ha)	217	261	62	229
Rotation age (yr)	76	66	87	
Average (m^3/ha·yr)	2.9	4.0	0.7	3.3
(m^3/ha at yr 75)	214	297	54	249
Lumber (%)	80.5	80.5	54.8	78.1
Pulpwood (%)	19.5	19.5	45.2	21.9

Inland Northwest alternate case	66 – 87			yr in rotation
Base year for comparison	75			yr
	State and private		National forest	
	Dry	Moist/cold	Dry/moist/cold	Regional average by volume
Percent of total volume	27.5%	52.9%	19.6%	100.0%
Volume (m^3/ha)	450	519	101	418
Rotation age (yr)	81	78	75	
Average (m^3/ha·yr)	5.6	6.7	1.3	5.3
(m^3/ha at yr 75)	417	499	101	399
Lumber (%)	82.8	82.8	54.8	77.3
Pulpwood (%)	17.2	17.2	45.2	22.7

Table 4b. *Production volume for the Northeast/North Central for softwood and hardwood forests from each of the management intensity options with a weighted average regional production estimate weighted by area in each category.*

Northeast/North Central softwood base	55 – 75			yr in rotation
Base year for comparison	65			yr
			Softwood forests	
	Low	Medium	High	Regional average by area
Classification (%)	47.4	34.0	18.7	100.1
Volume (m^3/ha)	302	282	194	275
Rotation age (yr)	75	65	55	
Average (m^3/ha·yr)	4.0	4.3	3.5	4.0
(m^3/ha at yr 65)	262	282	229	263
Lumber (%)	54.3	52.9	45.9	52.3
Pulpwood (%)	45.7	47.1	54.1	47.8

Northeast/North Central hardwood base	80 – 120			yr in rotation
Base year for comparison	120			yr
			Hardwood forests	
	Low	Medium	High	Regional average by area
Classification (%)	59.3	26.8	13.9	100.0
Volume (m^3/ha)	339	254	218	299
Rotation age (yr)	120	98	82	
Average (m^3/ha·yr)	2.8	2.6	2.7	2.7
(m^3/ha at yr 120)	339	311	318	328
Lumber (%)	44.8	44.4	33.5	43.1
Pulpwood (%)	55.2	55.6	66.5	56.9

Table 5a. *Base and alternate case–weighted average across the three management intensity levels for the Inland Northwest (INW) and Northeast/North Central (NE/NC) regions: land allocation and volume output.*

	Inland Northwest		Northeast/North Central	
	Base case	Alternate case	Softwood	Hardwood composite
Base year for comparison	75	65		120
Percentage of land area and volume in site/management category				
	Base case	Alternate case	Base case	Base case
INW: state/private–dry (%)	30	28	—	—
INW: state/private moist-cold (%)	60	53	—	—
INW: national forest–all (%)	9	20	—	—
Low-intensity management (%)	—	—	47	59
Mid-intensity management (%)	—	—	34	27
High-intensity management (%)	—	—	19	14
Average one-way haul distance (km)	129	129	109	125
Harvesting systems	Ground	Cable	Helicopter	
INW: state/private–dry (%)	90	10	0	
INW: state/private moist-cold (%)	70	30	0	
INW: national forest–all (%)	50	50	0	
NE/NC: softwood (%)	100	0	0	
NE/NC: hardwood composite (%)	100	0	0	
	Base case	Alternate case	Softwood	Hardwood composite
	By volume	By volume	Base case	Base case
Volume removed in thinning and final harvest				
Volume (m^3/ha)[a]	249	399	263	328
Lumber (%)	78	77	52	43
Pulpwood (%)	22	23	48	57

[a] Percentage lumber includes small logs under 300-mm large-end diameter.

399 m^3/ha with 77% into sawlogs (Table 5a) corresponding to an increase in yearly removals of 3.3 – 5.3 m^3/ha·yr. However, in the near term, there is a decrease in sawlog availability in some parts of the INW related to changing management practices that may alter future management options because of loss in milling capacity. Lost milling capacity and infrastructure may alter the likelihood of attaining the positive gains that are possible under the alternate scenario because these gains presume adequate investment.

For the NE/NC softwoods, the shift to the higher intensity scenario did not increase the production of merchantable volume. The lack of response to increasing management intensity illustrates how assumptions on shortening rotations with more intermediate thinnings on higher site-quality forests and growth model responses may not always yield increased volumes of high-value products. Maximizing volume outputs of high-value products may require reduced emphasis on early commercial thinning and longer intervals between thinning and final harvest. The results are an indication that increasing land productivity in the NE/NC region may be difficult. Only results for the base case are presented. Base case removals produced 263 m^3/ha with 52% of the harvested volume going into sawlogs. Removals (Table 5b) averaged 4.0 m^3/ha·yr. Similarly for the NE/NC hardwoods, the impact of a shift to a higher intensity scenario was insignificant. Base case removals of merchantable volume produced 328 m^3/ha with 57% of the harvested volume going into sawlogs. Volume removals averaged 2.7 m^3/ha·yr.

Table 5c provides estimates of the carbon harvested and removed through thinning and harvesting activities that were developed as multipliers of carbon weight per merchantable volume. Although volume estimates of the

Table 5b. *Base and alternate case-weighted average across the three management intensity levels for the Inland Northwest and Northeast/North Central regions: system cost and fuel consumption.*

	Inland Northwest		Northeast/North Central	
	Base case	Alternate case	Softwood	Hardwood composite
System costs	By volume	By volume	Base case	Base case
Preparation, plant ($/ha)	637	730	0	0
Precommercial thin ($/m^3)	2.56	1.83	0.00	0
Stump to ($/ha)	2880	4620	5041	8686
Truck ($/m^3)	11.58	11.58	19.17	26.44
Hauling (km)	129	129	109	125
Truck to ($/ha)	4260	6830	9167	11452
Mill ($/m^3)	17.13	17.13	34.86	34.86
Total cost ($/ha)	7780	12200	14208	20138
($/m^3)	31.26	30.53	54.04	61.31
Electric, fuel, and lubricant consumption				
Seedling, site preparation, plant, precommercial thin				
Fuel (L/ha)	84	106.2	0	0.0
(L/m^3)	0.337	0.266	0.000	0.000
Lubricants (L/ha)	1.51	1.911	0.00	0.000
(L/m^3)	0.006	0.005	0.000	0.000
Electric (MJ/ha)	131	125	0	0
(MJ/m^3)	0.526	0.314	0.000	0.000
Stump to truck				
Fuel (diesel) (L/ha)	734	1180	1090	1400
(L/m^3)	2.95	2.95	4.14	4.27
Lubricants (L/ha)	13.2	21.2	19.6	25.2
(L/m^3)	0.053	0.053	0.074	0.077
Hauling (km)	129	129	109	125
Fuel (diesel) (L/ha)	1470	2350	2830	3540
(L/m^3)	5.89	5.89	10.77	10.77
Lubricants (L/ha)	26.4	42.3	51.0	63.7
(L/m^3)	0.106	0.106	0.194	0.194
Fuel (diesel) (L/ha)	2290	3630	3920	4940
(L/m^3)	9.18	9.11	14.91	15.04
Lubricants (L/ha)	41.1	65.4	70.6	88.9
(L/m^3)	0.165	0.164	0.268	0.271

merchantable stem represent estimates of the wood content, the multiplier includes an estimate of carbon in both the stem and attached bark. The values are expressed as units of carbon mass per unit area. For the INW, forest carbon can be increased from its current levels with substantial gains in carbon sequestration in product and substitution pools under active management regimes. For the INW, the average of harvested carbon pools is 56.4 t/ha for the base case and 90.2 t/ha for the more intensive management of the alternate case. These removals also significantly reduce potential emissions from wildfire, although residuals of the unused stem and crown left onsite that require disposal are equal to 30.8 t/ha under the base case and 56.3 t/ha for the alternate case. In the most commonly used harvest systems in the INW, a substantial portion of these residuals are taken to the landing for disposal as part of the harvest operation and some may become renewable fuel feedstocks in the future. However, the residuals also contribute to habitat and nutrient goals. Graham et al (1994) suggest that depending on habitat type, 6 – 74 t/ha of material greater than 75-mm dia, exclusive of roots, should remain onsite as coarse woody debris to maintain long-term soil productivity.

For NE/NC softwoods, the average of harvested carbon in stem and bark is 64.2 t/ha for the base. For the NE/NC hardwood composite, the average

Table 5c. *Base and alternate case-weighted average across the three management intensity levels for the Inland Northwest and Northeast North Central regions: fertilizer use and carbon pools.*

	Inland Northwest		Northeast/North Central	
	Base case	Alternate case	Softwood	Hardwood composite
	By volume	By volume	Base case	Base case
Fertilizer				
Nitrogen (kg/ha)	0.035	0.036	0.000	0.000
(kg/m^3)	0.000	0.000	0.000	0.000
Phosphate (kg/ha)	0.058	0.060	0.000	0.000
(kg/m^3)	0.000	0.000	0.000	0.000
Potassium (kg/ha)	0.142	0.147	0.000	0.000
(kg/m^3)	0.001	0.000	0.000	0.000
Carbon pools at end of rotation				
	Residual of harvested material			
Stem + bark (kg/ha)	10,400	21,600	6,510	10,200
Crown (kg/ha)	20,400	34,700	25,300	45,200
Roots (kg/ha)	18,700	31,400	21,700	31,800
Total (kg/ha)	49,400	87,700	53,600	87,200
	Removed through thinnings and final harvest			
Stem (kg/ha)	51,800	82,800	58,600	91,600
Bark (stem) (kg/ha)	4,600	7,400	5,600	9,700
Crown (kg/ha)	0	0	0	0
Roots (kg/ha)	0	0	0	0
Total (kg/ha)	56,400	90,200	64,200	101,300
(kg/ m^3)	208	208	223	279
Stem carbon	Carbon in stem + bark			
Crown carbon	Carbon in branches + foliage − litter			
Roots	Carbon in course and fine roots			

of harvested carbon in stem and bark is 101.3 t/ha for the base case. Although the hardwood composite generates more, and the NE/NC softwood harvests generate almost as much residual slash as the INW, no reported requirements for slash abatement and fire risk reduction were noted in the literature or from field practitioners in the NE/NC region. These differences in management philosophy, regulation, and risk influence the near-term forest carbon dynamics in the two regions. In the long term, decomposition of slash may release carbon to the same extent as slash burning, but estimating time-dependent impacts is difficult at present because of large uncertainties around the extent of complete combustion in slash burning and any soil carbon interactions in both regions.

The emissions to the air for operations in both regions are presented in Tables 6a and 6b. The impact of slash burning on direct air emissions is obvious in the comparison between the case when slash is burned in the INW and when piled and left in the forest (Table 6a). Outputs for the case in which the slash is not burned were developed to allow better comparison with results from other regions. The emissions to the air from the NE/NC region are generally lower than for either of the INW cases, reflecting the impact of fewer entries and less mechanized equipment in the NE/NC.

The dimensionless indices developed from SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E are presented in Tables 7a and 7b. The indices with and without slash burning are presented for the INW (Table 7a) and are higher for both cases than for those of the NE/NC (Table 7b). The factor that dominates the index for the slash burning case is for respiratory inorganics.

Table 6a. *Projected emissions to the air for the Inland Northwest for both the base and alternate case with and without slash burning using SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E.*

	With slash burning		Without slash burning	
	Base case	Alternate case	Base case	Alternate case
Ammonia	6.80E-02	1.00E-01	1.61E-05	1.60E-05
CO	9.43E+00	1.39E+01	1.02E-04	1.14E-01
CO_2 (fossil)	1.00E+01	9.98E+00	1.00E+01	9.94E+00
CO_2 (nonfossil)	2.37E+02	3.52E+02	2.41E-03	2.40E-03
Formaldehyde	1.52E-01	2.23E-01	2.73E-03	2.71E-03
Methane	1.68E-03	1.65E-03	1.67E-03	1.65E-03
Methane, fossil	6.39E-01	9.30E-01	0.00E+00	0.00E+00
Methanol	9.26E-02	1.36E-01	0.00E+00	0.00E+00
Nonmethane VOC	5.82E-01	8.22E-01	3.60E-02	3.63E-02
NOx	7.73E-01	9.87E-01	1.83E-01	1.82E-01
Particulates	1.94E+00	2.85E+00	1.18E-04	1.27E-02
Particulates (PM10)	1.24E+00	1.83E+00	1.29E-02	3.17E-06
Particulates (PM2.5)	1.10E+00	1.61E+00	0.00E+00	0.00E+00
SO_2	1.96E-01	2.67E-01	4.83E-06	3.61E-06
SOx	2.25E-02	2.23E-02	2.24E-02	2.22E-02
VOC	7.93E-01	1.17E+00	8.19E-09	6.11E-09

VOC, volatile organic compounds.

Table 6b. *Projected emissions to the air for the Northeast/North Central (NE/NC) region for softwood and hardwoods for both the base and alternate case using SimaPro Eco-indicator 99 (E)/Europe EI 99 E/E.*

	NE/NC softwoods	NE/NC hardwoods
	Base case	Base case
Aldehydes	6.61E-06	6.80E-06
Ammonia	5.62E-07	5.79E-07
CO	1.87E-03	2.79E-03
CO_2 (fossil)	3.60E-01	3.69E-01
CO_2 (nonfossil)	8.57E-05	8.83E-05
Formaldehyde	9.82E-05	1.01E-04
Methane	5.69E-05	5.86E-05
Nonmethane VOC	1.24E-03	1.30E-03
NOx	6.68E-03	6.81E-03
Organic substances	4.22E-06	4.34E-06
Particulates	4.69E-04	4.78E-04
Particulates (unspecified)	2.32E-05	2.36E-05
SOx	7.99E-04	8.18E-04

VOC, volatile organic compounds.

DISCUSSION

Comparing average softwood removals and forest carbon from the four regions, including INW, NE/NC base case, and Johnson et al (2005) data for the Southeast (SE) and Pacific Northwest (PNW) base management levels, we found that removals from softwood forests were estimated at 3.3, 4.0, 8.9, and 11.1 m^3/ha·yr, respectively. This corresponds to a carbon transfer from the forest to the mill of approximately 751, 988, 1621, and 3475 kg/ha·yr, respectively. At the mill, carbon enters either the product stream where it is turned into long-, medium-, or short-lived consumer products or it is used as a renewable energy resource to power various mill processes. For comparison, the NE/NC hardwood harvests are estimated to remove 2.73 m^3/ha·yr over an average 120-yr rotation. Overall removals averaged 108 t/ha of stem and bark carbon with an additional 87 t/ha of carbon left in the forest to decompose, providing for long-term soil enhancement and nutrient capital on the hardwood forests. Total forest stem and bark carbon taken to the mill from harvest activity, including commercial thinning volume, was 56, 69, 56, and 156 t/ha by region for the softwood forests. Commercial thinning in the SE and PNW accounts for 40 and 14% of the total carbon removed. Carbon content of residuals left in the forest or on the landing after all harvests (including roots) averaged 49, 54, 44, and 55 t/ha for each softwood region, respectively. Some material may be removed in the future to supply an emerging market for cellulosic biomass for renewable energy markets. Although not all carbon will, or should be, recoverable in such endeavors, the initial analysis suggests that substantial recovery opportunities exist from normal harvesting operations.

Table 7a. *Overall impact factors by management scenario for the Inland Northwest region with and without the burning of slash as developed through the Eco-indicator 99 (E)/Europe EI 99 E/E method of SimaPro.*

	With slash burning		Without slash burning	
	Base case	Alternate case	Base case	Alternate case
Carcinogens	0.0042	0.0055	0.0013	0.0013
Respiratory organics	0.0282	0.0406	0.0010	0.0010
Respiratory inorganics	25.7848	37.5681	0.3423	0.3394
Climate change	1.0085	1.4763	0.0409	0.0407
Ozone layer	0.0000	0.0000	0.0000	0.0000
Ecotoxicity	0.0006	0.0006	0.0006	0.0006
Acidification/eutrophication	0.5562	0.7316	0.1044	0.1035
Fossil fuels	0.3866	0.3855	0.3856	0.3842
Total	27.7691	40.2082	0.8761	0.8706

Table 7b. *Overall impact factors by management scenario and species for the Northeast/North Central (NE/NC) region as developed through the Eco-indicator 99 (E)/Europe EI 99 E/E method of SimaPro.*

	Weighted average impact factors	
	NE/NC softwood	NE/NC hardwood
	Base case	Base case
Carcinogens	0.000046	0.000047
Respiratory organics	0.000033	0.000035
Respiratory inorganics	0.012434	0.012691
Climate change	0.001471	0.001508
Ozone layer	0.000000	0.000000
Ecotoxicity	0.000021	0.000022
Acidification/eutrophication	0.003805	0.003879
Fossil fuels	0.013743	0.014147
Total	0.031553	0.032329

For the INW, increasing management intensity on state and private forests and increasing the treated land on national forest lands under the alternate case increases the amount of carbon removed from the forest by 58% to 1.3 t/ha·yr for land under active management. Because the alternate case assumes an additional 4.9 million ha of dry and moist forest types on the national forests are treated to reduce wildfire risk, the average yearly removal reflects not only gains in carbon per unit area, but a huge increase in the overall potential to sequester carbon in the product stream where it is protected from loss by catastrophic wildfire and insect and disease outbreaks. In addition to these carbon gains, a substantial benefit can accrue by reducing the risk of catastrophic wildfire on land that might not otherwise be treated under a base case scenario. Analysis of the likelihood of wildfire and anticipated carbon emissions from wildfire under treatment and no-treatment scenarios has demonstrated that the benefits of treatment in reducing fire risk augments gains in carbon sequestered in the product stream such that it increases the carbon output from the system 10 – 26% over a no-treatment alternative (Lippke et al 2008). Lippke et al (2008) assessed the impact of wildfire risk reduction treatments on carbon, demonstrating that both the aggressiveness of thinning and the rate of phasing in treatments were very important to avoid carbon losses to wildfire, thereby converting more biomass for storage in products and displacing fossil-intensive fuels and structural products.

Emission factors for slash burning were developed from published information related to prescribed burning (Battye and Battye 2002; Prichard et al 2006). Summaries of air emissions reflect the influence of forest ownership and forest type for both the base and alternate cases. The majority of the emissions are generated through activities on national forest lands. Their treatments generally involve removal of a significant amount of nonmerchantable material relative to the merchantable volume to reduce the risk of wildfire in these stands. Because the material is nonmerchantable, it is disposed of through either broadcast burning or a "pile and burn" treatment. Although these activities do produce emissions through disposal by burning, they are designed to prevent an even greater release of emissions through wildfire. These emissions are part of harvest operations, but they were not directly compared with emissions from wildfire that may be more likely to occur under a no-management scenario. Use of the residual material as a bioenergy feedstock would greatly decrease the level of emissions from these burning activities and provide an important carbon offset to fossil fuel use. Recovering some of these materials for energy production in the future will depend on efforts to incentivize the reduction of carbon emissions.

For the INW, the primary impact of the full range of forest management activities is from air emissions created from burning slash left after forest harvesting (Fig 2). The other source of direct emissions will be through the air emissions created by the combustion of diesel and gasoline engines, but this source is dwarfed by the need to abate fire risk under both the base and alternate cases. These substantial nonfossil CO_2 emissions shown in Fig 2 are derived from biomass and therefore are assumed to have a neutral impact in the overall life-cycle analysis across a sequence of sustained forest rotations. The basic assumption is that these materials will either be immediately combusted to control wildfire risk or decay over the ensuing decades, thus releasing carbon back into the atmosphere, but under a sustainable forest management regime, the carbon released will be offset by sequestration over the next rotation. In both the base case and alternate case, the commercial management regimes produce sustainable harvest flows of logs to mills and sustainable growth in the forest to support the removals.

When active management is foregone after catastrophic wildfire, or insect and pathogen outbreaks as is now occurring on INW national forests, this assumption of carbon neutrality must be examined in greater detail because forest carbon may deviate substantially from a sustainable management regime within even a 100-yr timeframe. Oneil et al (2010) have examined the carbon consequences of current forest management under these base and alternate cases using assumptions consistent with historical trends and future predictions of wildfire impacts.

FUTURE WORK

For consistency with prior studies of other supply regions, a detailed study of the losses from insects, disease, and wildfire was not integrated into this analysis. Given the extensive mortality in the INW from all these agents at the current time (Calkin et al 2005; Oneil 2006), future predictions of potential management activity, standing volume, and forest carbon may be

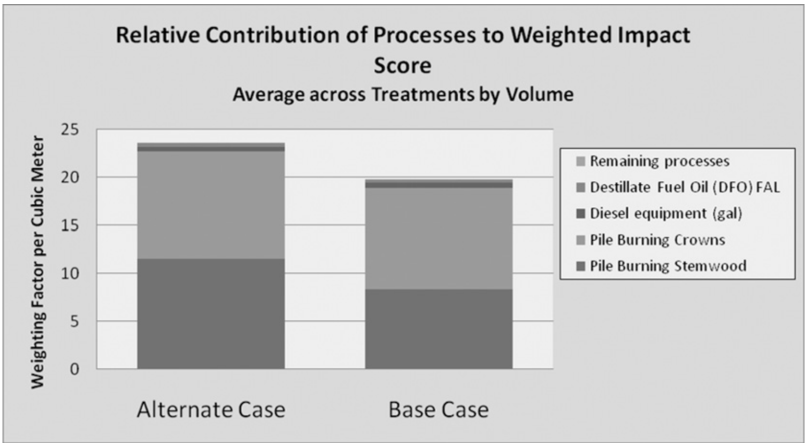

Figure 2. Relative contribution of primary processes and equipment to overall impact rating of emissions for alternate and base case from harvesting and site preparation in the Inland Northwest.

overstated, particularly on national forest lands where insect mortality is very high and treatments are often only permitted after a wildfire has occurred, if at all. The alternate case identifies a large carbon output and climate change impact associated with site preparation treatments on national forests. Because national forest treatment regimes were designed to reduce wildfire risk by removing small-diameter material and maintaining the largest trees, the impacts per unit of harvested merchantable volume are higher than for state and private harvesters. The impact scores reflect outputs associated with burning nonmerchantable material to reduce wildfire risk, which is the goal of the treatment regime. Although not measured in the current SimaPro analysis, these outputs provide an estimate of the reduced impacts that would be associated with any wildfire that might occur on treated land. Overall impact scores for national forests on a per-unit area basis would have to be assessed relative to the overall impact associated with wildfire on untreated land. A refinement of this approach to account for the level of wildfire activity that has occurred in the recent past, combined with the impacts of extensive insect and disease mortality, is warranted but was not conducted as part of this analysis. The impact scores associated with burning nonmerchantable stemwood and crowns could be dramatically improved with the introduction of a commercially viable mechanism that used this material in place of fossil fuel-generated sources of electrical and liquid fuels.

Consistent with the CORRIM Phase I carbon analysis (Perez-Garcia et al 2005), and many other carbon studies, published allometric equations were used to estimate the carbon content of forest products for these studies. We used the equation form and coefficients from the National-Scale Biomass Estimators for United States Tree Species (Jenkins et al 2003). These equations preclude addressing issues such as merchandising harvested material to a smaller diameter top, accounting for subregional differences in growth form, and differentiating between even-aged and uneven-aged growth forms within a given region.

ACKNOWLEDGMENTS

This research project would not have been possible without the financial and technical assistance provided by the USDA Forest Service Forest Products Laboratory (contract 04-CA-11111137-094), CORRIM's university memberships, and the contribution of many companies. We gratefully acknowledge the support of Dr. Jingxin Wang and Dr. Joe McNeel, West Virginia University, for their development of the harvesting and hauling operational estimates for the NE/NC region. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the contributing authors.

REFERENCES

Aber JD, Melillo JM (1991) Terrestrial ecosystems. Saunders College Publishing, Philadelphia, PA. 429 pp.

Battye W, Battye R (2002) Development of emissions inventory methods for wildland fire. Final Report for Environmental Protection Agency, Research Triangle Park, NC. EPA Contract No 68-D-98-046. February. 77 pp.

Biltonen T (2002) Bennett Lumber, Field Forester, Princeton, ID. Personal interview.

Calkin DE, Gebert KM, Jones JG, Neilson RP (2005) Forest service large fire area burned and suppression expenditure trends 1970 – 2002. J Forestry 103(4):179 – 183.

CORRIM (1998) Environmental performance research priorities: Wood products, Final report on the research plan to develop environmental performance measures for renewable building materials with alternatives for improved performance, DOE Agreement No. DE-FC07-961D13427, subcontract 417346, CORRIM Inc., Seattle, WA.

FIA (2009) USFS forest inventory and analysis program timber products output online reporting tool. http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int2.php (7 December 2009).

Goedkoop M, deGelder C (2001) SimaPro 5.0 reference manual. PRé Consultants. Amersfoort, The Netherlands.

Goedkoop M, Oele M (2001) SimaPro 5.0 user manual: Introduction to LCA methodology and practice with SimaPro 5.0. PRé Consultants. Amersfoort, The Netherlands.

Graham RT, Harvey AE, Jurgensen MF, Jain TB, Tonn JR, Page-Dumroese DS (1994) Managing coarse woody debris in forests of the Rocky Mountains. USDA Forest Service, Intermountain Research Station. INT-RP-477. 12 pp.

Grushecky ST, Wang J, McGill DW (2007) Influence of site characteristics and costs of extraction and trucking on logging residue utilization in southern West Virginia. For Prod J 57(7/8):63 – 67.

Hochrein P, Kellogg LD (1988) Production and cost comparison for three skyline thinning systems. West J Appl For 3(4):120 – 123.

Huyler NK, LeDoux CB (1999) Performance of a cut-to-length harvester in a single-tree and group-selection cut. USDA Forest Service. Res Pap NE-711. 6 pp.

Jenkins J C, Chojnacky DC, Heath LS, Birdsey RA (2003) National-scale biomass estimators for United States tree species. For Sci 49(1):12 – 35.

Johnson LR, Lippke B, Marshall JD, Comnick J (2005) Life-cycle impacts of forest resource activities in the Pacific Northwest and Southeast United States. Wood Fiber Sci 37(CORRIM Special Issue):30 – 46.

Jorgenson G (2002) Horizon Helicopters, Pilot, Laclede, ID. Personal interview.

Keegan CH, Fiedler C, Stewart F (1995) Cost of timber harvest under traditional and 'new forestry' silvicultural prescriptions. West J Appl For 10(1):36 – 41.

Kellogg LD, Bettinger P (1994) Thinning productivity and cost for a mechanized cut-to-length system in the Pacific Coast Region of the USA. J For Eng 5(2):43 – 54.

Kellogg LD, Bettinger P, Edwards R (1996) A comparison of logging planning, felling and skyline yarding costs between clearcutting and five group-selection harvesting methods. West J Appl For 11(3):90 – 96.

Lawson R (2002) Lawson Logging, Owner, Deary, ID. Personal interview.

Ledoux C (1984) Production rates and costs of cable yarding wood residue from clearcut units, For Prod J 34 (4):55 – 60.

LeDoux CB (1985) Stump-to-mill timber production cost equations for cable logging eastern hardwoods. USDA Forest Service, Northeastern Station. Res Pap NE-566. 6 pp.

LeDoux CB (1987) Estimating yarding costs for the Clearwater cable yarder. USDA Forest Service, Northeastern Station. Res Pap NE-RP-609. 4 pp.

LeDoux CB, Huyler NK (2001) Comparison of two cut-to-length harvesting systems operating in eastern hardwoods. J For Eng 12(1):53 – 59.

Lippke B, Comnick J, Mason L, Stokes B (2008) Impacts of thinning intensity and implementation schedules on fire, carbon storage, and economics. Pages 47 – 55 *in* JR Shelly, ME Puettmann, KE Skog, HS Han, eds. Woody biomass utilization: Challenges and opportunities; 26 June 2006; Newport Beach, CA. Forest Products Soc, Madison, WI.

Long CR (2003) Production and cost analysis of two harvesting systems in central Appalachia. Master thesis. West Virginia University, Morgantown, WV. 80 pp.

Marshall JD, Waring RH (1986) Comparative methods of estimating leaf area in old-growth Douglas-fir. Ecology 67:975 – 979.

McCarter JB, Wilson JS, Baker PJ, Moffett JL, Oliver CD (1998) Landscape management through integration of existing tools and emerging technologies. J Forestry 96 (6):17 – 23.

Miyata ES (1980) Determining fixed and operating costs of logging equipment. USDA For Serv Gen Tech Rep NC-55. 20 pp.

Monserud RA, Marshall JD (1999) Allometric crown relations in three North Idaho conifers. Can J Res 29:521 – 535.

Oneil EE (2006) Developing stand density thresholds to address mountain pine beetle susceptibility in eastern Washington forests. PhD dissertation. University of Washington, Seattle, WA. 99 pp.

Oneil EE, Lippke BR (2010) Integrating products, emission offsets, and wildfire into carbon assessments of inland northwest forests. Wood Fiber Sci 42(CORRIM Special Issue):144 – 164.

Perez-Garcia J, Lippke B, Comnick J, Manriquez C (2005) An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood Fiber Sci 37(CORRIM Special Issue):140 – 148.

Prichard S, Ottmar R, Anderson G (2006) Consume 3.0 user's guide. Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, Seattle, WA. 231 pp.

Puettmann ME, Wagner FG, Johnson L (2010) Life cycle inventory of softwood lumber from the inland northwest US. Wood Fiber Sci 42(CORRIM Special Issue):52 – 66.

Reiginger TW, Gasslgher TV (2001) Evaluation and comparison of two tree-length harvesting systems operating on steep slopes in West Virginia. Pages 56 – 64 *in* Proc 24th Annual COFE Meeting; Snowshoe, WV; 15 – 19 July 2001.

Reynolds M (2002) Mike Reynolds Logging, Owner, Priest River, ID. Personal interview.

Schlosser WE, Bassman JH, Wandschneider PR, Everett RL (2003) A carbon balance assessment for containerized *Larix gmelinii* seedlings in the Russian Far East. For Ecol Manag 173(1 – 3):335 – 351.

Stevens P, Clarke E (1974) Helicopters for logging; Characteristics, operation, and safety considerations, USDA For Serv Gen Tech Rep PNW-20. 16 pp.

Sturos JA, Thompson MA, Blinn CR, Dahlman RA (1996) Cable yarding as a low-impact alternative on sensitive sites in the lake states. Pages 109 – 116 *in* Proc Papers Presented at the Joint Meeting of the Council on Forest Engineering and International Union of Forest Research Organizations; 29 July – 1 August 1996; Marquette, MI.

Thompson MA, Sturos JA, Christopherson NS, Sturos JB (1995) Performance and impacts of ground skidding and forwarding from designated trails in an all-age northern hardwood stand. Pages 55 – 67 *in* Proc 18th Annual Meeting of the Council on Forest Engineering: Sustainability, Forest Health & Meeting the Nation's Needs for Wood Products; 5 – 8 June 1995. NC State University, Raleigh, NC.

Wang J, Grushecky ST, McNeel J (2005) Production analysis of helicopter logging in West Virginia: A preliminary case study. For Prod J 55(12):71 – 77.

Wang J, Long C, McNeel J, Baumgras J (2004a) Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. For Prod J 54 (12):45 – 51.

Wang J, Long C, McNeel J (2004b) Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. For Prod 54(12):159 – 167.

Wang J, McNeel J (2006) A spreadsheet program for estimating harvesting system rates and costs in Northeastern and North Central regions. Final Technical Report to CORRIM. University of Washington, Seattle, WA. 24 pp.

Wenny D (2003) Fertilizer treatments of seedlings at the University of Idaho Forest Nursery. Personal communication.

Wykoff WR (1986) Supplement to the user's Guide for the Stand Prognosis Model—Version 5.0. Gen Tech Rep INT-281. USDA For Serv Intermountain Research Station, Ogden, UT. 40 pp.

Wykoff R, Crookston NL, Stage AR (1982) User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. USDA For Serv Intermountain Forest and Range Experiment Station, Ogden, UT. 112 pp.