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Carbon and Greenhouse Gas Accounting of Forest Operations in FPInterface

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Abstract

Developed by FPInnovations, FPInterface is an operational-level simulation platform for forest supply activities from the harvest site to the mill gate. The software can model, simulate and optimize forest operations directly from the GIS planning maps. The analysis is done at the block level for a forest management unit and provides the cost and volumes of all products harvested from the selected blocks. The basic platform allows for cost calculations of harvesting, road construction, transport and regeneration. Additional modules are also available for optimizing transport routes, biomass supply flow and cost estimates, operational scheduling and value chain decisions. The software offers a tactical and operational forest planning tool in the context of Canadian forest operations.

FPInterface considers all fossil fuel inputs and biomass outputs based on product specifications, harvesting decisions, equipment selection, road network and stand conditions. Therefore, the software offers an opportunity for the development of functionalities for greenhouse gas emissions accounts and carbon budgets for woody feedstock. The main objective of this paper is to describe the calculation of carbon ratio in a module of the FPInterface software. Furthermore, a scenario analysis was conducted, where the usability of the module was demonstrated. The objectives of the analysis were to show the impact of tree size on carbon emissions and to compare different supply chains for biomass in terms of carbon ratios.

Keywords: carbon emissions, forest planning, logging operations, biomass, FPInterface.
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Introduction

FPInterface software is a GIS platform for a series of modules based on a deterministic approach for planning forest operations. The software, developed by FPInnovations, enables users to model, simulate and optimize forest operations directly on digital maps. It allows users to accurately plan their operational logistics and budgets. FPInterface uses spatial data to create harvest and regeneration scenarios. The objective is to calculate an overall supply cost that includes harvesting; biomass recovery; regeneration; road construction and maintenance; and transportation to receiving mills over logging roads. The program runs on a Windows platform and does not require other software. A forest map, in shapefile format showing cutblocks and a road system, is imported before scenario development begins.

Because of the use of biomass for energy and the desirability of determining the carbon footprint of the forest operations, a module to calculate greenhouse gas emissions and the resulting carbon ratio was developed.

Strategic models help in getting a broader view of a problem, but they sometimes make it difficult for users to relate to the results because they normally use a low-resolution approach. By working directly at the block level, with planning from the forest companies, the FPInterface tactical and operational software allows the calculation of greenhouse gas emission and carbon ratio with a high level of resolution. The software's flexibility will let users easily update their planning to evaluate the impacts of their decisions compared to alternate scenarios.

The main objective of this paper is to describe the calculation of carbon ratio in a module of the FPInterface software. Furthermore, a scenario analysis was conducted, where the usability of the module was demonstrated. The objectives of the analysis were to show the impact of tree size on carbon emissions and to compare different supply chains for biomass in terms of carbon ratios.

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Materials and Methods

The carbon module calculations are based on the direct emissions from conducting the forest operations and the carbon contained in the products. Given this information, it is possible to calculate the carbon ratio for the wood supply.

Main inputs for the carbon module

Emissions

Emissions calculations are based on the following four parameters:

- Harvested wood volume
- Tonnage of biomass recovered
- Productivity of equipment
- Hourly fuel consumption of equipment

The merchantable volume (under bark) of wood harvested is imported in FPInterface from the GIS database of the user. Data are normally generated from local forest inventories. Stand volume is separated by species and then allocated to different products. Mean tree size (merchantable volume per stem) per species is also imported from the user's GIS database. The volume is used as the basis for comparing emissions, while tree size is needed for estimating the potentially available biomass from harvesting residues and equipment productivity.

The amount of biomass generated from a stand is estimated in oven dry metric tonnes (odt, 1 tonne = 1000 kg) using single tree equations from Lambert et al. (2005) that are adapted with volume equations from Honer et al. (1983) to consider the effect of topping diameter. Based on validation trials, factors are also applied depending on recovery systems to estimate the percentage of the potentially available biomass that will be recovered (Ralevic et al. 2010). Biomass tonnage is also used for comparing emissions of the recovery equipment.

Equipment productivity depends on several factors and varies from one piece of machinery to the next. Generally speaking, it depends on the properties of the stands harvested and the prevailing terrain conditions in the cutting area. FPInterface is designed to store all the factors and calculate the productivity of each machine that will be used. The software calculations use mathematical equations on productivity that have been developed by FPInnovations for more than 35 years.

The transportation cycles are defined based on the actual road network. Considering the road classes, FPInterface automatically determines the best path to transport the products from the cutting blocks to the mills. FPInterface associates a speed limitation and a fuel consumption for each road segment based on the road class and on the type of truck used. The software can then calculate the total cycle time and the fuel consumed.

Hourly fuel consumption of equipment is an input stored in the FPInterface database of default values. The database is updated periodically from a survey, conducted by FPInnovations, of forestry equipment manufacturers, and with measurements taken during equipment testing.

Sequestration (carbon "delivered")

In the model, the volume of sequestered carbon depends solely on the quantity of roundwood harvested and recovered residues. To avoid confusion, because the model boundary is from stump to mill gate, and biomass usage is not considered, delivered carbon will be used instead of sequestered carbon. This information is already stored in FPInterface, so only the appropriate conversion factors need to be applied to obtain the carbon content in the delivered products.

Several conversion factors are needed to obtain the quantity of emitted and delivered carbon. Converting volume to mass was done using basic wood densities (dry mass by green volume) for the main softwood and hardwood species for central and eastern Canada (Table 1). Mass to carbon content conversion was based only on broader wood types; one unit of wood mass is assumed to contain 0.521 and 0.498 units of carbon for softwoods and hardwoods, respectively (Birdsey 1996).

Table 1. *Density of tree species, used in the estimation of carbon delivered. Source: Alemdag (1985).*

Wood type	Species	Density (*kg/m³*)
Softwood	Black spruce *(Picea mariana)*	437
	White spruce *(P. glauca)*	383
	Balsam fir *(Abies balsamea)*	341
	Jack pine *(Pinus banksiana)*	418
	White pine *(P. strobus)*	342
	Red pine *(P. resinosa)*	372
	Larch *(Larix laricina)*	494
	Cedar *(Thuya occidentalis)*	311
	Hemlock *(Tsuga canadensis)*	406
	Other softwoods	400
Hardwood	Trembling aspen *(Populus tremuloides)*	387
	Largetooth aspen *(P. grandidentata)*	388
	Balsam poplar *(P. balsamifera)*	354
	White birch *(Betula papyrifera)*	539
	Yellow birch *(B. alleghaniensis)*	596
	Sugar maple *(Acer saccharum)*	616
	Red maple *(A. rubrum)*	588
	Silver maple *(A. saccharinum)*	480
	White ash *(Fraxinus americana)*	594
	Black ash *(F. nigra)*	545
	Red ash *(F. pennsylvanica)*	550
	American linden *(Tilia americana)*	428
	Beech *(Fagus grandifolia)*	607
	Cherry *(Prunus serotina)*	569
	Elm *(Ulmus americana)*	580
	Hickory *(Carya cordiformis)*	616
	White oak *(Quercus alba)*	646
	Red oak *(Q. rubra)*	590
	Other hardwoods	594

Calculations

Emissions

Calculation of emissions is essentially based on the time required for each supply chain operation. The processing time (productive machine hour (PMH) per cutblock) for harvesting and skidding commercial timber and for recovering and chipping biomass can be determined quickly for each machine with the following formula:

$$\text{Processing time} = \text{Quantity processed} / \text{Productivity} \quad (1)$$

The quantity processed (m^3 or odt) and the productivity (m^3 per PMH or odt per PMH) relate to each cutblock processed, so the total duration can be expressed by cutblock. Productivity functions used are based on mean tree size for harvesting operations and mean skidding distances, and this calculation assumes that hourly fuel consumption is constant but specific for each processing machine. The fuel consumption for wood processing per cutblock (L) is therefore the sum of the processing time for each machine *i* multiplied by its hourly fuel consumption (L per PMH):

Processing consumption =

$$\sum_i ((\text{Processing time})_i \times (\text{Hourly consumption})_i) \quad (2)$$

Wood transport fuel consumption per trip (L) is based on the distance traveled one way) on each road class *j*, with specific fuel consumption (L/km) per road class for loaded and unloaded trucks (Equation 3). The type of truck selected will also have an impact on the travel speed and the payload per trip.

Transport consumption =

$$\sum_j (\text{Distance}_j \times (\text{Consumption loaded} + \text{Consumption unloaded})_j) \quad (3)$$

The transportation consumption per cutblock corresponds to the consumption per trip multiplied by the number of trips needed to haul all the wood from the block (quantity processed by payload).

Therefore, the total fuel consumption at the cutblock level will be the sum of the processing and the transport consumption.

Once the fuel consumption is known for both the processing and transport of the wood from the cutblock, the program will first calculate the quantity (kg) of CO_2 emitted, and then the quantity (kg) of carbon. These calculations are based on two constants:

1) CO_2 emissions coefficient—because all logging equipment runs on diesel fuel, a CO_2 emission coefficient of 2.663 kg/liter is used (Environment Canada, 2008).
2) Mass of carbon emitted in CO_2—considering the relative atomic mass of carbon and oxygen, 27.2912% of each kilogram of CO_2 results in carbon emissions.

Then the carbon emissions (kg per cutblock) can be calculated by Equation 4.

$$\text{Carbon emission} = \text{Total consumption} \times 2.663 \times 0.272912 \quad (4)$$

Delivered Carbon

The amount of carbon in wood delivered to mills is related to the quantity per species harvested. For roundwood dedicated for traditional commercial products, FPInterface tracks all merchantable harvested volume (m^3, under bark) on a species basis. To get the amount of delivered carbon (kg per cutblock), the volume (m^3) of roundwood is converted into mass (kg) using the appropriate species density (see Table 1). Knowing the percentage of carbon in the wood of each group of species (see the "Sequestration" section above), the mass of the sequestered carbon can be obtained.

Delivered roundwood carbon =

$$\text{Volume} \times \text{Density} \times \text{Carbon content} \quad (5)$$

For wood dedicated for biomass products, FPInterface already provides the dry mass (odt per cutblock) of biomass that will be shipped to mills. This result just needs to be multiplied by the carbon content.

$$\text{Delivered biomass carbon} = \text{Mass} \times \text{Carbon content} \quad (6)$$

Scenario Analysis

A scenario analysis is conducted to demonstrate the usability of the new carbon module of FPInterface. The objectives of the analysis were to show the impact of tree size on carbon emission and to compare different supply chains for biomass in terms of carbon ratios.

The analysis is based on GIS data from a harvesting sector located 35 km north of La Sarre, in the Abitibi-Témiscamingue region of the province of Quebec. The sector is composed of 30 boreal forest cutblocks that are mainly composed of softwood (81.1%) with an average merchantable volume per stem of 0.115 m^3 (Table 2). Based on the CPPA classification (Canadian Pulp and Paper Association, 1980), the terrain conditions are uniform, with a clay soil covered by a thick organic layer and an average level slope. Machine productivities were adjusted in the analysis to consider the impact of lower soil-bearing capacity.

Scenario 1—Impact of tree size on carbon emissions

During the harvesting phase, mean tree size is the most important single factor affecting operation productivity. Therefore, the time required, and consequently the diesel fuel consumption as well, are directly related to the size of the trees in the stands (Table 3). Simulating a full-tree harvest of stands

Table 2. *Merchantable volume per species in the sector analyzed.*

Species	Volume (m³)	Percentage (%)
Balsam fir	1 590	3.4
Black spruce	21 305	45.4
Jack pine	23 994	51.2
Balsam poplar	10 311	94.5
White birch	598	5.5
Softwoods pooled	*46 888*	*81.1*
Hardwoods pooled	*10 908*	*18.9*
All species pooled	*67 796*	*100.0*

with higher merchantable volume per stem, the model generated lower carbon emissions per m^3 than for stands with smaller tree size (2.2 kg/m^3 compared to 3.2 kg/m^3). Considering trees with an average wood density of 420 kg/m^3, the harvesting operation in a stand with larger trees would have produced a carbon emission of 2 kg/odt lower than a stand with smaller trees (5.2 kg/odt compared to 7.2 kg/odt).

Table 3. *Impact of the mean tree size on carbon emission of full-tree harvesting operations.*

Operation	Fuel (L/PMH)	0.10 m³/tree		0.30 m³/tree	
		Productivity (m³/PMH)	Fuel used (L/m³)	Productivity (m³/PMH)	Fuel used (L/m³)
Feller-buncher	35	35.3	1.0	64.9	0.5
Skidder	25	16.7	1.5	16.7	1.5
Stroke-delimber	25	13.0	1.9	24.7	1.0
All operations pooled			*4.4*		*3.0*

Scenario 2—Impact of harvesting system on carbon emissions from biomass recovery

A second scenario is used to compare carbon emissions from biomass recovery operations after a full-tree and a cut-to-length harvesting system (Table 4). As with the above example, the full-tree system comprises the use of a feller-buncher, a grapple skidder and a stroke delimber. In this system, delimbing residues are generated at roadside. While these residues do not need a primary transportation phase, pre-piled is often needed to ease handling during the comminution phase, and to help lower the moisture content of the biomass. Because of the level of contamination of roadside residues, comminution is done with a grinder.

Branches are left scattered on the cutover with a cut-to-length system using a harvester and a forwarder, compared to the recovery of residues from a full-tree system. In this case, a forwarder is needed to collect the branches and pile them on the side of the road. These piles tend not to be contaminated by rocks and can therefore be comminuted by a chipper. However, even if the biomass can be treated with a more efficient machine, the forwarder needed to bring the cut-to-length residues to the roadside will raise the carbon emission to 1.1 kg/odt greater than with the full-tree system (5.3 kg/odt compared to 4.2 kg/odt).

Table 4. *Impact of harvesting system on biomass recovery.*

System	Operation	Fuel used (L/odt)
Full-tree	Operations pooled	5.8
	Pre-pilling	0.4
	Grinding	5.4
Cut-to-length	Operations pooled	7.3
	Forwarding	3.2
	Chipping	4.1

Scenario 3—Impact of product type and hauling distance on transport carbon emissions

With regard to the transportation of commercial timber and biomass, the main aspects that influence carbon emissions are the travel distance, the types of roads used and the volume transported. The farther the distance, the greater the amount of fuel that will be consumed per unit of wood delivered. The breakdown of the distance according to the different types of roads used will also affect carbon emissions. For example, if the timber from one of the cutblocks has a longer hauling distance over logging roads, the inherent slower travel speed will lower the truck fuel efficiency and result in higher carbon emission.

When comparing comminuted biomass to roundwood transported over the same types of roads and similar trucks (4-axle semi-trailers), the effect of the travel distance becomes quickly evident (Table 5). The difference of about 7% in carbon emission between the two types of products is caused by the lower bulking factor of comminuted biomass compared to roundwood and to the type of trailer used for each material.

Table 5. *Impact of transportation distance on carbon emission (kg CO_2/km) based on product type.*

Distance (km—one way)	Transported material	
	Comminuted biomass	Roundwood
50	2.5	2.3
100	5.0	4.7
150	7.3	6.8

Carbon ratio comparison of logs and comminuted wood delivery in a full-tree harvesting system

Carbon emissions from forest operations are easier to put in perspective when expressed by a ratio that considers the amount of carbon delivered to a mill. Considering a full-tree harvesting system of a softwood stand (carbon content of 521 kg/odt) with an average tree size of 0.2 m^3/stem (6.2 kg C/odt emitted for harvesting), and the hauling of roundwood to a mill located at 150 km (6.8 kg C/odt emitted for transport), the total 13.0 kg/odt of carbon emitted by forest operations represents a 40:1 ratio over the carbon content in the delivered wood (Table 6). For the delivery of roadside biomass, even if no felling or forwarding are involved, the use of a grinder to comminute the material for transportation makes the operation only slightly more efficient than the roundwood operation with a 45:1 ratio.

Table 6. *Carbon emitted and carbon ratio for a full-tree system to mill gate with a one-way transportation distance of 150 km.*

Carbon emission	Traditional harvesting (roundwood)	Roadside recovery (comminuted)
Carbon emitted (kg/odt)	13.0	11.5
Carbon ratio	40:1	45:1

Discussion & Conclusions

Considering the interest and controversy attending the use of biomass to replace fossil fuels (Paré et al. 2011, Manomet 2010, Börjesson 2008), the tools to generate reliable data on carbon emissions from forest operations will help evaluate the value of a bioenergy project on the basis of carbon efficiency. The model uses a detailed forest operation simulation approach to estimate fuel consumption and carbon emission. It does offer the potential for a high level of accuracy, but the results will always depend on the quality of the GIS dataset used for the analysis. A number of factors are likely to affect result accuracy. The main ones are the following:

1) Information consolidation—depending on the user's needs, the data initially provided in FPInterface tend to be amalgamated to speed up the calculation process. For example, in the scenarios analyzed, forest data for some similar adjacent cutblocks were combined in a weighted average. For these cutblocks, the emission and sequestration outputs per hectare become identical.

2) Inventory data quality—the stand data (species composition, merchantable volume per species and mean tree size per species) that users input into the software come from forest inventories. Many forest managers have warned us that the degree of accuracy and the quality of the data drawn from inventories could be highly variable.

3) Road network quality—GIS road networks are seldom used for optimizing the transport and are typically updated on an irregular basis. Many segments are misidentified, or closed road segments are just not deleted from the network and will lead to inaccurate results.

The carbon module, which mainly focuses on the carbon ratio for wood harvesting to mill gate delivery, provides useful results by demonstrating the value of implementing environmental factors to help assess the global value of bioenergy projects. The information contained in the software will ultimately enable users to manage the carbon footprint for their supply operations and provide input data for planning operations.

The scenarios used in this report also show that even if forest products are not entirely carbon neutral, the carbon footprint of forest operations is very light, with ratios of over 40:1. Operational parameters will have an impact on the carbon emissions, but the main factor will remain the transportation distance.

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