Environmental Impacts From Clean Wood Waste Management Methods: Preliminary Results

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1. Introduction and Summary

This report compares the climate change impacts of four methods currently used to manage clean wood waste – i.e., wood that has been neither treated nor painted -- generated by construction and demolition activities:

1) Reuse for remodeling or new construction.
2) Recycle via chipping and pulping into a feedstock for papermaking.
3) Recover energy via chipping into a fuel source for industrial boilers as a substitute for natural gas or coal.
4) Landfill with or without landfill gas collection, and if with gas collection, with or without electricity generation.

This report details the methodology and data used to estimate climate change impacts for these clean wood waste management options. This report also discusses other environmental impacts from wood waste management, including human health, ecosystems sustainability, acidification, and eutrophication. The rankings of management options based on these other environmental impacts are, in many cases, quite different than their rankings with respect to the climate change impact.

Figure 1, Greenhouse Gas Increase/(Decrease) for Clean Wood Waste Management Options [Pounds CO2 Equivalents per Ton Wood], indicates that all but one of the current wood waste management methods actually decrease greenhouse gas (GHG) emissions. The exception is disposal in a landfill that vents landfill gases to the atmosphere.

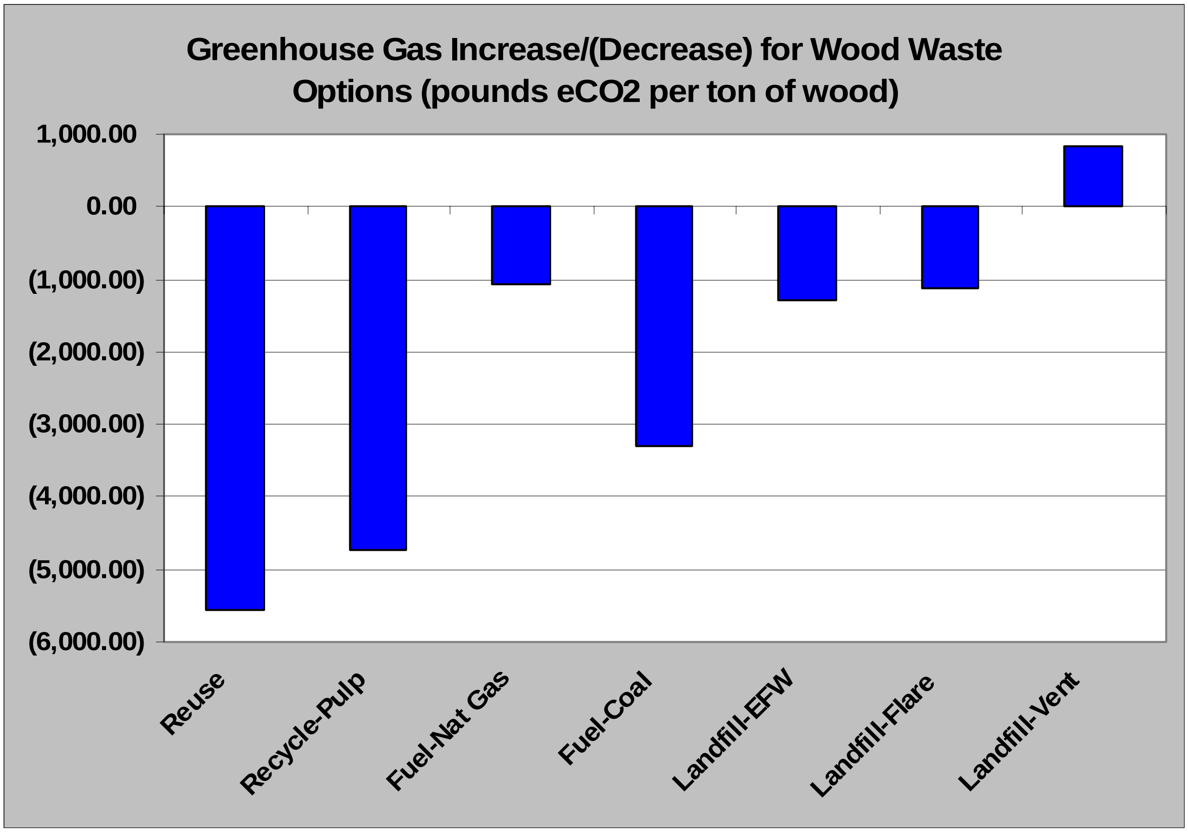
Reuse of wood waste for the purposes for which dimensional lumber and engineered wood products were originally manufactured provides the greatest climate change benefit – reducing emissions by 5,600 pounds of carbon dioxide equivalents (eCO2) per ton of wood. This is mainly due to the avoidance of additional tree harvesting and continued storage of carbon in the dimensional lumber or engineered wood products that are reused. This carbon was originally sequestered during the growth of trees before they were harvested to manufacture wood products.

Second place goes to recycling wood chips into pulp for paper manufacturing. This management method reduces GHG emissions by 4,700 pounds eCO2.

Coming in third among the seven management options shown in Figure 1 is processing of scrap wood into chips as a fuel substitute for coal. Substituting wood chips for coal in industrial boilers reduces GHG emissions by 3,300 pounds of carbon dioxide equivalents. The difference between recycling and combustion of wood chips as a replacement for coal combustion is due to the difference between avoided tree harvest under recycling and avoided coal emissions under combustion. Coal fossil fuel emissions reductions amount to

4,300 pounds eCO2 per ton of wood chips, compared with the 5,600 pounds eCO2 that are saved by replacing chips from newly harvested trees for manufacturing papermaking pulp.

Figure 1
Greenhouse Gas Increase/(Decrease) for Clean Wood Waste Management Options
[Pounds CO2 Equivalents per Ton Wood]



Fourth and fifth places go to two of the landfill options – landfilling with and without energy recovery, respectively. When wood is landfilled much of the carbon stored in wood remains sequestered due to the very slow decomposition of wood in modern landfills.[1] Methane generation from wood waste is thus relatively low.[2] This explains the rather small climate change benefit for wood in landfills that recover energy from collected landfill gases (LFGs) compared with those that simply flare captured LFGs.

Coming in sixth is the substitution of chips from recycled wood for natural gas as fuel for industrial boilers. Fossil fuel emissions reductions from substituting wood chips for natural gas total 2,100 pounds eCO2 per ton of wood chips. This compares with 4,300 pounds of

[1] See EPA(2006) for an explanation of the methodology EPA used to estimate long term carbon storage in landfills. EPA did not specify the time period for long term carbon storage.
[2] We assume a landfill gas capture efficiency of 75% - the same as the default capture efficiency used in EPA's WARM (EPA 2006). Some argue that modern landfills capture 90% or more of landfill gas emissions, while others argue that the effective rate is much lower. See Anderson (2007) for an example of the latter point of view.

eCO2 reduction for the substitution of wood for coal. The difference is due to natural gas producing only 117 pounds eCO2 per million Btus compared with 283 pounds eCO2 for coal.

Finally, burying a ton of wood waste in a landfill that does not collect landfill gas results in a net increase in GHG emissions of over 800 pounds eCO2. Most of the emissions from burying wood in a landfill that does not control landfill gas emissions is due to methane that is produced when a ton of wood waste decomposes anaerobically. In addition, there is the investment of over 650 pounds eCO2 in the production and distribution of each ton of dimensional limber and plywood. This investment is destroyed when construction and demolition wood waste are not reused. These emissions are offset by the continued storage of 2,500 pounds of eCO2 as a result of the very slow decomposition of wood in a landfill.

2. Methodology & Data for Estimating Wood Waste Climate Impacts

The choice among management methods for wood waste has environmental impacts much beyond the boundaries of the processing or disposal facility where wood wastes are sent. To fully account for these impacts one needs to examine the entire life cycle of wood products from tree growth through to the point at which wood products become waste generated during construction and/or demolition activities.

That life cycle begins with sequestration of carbon and other substances in trees as they grow. After harvest, the tree wood becomes a feedstock for sawmills to make dimensional lumber and for manufacturers to produce engineered products such as plywood and oriented strand board (OSB). These wood products are used in construction activities where a minor portion becomes scrap as a result of wood being shaped for incorporation in structures. After a time, the remaining major portion also becomes scrap when structures are dismantled during demolition activities.

Table 1, Clean Wood Waste Management Emission and Emission Offsets Sources, shows the stages in the wood product life cycle where emissions occur as a result of the management method used for clean wood waste. The table also shows the offsets, or emissions decreases, which occur as a result of each management method.

For example, reuse of wood waste entails emissions from hauling reusable wood from generation site to the place where it gets used in another construction activity. Reusing the scrap wood preserves carbon sequestered in the wood product during tree growth. This stored carbon provides an offset to the carbon emissions from hauling. Reusing scrap wood also preserves an additional amount of sequestered carbon through the avoidance of tree harvesting. There is an approximate 2 to 1 ratio between the total carbon content taken down in tree harvests and the amount of carbon that remains in manufactured wood products. The tree harvest offset is shown as a separate line item from the carbon storage offset line in Table 1.

As shown in the table, the reuse management option is unique in not changing the characteristics of the wood waste; thus, allowing the scrap wood to be used for the same purpose for which the wood product was originally manufactured. The other six management options all entail destruction of the scrap wood product so that it can no longer be used for its original purpose. These options either involve grinding the waste into chips or burying them in a landfill where they undergo biodegradation. As a result new wood products need to be manufactured to take the place of the destroyed products. This results in emissions from manufacturing tree wood into new products.

Table 1
Clean Wood Waste Management GHG Emissions and Emission Offsets Sources

	Reuse	Recycle To Paper Pulp	Fuel Replace Nat. Gas	Fuel Replace Coal	Landfill Recover Energy	Landfill Flare LFG	Landfill Vent LFG
Emissions							
New Wood Production		X	X	X	X	X	X
Processing & Chipping		X	X	X			
Chip Storage		X	X	X			
Hauling	X	X	X	X	X	X	X
Combustion			X	X			
Biodegradation					X	X	X
Internal Combustion Engine for Electricity Generating Equipment					*X*		
Landfill Gas (LFG) Flare						*X*	
Landfill Operations					X	X	X
Offsets							
Carbon Storage	(X)	(X)			(X)	(X)	(X)
Tree Harvest	(X)	(X)					
Pulping Wood Production		(X)					
Natural Gas Production & Combustion			(X)		(X)		
Coal Production & Combustion				(X)			

At the same time, the recycling and landfilling management options all involve preservation of some of the carbon sequestered in growing trees. In the case of the recycling option, some of this sequestered carbon is stored in the paper or paperboard that is manufactured from the pulp produced from the chipped wood waste. Recycling also yields an additional offset due to avoided tree harvests that would otherwise occur to provide the wood chip inputs for pulp mills.

In the case of the three landfill alternatives, the very slow degradation of wood in a landfill results in much of the sequestered carbon remaining stored in the buried wood waste. Thus these options also get an offset for the continued carbon storage. However, landfilling does not avoid additional tree harvests and so does not get the additional offset like reuse and recycling do.

In the case of the two combustion options, most of the carbon stored in the wood product waste is liberated as CO2 during the combustion process. However, these CO2 emissions do no count as GHG releases as long as the forests that produce the trees used to manufacture lumber and engineered wood products are sustainably managed. That is, enough trees are growing over a fairly long time frame (100 years is often the reference time period) such that the carbon sequestered by tree uptake as forests grow is at least equal to the carbon released by the harvesting of trees and the ultimate release of carbon from forestry products such as paper and furniture when they are discarded and landfilled or burned. In practice, the assumption is that forests are being sustainably managed so that combustion of forestry products at the end of their useful life is assumed to be climate neutral, i.e., to cause no GHG releases.

The combustion options do get an offset as a result of substituting clean wood chips as a fuel for natural gas or coal. This offset includes:

- Avoided GHG emissions that would otherwise be generated during fuel resource extraction (mining or drilling), refining and distribution, and,
- Avoided GHG emissions that would otherwise be generated during natural gas or coal combustion.

The other offset shown in Table 1 is the avoidance of GHG emissions from tree harvesting operations and preparation of pulp wood for manufacture into papermaking pulp. This avoidance is made possible when wood wastes are processed and chipped for input to pulp mills.

Most of the remaining emissions producing activities shown in Table 1 for each wood waste management option are self explanatory, with the possible exception of the line item for wood chip storage. Wood chip storage often results in methane and nitrous oxide emissions due to anaerobic conditions in piles of wood chips that are accumulated at the pulp manufacturing or wood chip combustion sites.

2.a. Data Sources for Estimation of Emissions and Offsets

Data and methods used to estimate GHG and other emissions from wood waste management, to estimate the potential environmental impacts caused by those emissions, and to estimate economic costs for the environmental impacts are from a variety of sources, including:

- US EPA’s WARM model (available on the internet at http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html).

- US EPA's MSW Decision Support Tool (available through Research Triangle Institute[3]).
- Carnegie Mellon University Green Design Institute's Economic Input-Output Life Cycle Assessment model (available on the internet at www.eiolca.net).
- US NIST BEES model (available on the internet at http://www.bfrl.nist.gov/oae/software/bees/model.html).
- US EPA's TRACI model (information about TRACI is available on the internet at http://www.epa.gov/nrmrl/std/sab/traci/).
- US EPA's AP-42 emissions data (available on the internet at http://www.epa.gov/ttn/chief/ap42/).
- Peer-reviewed journal articles including Morris (2005), Wihersaari (2005b), and Morris and Bagby (2008).
- A comprehensive waste management system environmental costs and benefits valuation model (available through Sound Resource Management[4]).

The following section details how we used these data and methods to estimate the climate change impacts of wood waste management methods.

3. GHG Releases & Offsets from Wood Waste Management

Table 2, Estimated GHG Increase/(Decrease) for Clean Wood Waste Management Methods, shows the estimated greenhouse gas (GHG) releases or reductions for each management method currently used to handle wood waste generated by construction and demolition (C&D) activities. This section lays out the methodology and emissions estimate for each individual activity and offset listed in Table 1 of the previous section.

The emissions from these activities minus the offsets add up to the GHG totals listed in Table 2 for the wood waste management options. Table 3, Clean Wood Waste Management GHG Emissions and Emission Offsets, shows the GHG release or offset estimates for each of the line items laid out in Table 1.

Table 2
Estimated GHG Increase/ (Decrease) for Clean Wood Waste Management Methods (pounds CO2 equivalents per ton wood waste)

Management Method	*Pounds eCO2/ton*
Reuse	(5,572)
Recycling to Paper Pulp	(4,733)
Fuel Sub for Coal	(3,306)
Landfill with Energy Recovery	(1,297)
Landfill with LFG Flaring	(1,115)
Fuel Sub for Natural Gas	(1,072)
Landfill without LFG Capture	825

[3] See Research Triangle Institute (1999a and 1999b)
[4] The model is reviewed in Morawski (2008).

Table 3
Clean Wood Waste Management GHG Emissions and Emission Offsets
(pounds eCO2/ton wood waste)

	Reuse	Recycle To Paper Pulp	Fuel Replace Nat. Gas	Fuel Replace Coal	Landfill Recover Energy	Landfill Flare LFG	Landfill Vent LFG
Emissions							
New Wood Production		.5*660 + .5*673 = 666	.5*660 + .5*673 = 666	.5*660 + .5*673 = 666	.5*660 + .5*673 = 666	.5*660 + .5*673 = 666	.5*660 + .5*673 = 666
Processing & Chipping		141	141	141			
Chip Storage		100	100	100			
Hauling	6	29	17	17	12	12	12
Combustion			68	68			
Biodegradation					647	647	2,587
Internal Combustion Engine for Electricity Generating Equipment					*0*		
Landfill Gas (LFG) Flare						*0*	
Landfill Operations					*66*	*66*	*66*
Offsets							
Carbon Storage	-2,878	-2,878			-2,506	-2,506	-2,506
Tree Harvest	-2,700	-2,700					
Pulping Wood Production		-92					
Natural Gas Production & Combustion			-2,066		-182		
Coal Production & Combustion				-4,299			
Net Emissions	-5,572	-4,733	-1,072	-3,306	-1,297	-1.115	825

Note: Columns may not total to the number shown for Net Emissions due to rounding.

3.a. Production of Dimensional Lumber and Engineered Wood Products

The estimates for GHG emissions from manufacturing of wood products are 660 and 673 pounds of carbon dioxide equivalents (eCO2) per ton of lumber and engineered wood products, respectively. We calculated these estimates using Carnegie Mellon University Green Design Institute's Economic Input-Output Life Cycle Assessment (EIO-LCA) model.[5]

One million dollars (1997 $) of purchases from the sawmill industry (EIOLCA sector 321113) results in 705.6 metric tons eCO2 emissions. These emissions occur due to the lumber manufacturing processes, as well as timber harvesting operations and other material and energy inputs from across the entire sawmill supply chain. Based on recent and historical wholesale prices and producer price indices for dimensional lumber, the purchase price for a ton of dimensional lumber products in 1997 was $424. This yields the estimate of 660 pounds eCO2 life cycle emissions to manufacture one ton of dimensional lumber.

[5] Hendrickson *et al* (2006) provides an overview of the use of input-output analysis for calculating life cycle emissions. Cicas et al (2006) explains the 1997 benchmark version of the Green Design Institute's EIO-LCA model.

The same procedure for a million dollars of purchases from the veneer and plywood industry (EIOLCA sector 32121A) yields the estimate 673 pounds eCO2 life cycle emissions to manufacture one ton of engineered wood products. For this industry our estimate of the purchase price from manufacturers in 1997 for one ton of engineered wood products is $388.

We assumed that lumber and engineered wood products would be evenly split in the wood waste generated from C&D activities. Thus, our estimate for eCO2 emissions for new wood products manufacturing is 666 pounds per ton of wood waste.

3.b. Processing and Chipping Wood Waste

We estimated GHG emissions of 141 pounds eCO2 per ton of wood waste processed and chipped for use as a fuel or for manufacturing into papermaking pulp. This estimate is based on the MSW Decision Support Tool (DST) estimate of 189 pounds eCO2 emissions necessary to process a ton of recyclables, and an estimate based on Wihersaari (2005a) that over 40 pounds eCO2 is emitted from the energy used to grind one ton of naturally dried forestry residues into chips for use as fuel.

The assumption is that processing recyclables and processing wood waste both require similar amounts of power for material moving equipment and conveyor systems. Further, the magnets and trommels used for separating commingled recyclables may be equivalent in per ton energy intensity to the chippers and magnets used to grind wood waste and separate nails from wood.

However, the building for processing recyclables likely is more energy intensive than the building for processing wood waste, because wood sorting operations are often in covered but not enclosed structures. On this basis we assumed that processing and chipping wood waste would require 75% of the energy intensity of processing recyclables, and consequently 75% of the eCO2 emissions as well.

3.c. Methane Emissions from Wood Chip Piles

Wihersaari (2005b) reported that her study of methane and nitrous oxide emissions from wood chip storage piles yielded an estimate of nearly 300 pounds eCO2 emissions per ton of chips from naturally dried forest residues, when the chips were stored in piles for 6 months. Assuming a storage period of just 2 months and less moisture in chips from C&D wood waste, 100 pounds eCO2 per ton may be a reasonable estimate for GHG releases due to methane and nitrous oxide production under anaerobic conditions in chip piles.

3.d. GHG Emissions from Hauling

The MSW DST data base estimates that GHG emissions for long distance truck hauling amount to under 0.12 pounds eCO2 per ton mile. Round trip mileage for the four wood waste management methods are assumed to total 50 miles for reuse, 150 miles for combustion in industrial boilers, 250 miles for recycling into papermaking pulp, and 100 miles for landfill.

These distances yield eCO2 emissions of 6, 17, 29 and 12 pounds per ton for the four respective management options.

3.e. GHG Emissions from Combustion

According to US EPA AP-42 emissions estimates there are a number of GHGs that are released when wood is combusted in industrial boilers. These include, 1,1,1-trichlooethane, carbon tetrachloride, CFC-11, chloroform, methylene chloride, methane, methyl bromide, methyl chloride, and nitrous oxide. In total these releases amount to 68 pounds eCO2 per ton of wood chips.

3.f. GHG Emissions from Biodegradation & Carbon Storage in Landfills

According to EPA (2006) 2,506 pounds of eCO2 remains stored and does not biodegrade in a ton of wood that has been landfilled. In a landfill that vents landfill gases (LFG) to the atmosphere the amount of methane released is equivalent to 2,587 pounds eCO2. In a landfill that captures 75% of LFGs, the 25% emitted amounts to 647 pounds eCO2.

3.g. GHG Emissions from Internal Combustion Engines Used to generate Electricity from Captured Landfill Gas, or from Flaring of Landfill Gas

Because the internal combustion engines (ICE) typically used to generate electricity from landfill gas run on the methane generated by the biodegradation of wood the convention is to categorize CO2 emissions from ICE exhaust as biogenic. On this basis there are no anthropogenic carbon emissions from the ICEs powered by LFGs.

Similarly, the CO2 emissions from flaring captured LFGs are not an anthropogenic source of carbon emitted to the atmosphere.

3.h. GHG Emissions from Landfill Operations

EPA's WARM model includes 88 pounds eCO2 for curbside collection of a ton of garbage, hauling the garbage to the landfill, and managing the garbage once it is at the landfill site. Because there is no curbside collection involved with wood waste generated at construction or demolition sites, and because hauling emissions are accounted for separately in our calculations, we reduced the 88 pounds to 66 to cover landfill operations for wood waste.

3.i. GHG Offsets for Carbon Stored in Reused or Recycled Wood

Subsection 3.f. already covered the estimate of carbon storage when wood waste are landfilled. Based on the EPA AP-42 estimate of 195 pounds of biogenic carbon dioxide releases per million Btus from wood combustion, and the estimate of 7,380 Btus per pound of wood, a ton of wood waste contains 2,878 pounds of eCO2. This CO2 continues to be stored in wood that is reused or in the paper or paperboard that is manufactured from pulp produced from recycled wood waste.

3.j. GHG Offsets for Avoided Tree Harvesting

According to EPA (2006) recycling of wood products avoids emissions of 2.53 metric tons of eCO2 due to reduced harvesting of trees. This is 5,578 pounds of eCO2. Wood waste themselves contain 2,878 pounds of eCO2, as discussed in the previous subsection. Thus, reuse or recycling a ton of wood waste avoids release of an additional 2,700 pounds of eCO2 related to carbon that is removed from forests during tree harvest but that is not incorporated into dimensional lumber or engineered wood products.

3.k. GHG Offsets for Avoided Production of Forestry Wood for Pulping

According to the EIO-LCA model a million dollars of purchases from the pulp mill industry (EIOLCA sector 322110) results in generation of 4,616,500 pounds eCO2. At an estimated wholesale price for papermaking pulp in 1997 of $485 per ton, this amounts to eCO2 releases of 2,239 pounds per ton of virgin pulp.

To estimate the reduction in GHGs when pulp is manufactured from recycled wood chips rather than newly harvested trees, we used the EIO-LCA model to compute the value of logging and lumber industry inputs to the pulping industry per million dollars of pulp purchases. Inputs from these two industries amounted to, respectively, 9.2% and 4.5% of pulp industry purchases per million dollars worth of pulp. Using the EIO-LCA model to calculate eCO2 releases from $92,000 in purchases from the logging industry and $45,000 in purchases from lumber manufacturing, we determined that 4.1% of the pulp industry's GHG emissions were embodied in purchases of forestry and lumber making residues. On this basis we estimate that using recycled wood chips to produce papermaking pulp saves 92 pounds of eCO2 per ton of wood chips.

3.l. GHG Offsets for Avoided Production & Combustion of Natural Gas

We used the EIO-LCA model to estimate GHG releases from production and distribution of natural gas. Emissions from purchases of natural gas from the natural gas distribution industry (EIOLCA sector 221200) amount to 22 pounds eCO2 per 1000 cubic feet of gas, based on a 1997 wholesale price of $4.52 for 1000 cubic feet.

Chips from wood waste have an average heating value of 7,380 Btus per pound, or 14.76 million Btus per ton. Natural Gas has a heating value of 1.03 million Btus per 1000 cubic feet. Thus, one ton of wood chips supplant 14,390 cubic feet of natural gas.

EPA's AP-42 reports CO2 emissions per 1000 cubic feet of natural gas combustion at 121.3 pounds. Combining production and combustion emissions for natural gas, one ton of wood chips used as a fuel substitute for natural gas saves 2,066 pounds of eCO2 emissions.

To estimate the GHG offset for electricity production from landfill gas produced when wood waste are landfilled, we used EPA's WARM model adjusted as follows. WARM provides an estimate of the fossil fuel emissions offset from producing electricity with collected landfill gas. That offset is based on the mix of coal, natural gas and petroleum used for electricity generation in the US. However, as discussed in RW Beck (2007), it is more realistic to base avoided emissions on production of electricity from natural gas combustion in a modern combined-cycle plant capable of recovering 40% of the energy in gas as electricity. That is the source of marginal electric power generation in the Northwest according to energy providers in this region. On that basis the GHG emissions from avoided natural gas combustion amount to 154 pounds eCO2. Adding in avoided GHG emissions from natural gas production and distribution, production of electricity via an internal combustion engine powered by landfill gas from wood waste avoids 182 pounds of eCO2 that would otherwise be released as a result of producing electricity using natural gas as fuel.

3.m. GHG Offsets for Avoided Production & Combustion of Coal

We used the EIO-LCA model to estimate GHG releases from production and distribution of coal. Emissions caused by purchases from the coal mining industry (EIOLCA sector 2i2100) amount to 161 pounds eCO2 per ton, based on a 1997 wholesale price of $18.14 per short ton.

Chips from wood waste have an average heating value of 7,380 Btus per pound, or 14.76 million Btus per ton. Coal's heating value on average is 20.68 million Btus per ton. Thus, one ton of wood chips can substitute for 0.71 tons of coal.

EPA's AP-42 reports CO2 emissions per ton of coal at 5,850 pounds. GHG emissions from coal combustion amount to 5,863 pounds eCO2 per ton, including emissions of other GHGs such as methane, chloroform and nitrous oxide that are released when coal is burned. Combining production and combustion emissions, substituting one ton of wood chips saves 4,299 pounds of eCO2 caused by coal combustion.

4. Other Environmental Impacts from Wood Waste Management

Life cycle analysis and environmental risk assessment provide the methodologies for connecting emissions of hundreds of pollutant to a handful of categories of environmental impact. The seven impact categories covered in our LCA of C&D wood waste management options include climate change, acidification, eutrophication, human health damage from particulates, human health damage from toxics, human health damage from carcinogens, and ecosystems damage from toxics.

To illustrate the methodology of aggregating pollutants into a single indicator for a particular environmental impact, releases of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs) and other pollutants cause global warming which leads to climate change. The United Nations Intergovernmental Panel on Climate Change (IPCC) has conducted studies and reviewed scientific data to determine the strength of each pollutant relative to carbon dioxide in causing global warming. Based on these IPCC studies, over a hundred year time frame methane is 23 times and nitrous oxide 296 times more harmful than CO2. Given these global warming potential factors (sometimes called global warming characterization factors) we can aggregate the emissions of all greenhouse gas pollutants into a single indicator quantity for global warming potential. This quantity is CO2 equivalents (herein denoted eCO2).

Similar scientific efforts enable us to express hundreds of pollutant releases in terms of a single indicator quantity for each of the other six categories of environmental damage covered in our LCA for wood waste management. This greatly simplifies reporting and analysis of different levels of pollution. By categorizing pollution impacts into a handful of categories, we are able to reduce the complexity of following trends for hundreds of pollutants. This simplifies life for policy makers.

The trade-off is that we have to sort through complex pollutant aggregation and weighting methodologies. As described in Sound Resource Management's report on our development of a Consumer Environmental Index (CEI) for the Washington State Department of Ecology, a "best-of" methodology is in development by the United Nations Environment Program and the Society of Environmental Toxicologists and Chemists.[6] Until that study is released, our environmental impact aggregation and weighting relies on the methodologies used in US EPA's TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) model and the Lawrence Berkeley National Laboratory's CalTOX model.[7, 8]

These tools provided aggregation factors for about half of the 535 substances tracked by TRI and included in the EIOLCA model used in our LCA. Aggregation factors for the other half of the TRI releases were not available at the time of this LCA study for wood waste management options. In addition, estimated emissions totals for human toxics and carcinogens and for ecosystem toxics do not include emissions for metals. This is due to an ongoing debate about the environmental impacts of metal emissions and the inability of the scientific community to as yet reach consensus on the environmental impacts of metals relative to each other and to other toxics and carcinogens.

Nevertheless, the TRACI and CalTOX models enabled us to aggregate pollution reductions or increases under each management option for over 250 pollutants into totals for the indicator pollutant for each impact category. These indicator pollutants are:

- Climate change – carbon dioxide equivalents (eCO2),
- Human health-particulates – particulate matter less than 2.5 microns equivalents (ePM2.5),
- Human health-toxics – toluene equivalents (eToluene),
- Human health-carcinogens – benzene equivalents (eBenzene),
- Eutrophication – nitrogen equivalents (eN),
- Acidification – sulfur dioxide equivalents (eSO2), and

[6] See Morris *et al* (2007).
[7] Bare (2002) and Bare *et al* (2003).
[8] See a description of the CalTOX model, references, and downloadable manual and software at http://eetd.lbl.gov/IED/ERA/caltox/index.html .

- Ecosystems toxicity – herbicide 2,4-D equivalents (e2,4-D).

Table 4, Environmental Impacts of Clean Wood Waste Management Options, shows estimated emissions increases or reductions for each wood waste management option for the seven environmental impact categories. The estimated impacts for each of the categories other than climate change use the same methodology and data sources described in Section 3 for the climate change impact category.

As indicated in the table, with two exceptions every wood waste management option shows increased emissions for all aggregated indicators of impact other than climate change. The two exceptions are for acidification and ecosystems toxicity when wood is substituted for coal as an energy source for industrial boilers. These results, thus, are quite different than for climate change where every management option other than a venting landfill reduced that particular environmental impact.

Given the estimated pollutant increases or reductions for each category of environmental impact, we now have the issue of figuring out how to compare the wood waste management options and determine which are preferable. Monetization provides a method for evaluating trade-offs between the seven types of environmental impacts, and is a standard approach within the field of environmental economics. The difficulty, as discussed in Morris *et al* (2007), is that monetization is controversial, especially regarding the issue of placing a dollar value on human and non-human lives. The benefit of monetization is that it allows us to summarize the value of the seven environmental impacts for each of our seven management options and compare the options against each other. It also allows us to compare overall environmental benefits or costs for any particular option against that option's financial costs and benefits.

The final step in estimating an environmental cost or benefit for each wood waste management option is, then, to determine a dollar value for the damage to public health and/or ecosystems caused by each of the indicator pollutants. The following list shows these estimated damage valuations and the source for each damage cost estimate[9]:

- eCO2 -- $36 per ton of carbon dioxide based on greenhouse gas offset valuation used by Seattle City Light.
- ePM2.5 -- $10,000 per ton of particulates no larger than 2.5 microns based on Eastern Research Group (2006).
- eToluene -- $118 per ton of toluene based on Morris and Bagby (2008).
- eBenzene -- $3,030 per ton of benzene based on Eastern Research Group (2006).
- eN -- $4 per ton of nitrogen based on Morris and Bagby (2008).
- eSO2 -- $661 per ton of sulfur dioxide based on average of 2005 ($690), 2006 ($860) and 2007 ($433) spot prices in EPA's annual acid rain allowance auction.

[9] The reader interested in the analytical basis for these valuations is invited to consult the reference for each impact valuation estimate.

- e2,4-D -- $3,280 per ton of 2,4-D based on Morris and Bagby (2008).

Based on these valuations for our seven categories of environmental impacts, each management option has the environmental cost or benefit shown at the bottom of Table 4. What is perhaps most surprising is that the ranking of wood waste management options under this overall environmental indicator is exactly the same as the ranking for GHGs shown in Table 2. That is, wood reuse has the highest environmental benefit at $100 per ton of C&D wood reused. Recycling wood waste into paper pulp has the second highest environmental value of $67 per ton of wood recycled. Substituting wood waste for coal in industrial boilers has the third highest value at $52. Overall environmental values for the other four options are very slight in the case of landfills that either flare or recover energy from collected landfill gases or strongly negative in the case of substituting wood waste for natural gas in industrial boilers or landfilling wood in a landfill that does not collect landfill gases.

Another interesting result is that non-metal toxics emissions for wood combustion in industrial boilers are an order of magnitude larger than for the other five management options. Removing metals from our emissions inventories decreased the toxicity impacts of wood combustion substantially. Yet the remaining toxics emissions from wood waste combustion remained a source of substantial difference between the combustion and non-combustion methods of managing C&D wood wastes.

Finally, the emissions of particulates from wood combustion versus natural gas combustion in industrial boilers is the other reason for the poor environmental performance of the combustion management option for C&D wood wastes.

Table 4
Environmental Impacts of Clean Wood Waste Management Options
(pounds and dollars per ton of wood waste)

Impact Category	Lumber Reuse	Recycling to Paper Pulp	Fuel Sub for Natural Gas	Fuel Sub for Coal	Landfill - LFG Energy	Landfill - LFG Flare	Landfill - LFG Vent	Environmental Value Per Ton of Emissions Reduction
	Pounds of Impact Category Emissions Released/(Reduced) Per Ton of Wood Waste							
Climate Change (eCO2)	(5,572.18)	(4,732.40)	(1,072.24)	(3,306.48)	(1,296.94)	(1,115.18)	824.89	$36
Acidification (eSO2)	0.05	4.42	8.04	(17.35)	3.58	3.35	3.30	$661
Eutrophication (eN)	0.00	0.33	0.31	0.44	0.16	0.15	0.15	$4
Human Health - Particulates (ePM2.5)	0.01	3.10	6.72	0.49	3.09	3.03	3.02	$10,000
Human Health - Toxics (eToluene)	0.00	24.37	204.49	207.66	26.02	26.03	26.02	$118
Human Health - Carcinogens (eBenzene)	0.00	0.00	0.16	0.15	0.00	0.00	0.00	$3,030
Ecosystems Toxicity (e2,4-D)	0.00	0.14	1.45	(1.27)	0.14	0.15	0.11	$3,280
Environmental Benefit/(Cost) of Management Option Per Ton Wood	**$100**	**$67**	**($32)**	**$52**	**$5**	**$2**	**($33)**	

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