METHOD FOR ESTIMATING GREENHOUSE GAS EMISSION REDUCTIONS FROM RECYCLING

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EXECUTIVE SUMMARY

This method quantifies the material-specific greenhouse gas emission reduction benefits associated with recycling. The life-cycle approach used in this method incorporates avoided emissions from manufacturing using recyclables, the use of raw materials in the manufacturing process (i.e., harvested wood), transportation emissions, and recycling efficiency. The following equation is used to calculate each recycling emission reduction factor (except dimensional lumber; RERF):

$$RERF = ((MS_{virgin} - MS_{recycled}) + FCS - T_{remanufacture}) * R_{use}$$

where,

RERF	=	Recycling emission reduction factor ($MTCO_2E$/ton of material)
MS_{virgin}	=	Emissions associated with using 100% virgin inputs for manufacturing the material ($MTCO_2E$/ton of material)
$MS_{recycled}$	=	Emissions associated with using 100% recycled inputs for manufacturing the material ($MTCO_2E$/ton of material)
FCS	=	Forest carbon sequestration ($MTCO_2E$/ton of material)
$T_{remanufacture}$	=	Transportation emissions associated with remanufacture destination ($MTCO_2E$/ton of material)
R_{use}	=	Recycling efficiency (fraction of material remanufactured from ton of recycled material)

The above equation uses an approach similar to one established by the United States Environmental Protection Agency (USEPA). This method modified USEPA's approach to include California-specific data and added a model to evaluate forest carbon sequestration. A summary is shown in Table ES-1.

Table ES-1. Recycling emission reduction factors (RERFs) for each material.

Material	RERF[a]	Material	RERF[a]
Aluminum	12.9	Magazines/3rd class mail	0.3
Steel	1.5	Newspaper	3.4
Glass	0.2	Office paper	4.3
HDPE	0.8	Telephone books	2.7
PET	1.4	Dimensional lumber	0.21
Corrugated cardboard	5.0	Mixed Plastics[b]	1.2

[a] Units are in $MTCO_2E$/ton of material.
[b] The mixed plastics average assumes a mix of 71% PET and 29% HDPE.

A qualitative uncertainty analysis performed for each of the above variables shows that the RERFs used in this method are in an appropriate range (with respect to the sensitivities of each variable) for each material. A literature review indicates each RERF is comparable to other emission factors in existing studies.

1. BACKGROUND

The benefits of recycling are multifaceted and range from the reduction of metal pollutants in leachate[1] to the reduction of greenhouse gas emissions[2-6]. In the past decade, many studies have discussed assigning specific materials greenhouse gas (GHG) emission reduction factors associated with recycling.[4,5,7,8] The GHG emission reduction factors are designed to encourage recycling from a climate change perspective and are typically based on relative emission reduction benefits. In the United States Environmental Protection Agency (USEPA) Waste Reduction Model (WARM), emission benefits of recycling, composting, or combusting wastes are calculated relative to landfilling.[4] Also, USEPA acknowledges that WARM is a planning tool and should not be used to quantify for greenhouse gas emission reductions in an accounting scheme (such as a GHG inventory).[4]

Greenhouse gas benefits from recycling are determined by using a life cycle approach that compares virgin material manufacturing with recycled material manufacturing.[9,10] For inorganic materials (i.e., aluminum, glass, steel, plastics), the manufacturing stage is limited to emissions associated with obtaining raw materials and raw material processing at the manufacturing location.[4,11] The manufacturing inputs for wood-based organic materials (i.e., office paper and newspaper) are similar to inorganic materials, but include a factor to account for forest carbon sequestration.[4] Forest carbon sequestration benefits from recycling result from the avoided emissions associated with tree harvesting and from the additional carbon storage in a tree that would have been harvested in the absence of recycling.[12-15] Forest carbon sequestration is difficult to quantify, leading most analyses to only qualitatively assess the benefit as greater than zero.[14,16] One study, conducted by the USEPA, quantifies the forest carbon sequestration benefit based upon the avoided emissions from mechanical or chemical pulp processing.[4] The results from WARM for forest carbon sequestration employ a stock change approach and are applicable to national-level planning goals for recycling.[4] The greenhouse gas inventory for forests in California uses an atmospheric flow model, which contrasts with the national model.[17]

The purpose of this method is to generate recycling emission reduction factors (RERFs) that are consistent with GHG accounting practices used in California. The RERFs calculated from this method are not intended to replace existing studies. This method estimates RERFs for the following materials: aluminum cans, steel cans, glass, high density polyethylene (HDPE), polyethylene terephthalate (PET), corrugated cardboard, magazines/3rd class mail, newspaper, office paper, phonebooks, dimensional lumber and mixed plastics (mix of HDPE and PET). The emission reduction factors are calculated from the best available data sources and include quantification methods for the process and transportation emissions associated with manufacturing, a forest carbon sequestration factor, transportation emissions associated with moving the recovered material to its point of remanufacture, and a recycling efficiency term. Lastly, a comparison to literature-based studies and a sensitivity analysis will be completed to validate this method in the context of existing work.

2. METHODS

The methods used to determine the RERFs for each material are described in the following section. The boundary,[18] or life cycle stages used to quantify each RERF, for this method defines the emission benefits of recycling, including manufacturing emissions and forest carbon sequestration. In addition, the transportation emissions associated with moving the recycled material to its point of remanufacturing will be considered as well as the recycling efficiency.

2.1 Process and transportation emissions

Life cycle greenhouse gas emissions associated with a manufactured material may be calculated as follows:

$$LCA = MS + US + EOLS \qquad (1)$$

where,

LCA	=	Life cycle greenhouse gas emissions of the material.
MS	=	Emissions associated with the manufacturing stage of the material
US	=	Emissions associated with the use stage of the material
EOLS	=	Emissions associated with the end of life stage of a material

The manufacturing stage includes the emissions associated with the generation of a particular material. This includes emissions from the mining, extraction, processing and transportation of the material inputs. The use stage accounts for the energy required to use the material or transform it into usable product. The end-of-life-stage includes material disposal. End-of-life options include landfilling, recycling, composting, or combusting the material.

When evaluating the life cycle emissions reductions due to recycling, the following equation applies:

$$LCA_{total} = (MS_{virgin} + US_{virgin} + EOLS_{virgin}) - (MS_{recycled} + US_{recycled} + EOLS_{recycled}) \qquad (2)$$

Assuming $US_{virgin} = US_{recycled}$ and $EOLS_{virgin} = EOLS_{recycled}$, then

$$LCA_{total} = MS_{virgin} - MS_{recycled} \qquad (3)$$

where,

LCA_{total}	=	Total life cycle emissions associated with recycling
MS_{virgin}	=	Emissions associated with using 100% virgin inputs for manufacturing the material

US_{virgin}	=	Emissions associated with the use stage of the virgin material
$EOLS_{virgin}$	=	Emissions associated with the end of life stage of the virgin material
$MS_{recycled}$	=	Emissions associated with using 100% recycled inputs for manufacturing the material
$US_{recycled}$	=	Emissions associated with the use stage of the recycled material
$EOLS_{recylced}$	=	Emissions associated with the end of life stage of the recycled material

The manufacturing datasets for each material were obtained from three main sources in Table 1.

Table 1. Material references for upstream process and transportation emissions.

Material	**Reference**
Aluminum	USEPA (1998)[a], USEPA (2003)[b]
Steel	USEPA (1998)
Glass	USEPA (2003)
HDPE	USEPA (1998), USEPA (2003)
PET	USEPA (1998), USEPA (2003)
Corrugated cardboard	USEPA (1998), USEPA (2003)
Magazines/3rd class mail	USEPA (2003)
Newspaper	USEPA (1998), USEPA (2003)
Office Paper	USEPA (1998), USEPA (2003)
Phonebooks	USEPA (1998), USEPA (2003)

[a] Ref. 10; [b] Ref. 9.

Datasets consisted of process emissions (emissions associated with manufacturing a material) and transportation emissions (emissions associated with transporting the raw inputs to the production site) for the manufacture of a particular material in a closed loop system. A closed loop system implies that recycled products are used to make a similar product (i.e., recycled aluminum cans are used to make more aluminum cans or office paper is used to make more office paper).[19] More detailed calculations for the raw data used to obtain the process and transportation emissions is shown in the Supplemental Spreadsheet. In two cases, the manufacturing process inputs included a recycled material component; virgin steel includes 20% recycled material and virgin cardboard contains 10% recycled material.[10]

With respect to electricity used in manufacturing, a national electricity emission factor was used because the manufacturing stage of each material does not necessarily take place in California.[20,21] Emission factors for various fuel types were obtained from the ARB's Local Government Operations Protocol[22] as a primary option and other sources as a secondary choice.[23,24] For all upstream process and transportation emissions, emissions for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) were calculated, multiplied by their global warming potentials (1 for CO_2, 21 for CH_4 and 310 for N_2O) and summed together in units of carbon dioxide equivalents(CO_2E; see Supplemental Spreadsheet).

Emissions associated with precombustion[25] (i.e., emissions associated with mining the fuels used in the manufacturing stage) were included in this method. Precombustion emissions were omitted for steel due to lack of data for this material. The precombustion emissions come from a single source.[9] The reported process and transportation emissions are an average of the two datasets (when applicable).[9,10]

2.2 Recycling Efficiency Factor

Studies have shown that recycled material is not fully recovered at a recycling facility nor is the recycled material used in a 100% capacity at the remanufacturing facility.[4] In order to account for these collection and use inefficiencies, a material-specific recycling efficiency factor will be applied to the RERF. The recycling efficiency factor is based on a previous study completed by the USEPA (Table 2).[4]

Table 2. Recycling efficiencies of each material.

Material	Recycling recovery efficiency (%) (a)	Recycling remanufacture efficiency (b)	Recycling efficiency (a x b)
Aluminum	100	0.93	0.93
Steel	100	0.98	0.98
Glass	90	0.98	0.88
HDPE	90	0.86	0.77
PET	90	0.86	0.77
Corrugated cardboard	100	0.93	0.93
Magazines/3rd class mail	95	0.71	0.67
Newspaper	95	0.94	0.89
Office Paper	91	0.66	0.60
Phonebooks	95	0.71	0.67

2.3 Transportation Correction Factor

The transportation emissions associated with moving the recycled material to its remanufacturing stage affects the overall RERF. In order to account for this, a correction factor will be applied to the RERF. Studies conducted by the California Department of Conservation,[26] the California Integrated Waste Management Board,[27] and the American Forest and Paper Association[28] produced data used to determine the final destination of the recycled material (Table 3).

Table 3. Remanufacturing distribution of recycled materials in California.

Material	Remanufacturing Destination
Aluminum[a]	99% Southeast, 1% Mexico, Europe, Brazil
Steel[b]	90% Pacific Rim, 10% California
Glass[a]	85 % California, 15% in Mexico, Texas, Colorado, Washington, Oklahoma
HDPE[a]	46 % California, 36 % in China, 18 % Southeast
PET[a]	77% China, 10 % Southeast, 14% California
Corrugated cardboard[c]	36% China, 64% United States mix
Magazines/3rd class mail[c]	36% China, 64% United States mix
Newspaper[c]	36% China, 64% United States mix
Office paper[c]	36% China, 64% United States mix
Phonebooks[c]	36% China, 64% United States mix

[a] Ref. 26. The data from this source is based on recycled beverage containers.
[b] Ref. 27.
[c] Ref. 28. The American Forest and Paper Association does not disaggregate to the state level. For more information, please see: http://paperrecycles.org/stat_pages/recovered_paper_goes.html.

The transportation miles were based on transportation scenarios within California, within North America, and overseas transport (Table 4). The transportation assumptions were based on average distances to each location and was sensitive to non-ocean going vessel transport at the destination site. For example, travel assumption 4 (International: Asia) assumes an average of 60 miles of truck and 300 miles of rail travel in California and 140 miles of truck and 700 miles of rail travel in its destination country. Transport emission factors were applied uniformly to all legs of the trip.

Using the appropriate fuel emission factors, greenhouse gas emissions from transportation were calculated for each transportation type: truck (101 g CO_2/net ton-mile), rail (22 g CO_2/net ton-mile) and ocean going vessel (19 g CO_2/net ton-mile).[29] The truck value is based on a California instate tractor trailer emission factor. Other types of trucks (e.g., drayage trucks or trucks that travel in multi-states) have varying emission factors, but only change the overall emission factor by ~1%.[30] The rail emission factor is based on fuel consumption rates provided by the Association of American Railroads[31] and a diesel emission factor from the Local Government Operations Protocol[22]. The ocean going vessel emission factor was generated from the ARB Marine Model, Version 2.3.[32] For information about the results the Marine Model produces, please see the Emissions Estimation Methodology for Ocean Going Vessels.[33]

Table 4. Transportation assumptions for recycled materials in California.

Destination	Truck miles	Rail miles	Ocean going vessel miles*	Justification
1.California	60	300	0	The majority of recycled materials in California are transported out of state by rail or ocean-going vessel. The major ports in California are located near population centers. On average, the trips in the population centers will have lower truck and rail miles, while transporting recycled goods to their remanufacturing location within in California may have higher truck and rail miles.
2. United States (Southeast)	200	2300	0	Most aluminum smelters that accept aluminum recycled in California are located in the Southeast. The Southeast destination assumes a trip that leaves California and arrives in Alabama as an average trip to the Southeast
3. United States (average)	200	1600	0	The trip mileage in this scenario assumes the average trip ends up in the Midwest.
4. International (Asia)	200	1000	7000	The trip mileage in this scenario accounts for the truck and rail miles associated with getting the recycled material to a port. The destination of the recycled goods is Mainland China and truck and rail mileage is included for transporting the goods in China.
5. International (other)	200	2000	4000	This mileage scenario assumes an average destination between Europe and South America (Brazil). It includes truck and rail transportation in California and the destination country.

*Ocean going vessel miles are based on nautical miles.

2.4 Forest Carbon Sequestration

A chemical composition approach was taken to assign a forest carbon sequestration factor to each wood-based organic material (corrugated cardboard, magazines/3rd class mail, newspaper, office paper, phonebooks, and dimensional lumber). On average, a tree contains about 50 percent carbon on a dry weight basis, with the rest of the elemental composition mainly hydrogen, oxygen, nitrogen, and other trace elements.[34] Additionally, information is available on the amount of harvested wood (not including bark, leaves, small stems, etc.) it takes to make a specific unit of material.[35,36] Table 5 shows the amount of virgin wood required to produce a ton of given paper product.

Table 5. Amount of virgin wood needed to produce one ton of each wood-based organic material.

Product	Amount of wood needed (lbs/ton)
Corrugated cardboard[a]	6,060
Newspaper[a]	4,180
Office Paper[a]	6,940
Magazines/3rd class mail[a,b]	6,940
Phonebooks[a,c]	4,180

[a] Ref. 36.
[b] Amount of wood needed for magazines is the same for office paper due to similar processing methods.
[c] Amount of wood needed for phonebooks is the same for newspaper due to similar processing methods.

When a tree is harvested from a forest, the carbon sequestration potential of the harvested tree is no longer available because it has stopped growing. Recycling a wood-based organic material alleviates the need to harvest trees because recycled wood products are substituted for virgin material. For this reason, the carbon sequestered by a tree due to recycling can be considered to be the growth of a non-harvested tree after the expected year of harvest.

$$\text{FCS} = \text{Carbon sequestered in tree } (\text{MTCO}_2\text{E}) = \sum_{h}^{99} (V_{h+1} - V_h) * d_t * 0.5 * 0.00016636 \quad (4)$$

where:

h	=	year the tree is harvested
V_h	=	volume of the tree in the h^{th} year (ft^3)
V_{h+1}	=	volume of the tree in the $(h+1)^{th}$ year (ft^3)
d_t	=	density of the tree, dry weight basis (lb/ft^3)
0.5	=	factor converting total mass of tree to carbon content
0.00016636	=	factor converting total carbon content to $MTCO_2E$ (includes factor for tree survival rate)[37]

The above equation (4) was used to calculate a forest carbon sequestration for each wood-based organic material.

The Forest Carbon Sequestration (FCS) model represents an average, or "theoretical" tree used in the production of wood products. The theoretical tree consists only of the trunk. The leaves, bark, stems, branches and roots were not considered in this model. The theoretical tree was based upon empirical loblolly pine (*Pinus taeda*) data that consisted of a Site Index of 80 (i.e., average tree height after 50 years is 80 feet for a given stand) for a natural pine plantation that lives 100 years[38,39]. The loblolly pine was chosen because it has a wide range in the Southeastern United States, is the most commercially viable species in this region, and is commonly used for pulp production and dimensional lumber[40,41]. The height of the tree as a function of time was constructed from two different sources and the diameter at breast height (dbh) was calculated using a tree growth rate table.[39,42] It was assumed that the tree had a dendrochronology of approximately 5 incremental growths per inch in its early life phases, which slowed to around 7 as the tree approached 100 years in age.[42] The volume of the tree was calculated by using a bole approach.[43] For this method, the middle portion (above the dbh and below the top section) of the tree was divided into tapered regions (up to 9, depending on height) and the top of the tree was modeled as a cone, while below the dbh was assumed a cylinder.

Once the volume was calculated, the increased growth was calculated by determining the volume increase on a yearly basis (e.g. volume in year 26 minus volume in year 25). The harvest year (h, equation 4) was year 25. The weight of the tree was determined by multiplying the volume by the density. The weight was divided by a factor of 2 to account for carbon content and then converted to units of $MTCO_2E$/tree (Equation 4). Lastly, the tree carbon sequestration value (Equation 4) was then divided by 10 to account for the mortality rate of the tree.[45-47]

2.5 Final recycling emission reduction factor (RERF)

The above four sections describe each variable under consideration for determining the RERF. The emission reductions from recycling occur during the manufacturing stage and the with forest carbon sequestration. The emissions occur during the transportation of the recovered material to its remanufacturing emissions. The sum of these above terms is then corrected by the recycling efficiency term. The final RERF value was obtained using the following equation:

$$RERF = ((MS_{virgin} - MS_{recycled}) + FCS - T_{remanufacture}) * R_{use} \qquad (5)$$

where,

RERF	=	Recycling emission reduction factor ($MTCO_2E$/ton of material)
MS_{virgin}	=	Emissions associated with using 100% virgin inputs for manufacturing the material ($MTCO_2E$/ton of material)
$MS_{recycled}$	=	Emissions associated with using 100% recycled inputs for manufacturing the material ($MTCO_2E$/ton of material)
FCS	=	Forest carbon sequestration ($MTCO_2E$/ton of material)
$T_{remanufacture}$	=	Transportation emissions associated with remanufature destination ($MTCO_2E$/ton of material)
R_{use}	=	Recycling efficiency (fraction of material remanufactured from ton of recycled material)

2.6 Emission reduction factor for dimensional lumber

Recycled dimensional lumber (e.g. 4x4, 2x4, 1x8 etc.) does not exhibit closed loop recycling in California. Instead, recycled lumber is chipped and used for biomass combustion. The recycling emission reduction factor for dimensional lumber was determined using the following equation:

$$RERF_{DL} = DL_b - DL_e \qquad (6)$$

where (all units in $MTCO_2E$/ton of lumber)

$RERF_{DL}$	= recycling emission reduction factor for dimensional lumber
DL_b	= avoided emissions associated with recycling dimensional lumber
DL_e	= emissions associated with processing recycled dimensional lumber

Recycling dimensional lumber increases biomass use for electricity generation, which alleviates the need to use fossil-fuel based energy sources. This was simulated by applying a California grid average electricity emission factor as the avoided emissions from using biomass.[22] It was also assumed that 1 dry ton of wood chips is equivalent to 2 green tons of lumber and 1 dry ton of wood chips is able to generate 1 MWh of electricity.[48] This value is conservative due to the drying steps lumber goes through during processing. Emissions from the biomass burning were not included in this calculation. The carbon dioxide emissions from biomass burning are considered biogenic and the methane and nitrous oxide emissions are small (0.006 $MTCO_2E$/MWh) when compared to the overall RERF. The emissions from processing recycling dimensional lumber into wood chip biomass were determined by evaluating the chipping rate from a standard chipper (3.3 dry tons/hour) and emissions (19.8 kg CO_2/hr).[49,50]

3. RESULTS AND DISCUSSION

The results of this method and a discussion that evaluates the validity of the recycling emission reduction factors (RERFs) are presented below. The first five sections focus on the inputs used to determine each RERF. The last sections present a qualitative uncertainty analysis of the method and a comparison of the results with the literature for each material.

3.1 Process and Transportation Emissions

This section evaluates the process and transportation emissions included in the RERF calculations. As described in the methods section, the boundaries for these emissions are restricted to the manufacturing stage of the life cycle. The emissions include all emissions associated with the production of a particular material.

The process and transportation emissions (including precombustion) for each material are shown in Tables 6, 7 and 8. An average of two studies[9,10] was used when available. In some cases, the raw transportation data were not included in the study. In these instances, the overall emission factor included only process emissions or the transportation data from USEPA (1998)[10] were used as a proxy for omitted USEPA (2003)[9] transportation data. Even though the transportation emission data set was not complete for all materials, the contribution of transportation emissions to the overall upstream emission value was generally small.

Table 6. Manufacturing stage emissions for each material.[a]

	Production Using Virgin Material Inputs						
	Process Emissions			Transportation Emissions			
Material	USEPA (1998)[b]	USEPA (2003)[c]	Average[d]	USEPA (1998)[b]	USEPA (2003)[c]	Average[d]	Total Emissions
Aluminum	13.3	14.1	13.7	0.3	0.5	0.4	14.1
Steel	2.0		2.0	0.1		0.1	2.1
Glass		0.34	0.34		0.04	0.04	0.38
HDPE	1.3	1.4	1.35	0.1	N/A[e]	0.1	1.4
PET	2.1	1.4	1.75	0.2	N/A[e]	0.2	2.0
Corrugated cardboard	2.3	2.2	2.25	0.1	0.1	0.1	2.4
Magazines/3rd class mail		2.3	2.3		N/A	N/A[f]	2.3
newspaper	2.0	2.4	2.2	0.1	0.03	0.07	2.3
office paper	4.4	3.1	3.75	0.2		0.2	3.9
phonebooks		2.6	2.6		N/A	N/A[f]	2.6
Production Using Recycled Material Inputs							
Aluminum	0.36	0.86	0.61	0.003	0.002	0.0025	0.6
Steel	0.35		0.35	0.08		0.08	0.4
Glass		0.21	0.21		0.02	0.02	0.23
HDPE	0.4	0.14	0.27	0.1	N/A[e]	0.1	0.37
PET	0.4	0.14	0.27	0.1	N/A[e]	0.1	0.37
Corrugated cardboard	1.1	0.9	1.0	0.1	0.1	0.1	1.1
Magazines/3rd class mail		2.2	2.2		N/A	N/A[f]	2.2
newspaper	1.3	1.2	1.25	0.05	0.002	0.026	1.3
office paper	1.6	1.3	1.45	0.1	0.06	0.08	1.5
phonebooks		1.4	1.4		N/A	N/A[f]	1.4

[a] All units are in $MTCO_2E$/ton of material.
b Ref. 10.
[c] Ref. 9.
[d] For steel cans, glass, magazines/3rd class mail, and phonebooks the average consists of only one value. Even though an n=1 does not constitute an average, this value was placed in this column for consistency purposes.
[e] The transportation data for HDPE and PET were not included in Reference 9. For this reason, the process emissions were averaged but only one transportation value was used.
[f] The transportation data was not included in Reference 9. It is assumed for magazines/3rd class mail and phonebooks that the transportation factor contributes negligibly to the overall emission reduction factor.

Table 7. Precombustion emissions for the manufacturing stage of each material.[a,b]

Material	Primary Production (virgin material)	Secondary Production (recycled material)
Aluminum	0.53	0.07
Steel[c]	N/A[d]	N/A[d]
Glass	0.12	0.03
HDPE	0.21	0.06
PET	0.43	0.06
Corrugated cardboard	0.03	0.03
Magazines/3rd class mail	0.07	0.07
Newspaper	0.16	0.09
Office Paper	0.04	0.06
Telephone books	0.11	0.06

[a] Units are in $MTCO_2E$/ton of material.
[b] The precombustion emissions were generated from Ref. 9.
[c] Precombustion emissions for steel was not included in Ref. 9.
[d] N/A = not available.

Table 8. Summary of the manufacturing emission reductions (sum of process and precombustion) for each material.[a,b]

Material	Primary production (virgin material) (a)	Secondary production (recycled material) (b)	Total manufacturing emission reductions (a-b)	Percent Reduction (%) ((a-b)/a)
Aluminum	14.6	0.7	14.0	95.9
Steel[c]	2.1	0.4	1.7	81.0
Glass	0.5	0.26	0.2	40.0
HDPE	1.6	0.43	1.1	68.8
PET	2.4	0.43	2.0	83.3
Corrugated cardboard	2.4	1.1	1.3	55.3
Magazines/3rd class mail	2.4	2.3	0.1	4.2
Newspaper	2.5	1.4	1.0	40.0
Office Paper	3.9	1.6	2.4	61.5
Telephone books	2.7	1.5	1.2	44.4

[a] Units are in $MTCO_2E$/ton of material, unless noted.
[b] The reported numbers from (a) and (b) may not sum together due to rounding.
[c] Steel does not have emissions from precombustion included.

The final emission reduction values vary for each material. The material with the highest reductions associated with recycling instead of using virgin material is aluminum (14.0 $MTCO_2E$/ton) while the lowest is magazines/3rd class mail (0.1 $MTCO_2E$/ton). The reason for the large discrepancies in each material type is due to the varied production mechanisms that occur. Aluminum refining requires a large electricity input while the production of glass (0.2 $MTCO_2E$/ton) does not require such an intensive use of electricity.

3.2 Transportation Correction Factor

Using the assumptions for recycled product distribution (Table 3) and miles travelled to reach that destination (Table 4), the overall transportation emissions associated with each material is shown in Table 9. This value specifically addresses the transportation associated with moving the recycled material from the location it was recovered to its remanufacturing destination. In many cases, this information may also be included in the transportation emissions that are included in the 100% recycled data (Table 6). However, the recycling transportation data listed in Table 6 does not disaggregate the transportation emissions from moving the recycled material from the total transportation emissions needed to remanufacture the recycled material.[10] For this reason, the $T_{remanufacture}$ term is included in the method, with the assumption that the recycling transportation term in the manufacturing stage (Table 6) may overlap with this term. This assumption leads to a more conservative RERF (by about 3%, on average).

Table 9. Destination assumptions used and $T_{remanufacture}$ for each material.

Material	Assumptions[a]	Emissions[b,c]
aluminum	2, 5	0.07
steel	1, 4	0.16
glass	1, 3	0.02
HDPE	1,2, 4	0.08
PET	1, 2, 4	0.14
corrugated cardboard	3, 4	0.10
magazines/3rd class mail	3, 4	0.10
newspaper	3, 4	0.10
office paper	3, 4	0.10
phonebooks	3, 4	0.10

[a] The assumption number corresponds to the mileage assumptions in Table 4 and are based upon the data accumulated in Table 3.
[b] The emission factors associated with the forms of transportation are: trucks - 101 g CO_2/net ton-mile, rail – 22 g CO_2/net ton-mile, and ocean going vessels – 19 g CO_2/net ton-mile (See Methods section for a list of references). The total transportation emission value was generated by multiplying the proportion of materials transported to each destination (i.e., California, etc.) by the amount of miles associated with each trip leg.
[c] Unit are in $MTCO_2E$/ton of material.

The destination values used for aluminum are based on a qualitative description because an exact number was not available.[26,51] Additionally, the value used for wood-based organic materials is a United States average number.[28] Due to the small magnitude of the emissions from $T_{remanufacture}$, the majority of the RERF value will be determined by the manufacturing emission savings and forest carbon sequestration (for wood-based organic materials only).

3.3 Forest Carbon Sequestration

The theoretical tree model was designed to compute the forest carbon sequestration potential for recycling each type of wood-based organic material. The model only includes the marketable component of the tree (i.e., trunk) and does not include any leaves, stems, roots or branches in the calculations. While carbon storage does occur in other parts of the tree besides the trunk,[52] a conservative approach is used in this study. The trunk of the tree was modeled based on *P. taeda* (loblolly pine) and the trunk dbh (Figure 1) and height (Figure 2) as a function of age were generated from previous studies.[38,39]

The dbh was determined from a study that showed an average loblolly pine dbh is 5.9 inches at a height of 35 feet and 11 inches at 66 feet.[38] This experimental information was combined with tree growth charts that estimated growth from the number of tree rings in the outer inch of the trunk.[39,42] To match the height curve, it was estimated that the growth in the diameter at breast height (dbh) was 3% from year 41-60, 2.2% from year 61-70, 1.2% from year 71-85 and 0.5% from year 85-100 (about 7 rings in the outer inch of the trunk). The height curve was consistent with a study completed by the Cooperative Extension Service at the University of Georgia.[39]

Figure 1. Graph showing the dbh of a tree as a function of age.

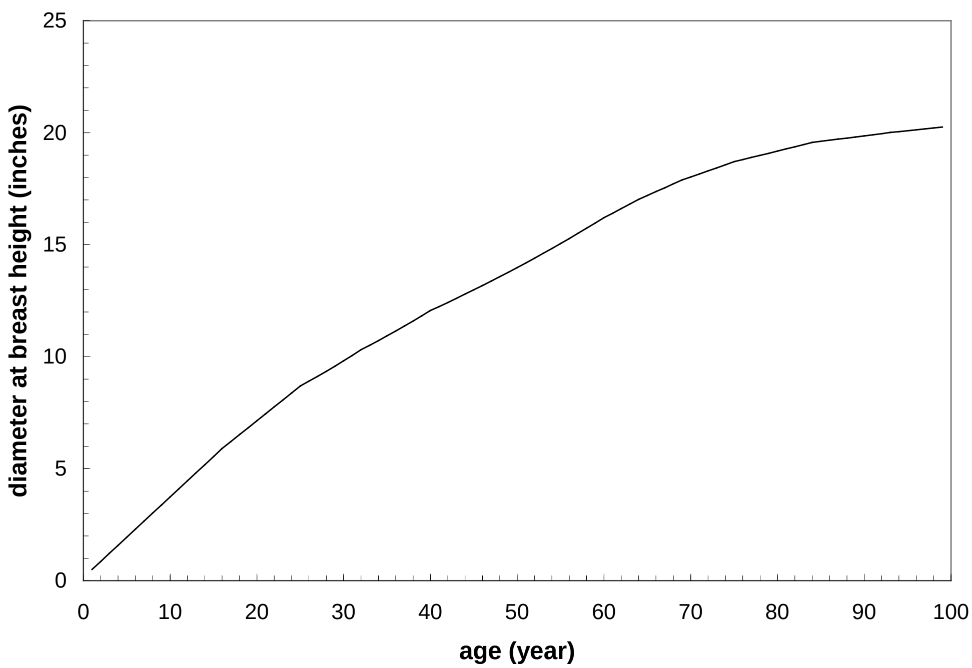
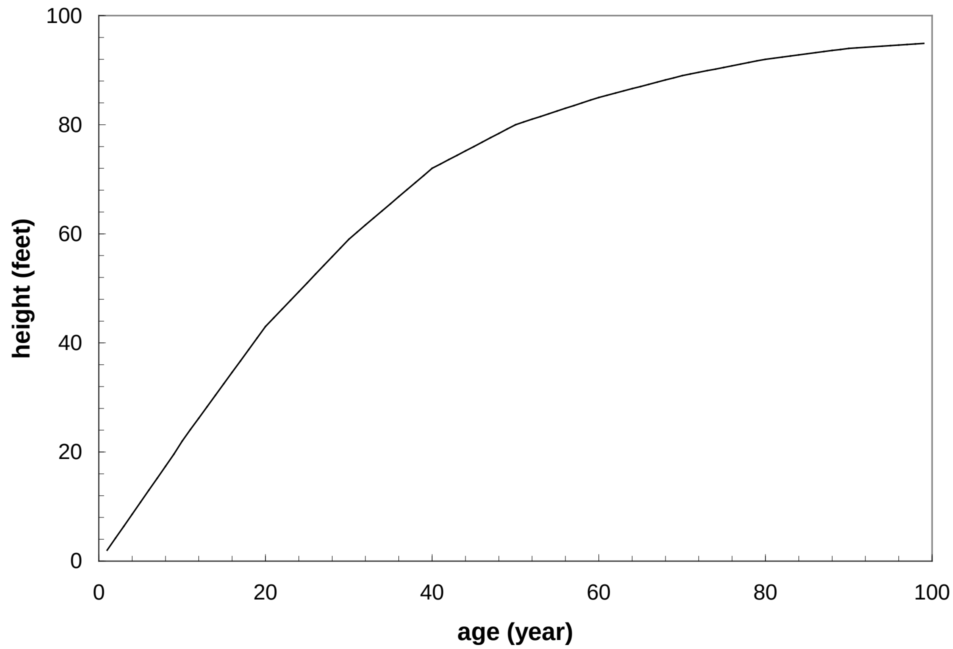
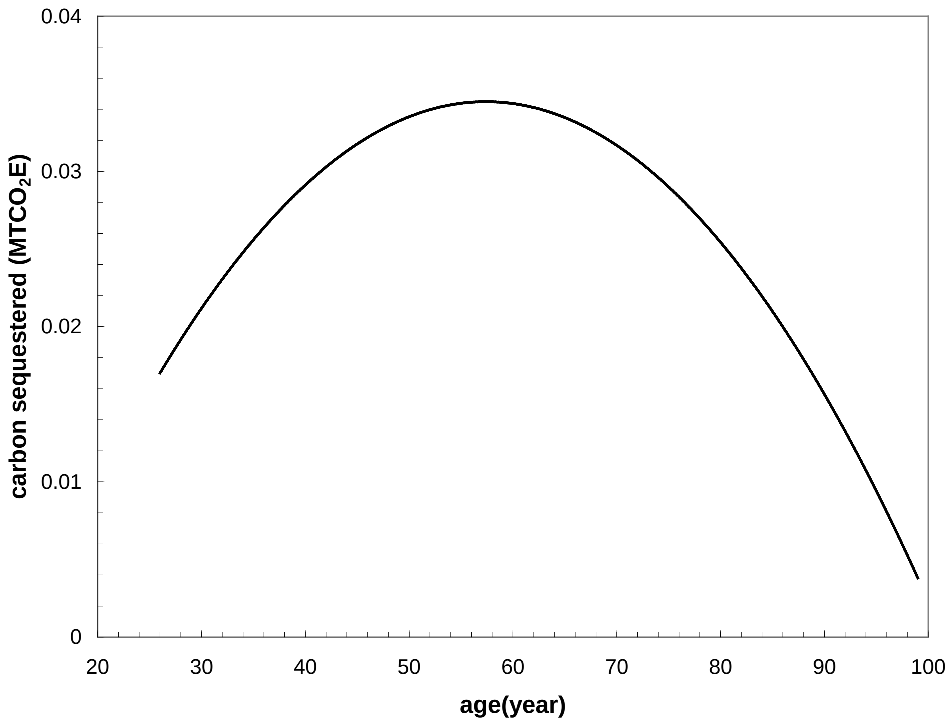


Figure 2. Graph showing the height of a tree as a function of age.



The incremental carbon storage per year (years 26-100) is shown in Figure 3. The growth curve is consistent with the slope of the curves for height and dbh (Figures 1 and 2). The sum of the incremental carbon storage from years 26-100 was 1.90 $MTCO_2E$/tree. Assuming an exponential death/harvest rate,[47] coupled with two experimental data points,[38] only 10% of the original trees survived to year 100. Because of this survival rate, the amount of carbon stored per tree was divided by ten to account for trees standing at 100 years. Therefore, the carbon storage value on a per tree basis is 0.19 $MTCO_2E$/tree.

Figure 3. Graph indicating the amount of incremental carbon stored ($MTCO_2E$/year) over the lifetime of a tree that was not harvested at year 25 due to recycling. The value at each year increment was generated using the theoretical tree model. The area under the curve was summed and divided by 10 to determine the overall amount of carbon sequestered in a single tree to year 100.



At year 25, the theoretical tree is harvested with a weight of 274 lbs. By year 100, the tree has attained a weight of 2594 lbs that equates to a volume of 2.5 m^3, assuming a density of 29.33 lb/ft^3.[44] Utilizing the data from Table 5 and the weight of tree at harvest, an average number of trees/ton per material produced and a forest carbon sequestration factor were generated (Table 10).[35,36]

Table 10. Amount of trees used to produce one ton of wood-based organic material and the corresponding forest carbon sequestration.

Material	**Tree equivalents (trees/ton of material produced)[a]**	**Forest carbon sequestration factor ($MTCO_2E$/ton of material)[b]**
Corrugated cardboard	22.1	4.2
Magazines/3rd class mail[c]	2.5	0.5
Newspaper	15.3	2.9
Office paper	25.3	4.8
Phonebook paper	15.3	2.9

[a] The amount of wood used from Table 5 was divided by the weight of a tree (274 lbs.) generated from the theoretical tree model.
[b] This value was determined by multiplying the number of tree equivalents by 0.19 $MTCO_2E$/tree.
[c] Only 10% of recycled magazines are used in secondary production .[9] In order to compensate for this discrepancy, 90% of virgin wood use for magazine production subtracted from the full value.

The forest carbon sequestration values were compared to existing literature studies to evaluate the validity of the assumptions.[52,53] The first source, published by the United States Department of Agriculture –Forest Service (USDA-FS), indicates that the volume of a loblolly-shortleaf pine stand on forest land 90 years after clearcut harvest in the Southeast is 299.6 m^3/ha.[52] Assuming a value of 123.6 trees/ha (based on an original planting of 500 trees/acre) and a volume of 2.37 m^3/tree for the theoretical tree model, the volume of the stand is 292.9 m^3/ha. This shows that the theoretical tree model predicts forest volume within 2% of the USDA-FS estimates.[52] Additionally, a book published by Thompson (1992), references a calculation attributing 24 trees used per ton of office paper produced, a value consistent with the theoretical tree model results presented in Table 10.[54]

3.4 Dimensional lumber

The recycling emission reduction factor for dimensional lumber, as discussed in the methods section, is not recycled in a closed loop in California. Instead, the recycled lumber is converted into wood chips, dried and used for electricity generation via biomass combustion. The emissions and emission benefits are calculated as follows:

$$DL_e = 19.8 \text{ kg } CO_2\text{/hr} / (3.3 \text{ dry tons/hour} * 2 \text{ green tons/1 dry ton})$$
$$= 3 \text{ kg } CO_2E\text{/ton}$$

$$DL_b = (1 \text{ dry ton/2 green ton})*(1MWh/1 \text{ dry ton})*(418.9 \text{ kg } CO_2E/1 \text{ MWh})$$
$$= 209 \text{ kg } CO_2E\text{/ton}$$

$$RERF_{DL} = DL_b – DL_e = 209 \text{ kg } CO_2E\text{/ton} – 3 \text{ kg } CO_2E\text{/ton}$$
$$= 206 \text{ kg } CO_2E\text{/ton} = 0.21 \text{ } MTCO_2E\text{/ton}$$

3.5 Overall Results

The final RERF was determined using equation 5 (section 2.5). A summary of the inputs into the equations the final RERF values are shown in Table 11.

Table 11. Summary of recycling emission reduction factors (RERFs) for each material.

Material	Total Upstream Emission Reductions[a] (a)	Remanufacture Transportation Emissions[a] (b)	Forest Carbon Seq.[a] (c)	Recycling Efficiency (d)	RERF[a] (a-b+c) *d
Aluminum	14.0	0.07	0	0.93	**12.9**
Steel	1.7	0.16	0	0.98	**1.5**
Glass	0.2	0.02	0	0.88	**0.2**
HDPE	1.1	0.09	0	0.77	**0.8**

PET	2.0	0.15	0	0.77	**1.4**
Corrugated cardboard	1.3	0.10	4.2	0.93	**5.0**
Magazines/3rd class mail	0.1	0.10	0.5	0.67	**0.3**
Newspaper	1.0	0.10	2.9	0.89	**3.4**
Office paper	2.4	0.10	4.8	0.60	**4.3**
Telephone books	1.2	0.10	2.9	0.67	**2.7**
Dimensional lumber	N/A	N/A	N/A	N/A	**0.21**
Mixed Plastics[b]	1.7	0.13	0	0.77	**1.2**

[a] Units are in $MTCO_2E$/ton of material.
[b] The mixed plastics average assumes a mix of 71% PET and 29% HDPE.[27]

3.6 Uncertainty Analysis

The following section gives an overview of the uncertainty associated with each step of the RERF determination. This will not be a quantitative uncertainty assessment due to the nature of many of the data sources used in this study. The qualitative assessment will serve to illuminate particular uncertainties and explain their impact on the overall RERF.

3.6.1 Process and Transportation Emissions:

The two most prevalent sources of error within this section are the reliability of the material life-cycle data and the representativeness of the emission factors to accurately portray the process emissions. The material life-cycle data used in this study[9,10] is relatively old when compared to the timescale technological development. For example, in a related study,[57] the mass of a computer was assigned a value of 70 pounds. As technology has advanced in the past five years, the weight of computer has declined, which would lead to different assumptions about its manufacturing stage in a life-cycle calculation. While most materials in this study do not change technologies as quickly as a computer, the overall data used to generate the emissions from manufacturing may need updating. Because industrial technology usually does not increase the energy inputs, the overall emissions for the upstream energy component of the RERF would more than likely decrease. However, the magnitude of this decrease is not known.

The emission factors used in this study were specific to either California (i.e., goods movement) or the United States (i.e., electricity use). However, in many cases, steps in the material manufacturing process and transportation emissions take place in countries that may have different emission factors. Specifically, the electricity grid may vary from the United States average and the vehicle fleet used in another country may be different. Of these two factors, the electricity component will play a larger role in the energy emissions because transportation emissions are negligible in comparison to process emissions (Table 6). After evaluating the electricity needs for virgin and recycled production (Supplemental Spreadsheet) of each material, aluminum would be most impacted by a varying electricity emission factor. Assuming the cleanest fuel mix would be all renewable is not likely. Therefore, assume a natural gas source for electricity generation as the cleanest and a coal source as the dirtiest. According to WRI, a coal-fired plant in China (including Hong Kong) generates 910.5 kg CO_2/MWh and a gas fired plant in China emits 387.9 kg CO_2/MWh.[56] In this method, a value of 676 kg CO_2/MWh was used.[20] Applying the gas and coal-sourced electricity generation as a low and high bound, respectively, sets the aluminum electricity requirement between 6.3 and 14.8 $MTCO_2E$/ton of material. The value used in this study (10.6 $MTCO_2E$/ton of material) is the median of the high and low estimate. The other materials did not significantly vary in electricity use between virgin and recycled material production.

3.6.2 Transportation Correction Factor:

The errors associated with these calculations mainly occur due to the lack of understanding in the goods movement process at the international level and the uncertainties that surround the fleet efficiency. In general, a shipping crate is transported, first by truck and/or rail to a port where it is loaded onto a ship and transported to another port where the crate is unloaded and transported via truck and/or rail to its final destination.[57] Each of the five transportation assumptions used in this study take these steps into account (when applicable, Table 4).

An incomplete understanding of the distance travelled during the goods movement process may lead to an underestimation of the transportation emissions associated with each RERF. For example, in the current study, it is assumed that there is an average of 100 truck-miles travelled to get the recycled material to a rail station or port and an average of 100 truck-miles travelled to get the recycled material to its point of remanufacture. Assuming these values were closer to 500 miles in each direction would increase the overall transportation emissions 0.1 $MTCO_2E$/ton of material. This equates in some cases to a large contribution to emissions (e.g. glass, magazines), but in most cases (at an average of 2.0 $MTCO_2E$/ton) it equates to a 5% or less decrease in the overall RERF. Increasing the rail or ocean going vessels miles travelled by 1000 miles increases the overall transportation by 0.02 $MTCO_2E$/ton, which is a negligible amount.

Uncertainties in the fleet efficiency can lead to over or underestimation of the transportation emissions. An efficient, modern fleet can have low emissions, while an old fleet with inefficient energy consumption can have high emissions. A study compared California in-state tractors trucks to drayage vehicles near the ports and found that, on average, the drayage vehicles are slightly less efficient by 3 g CO_2/net ton-mile.[30] This uncertainty has a negligible effect on the overall transportation emission component of the RERF. Because the rail and ocean going vessel factors are much smaller, even doubling the emissions under the most extreme conditions increases the transportation emission factor by 2% (assuming an additional 2300 rail-miles) and 7 % (assuming an additional 7000 nautical-miles), respectively (Table 4).

3.6.3 Forest Carbon Sequestration:

The theoretical tree model has many sources of error that can change the overall forest carbon sequestration value. Possible errors include modifications to the growth rate, height, dbh, density and mortality rate. Changing either of these variables in the model would either increase or decrease the amount of carbon sequestered in the theoretical tree. However, because this model is based on a loblolly pine and the assumptions match macroscale approximations,[52] small changes in the above variables would not play a large role in the overall results.

The largest area of uncertainty lies in the choice of the loblolly pine. Although ubiquitous in the Southeast United States, it is not common in other parts of the country. Other pine and fir species are used to produce lumber and paper products. In order to evaluate the range of possible forest carbon sequestration values using other tree species, macroscale growth predications for pines and firs around the country were evaluated using Smith et al (2006).[52] For the comparison, the mean timber volume from Tables A7, A12, A17, A18 A19, A20, A22, A24, A27, A28, A30, A32, A33, A37, A38, A40, A41, and A47 were summed together at year 90 (year 100 was not available for all species) and averaged.[52] The average value between these 18 tables was 318 m^3/ha with a range between 1088 m^3/ha (Douglas Fir, Pacific Northwest, West) and 116 m^3/ha (Ponderosa Pine, Rocky Mountain, South). The difference between the average volume value from Smith et al and this method is 7.7%.[52] Applying the 7.7 % to the theoretical tree model-generated forest carbon sequestration value adds 0.015 $MTCO_2E$/tree onto the 0.19 $MTCO_2E$/tree factor. This would increase the overall forest carbon sequestration for different materials by a maximum of 0.38 $MTCO_2E$/ton of material (e.g. office paper with a value of 25.3 tree equivalents/ton (Table 10)). Additionally, for office paper, this results in a 5% change in the overall RERF (Table 11).

3.7 Comparison to existing studies

The following section evaluates the RERF of each material compared to other studies completed in the literature or by government agencies. Table 12 compares the RERF values generated in this study to the Waste Reduction Model (WARM)[4] developed by the United States Environmental Protection Agency and the Greenhouse Gases Calculator for Waste Management (GGCWM)[5] developed by Environment Canada. The WARM and GGCWM values listed in Table 12 are not relative to other waste alternatives (as described in the background section). Instead, the listed values in Table 12 reflect only the recycling component of each tool.

The section is designed to verify that the RERFs in this method are consistent with existing literature; in situations when this is not the case, the differences will be evaluated. The differences in RERFs may be due to electricity mix, industrial location, life-cycle boundaries, or other factors.

Table 12. Comparison of RERFs to other recycling studies[a]

Material	This method	WARM[b]	GGCWM[c]
Aluminum	12.9	13.67	8.75
Steel	1.5	1.8	1.07
Glass	0.2	0.28	0.09
HDPE	0.8	1.4	2.06
PET	1.4	1.55	3.29
Corrugated cardboard	5.0	3.11	2.96
Magazines/3rd class mail	0.3	3.07	2.90
Newspaper	3.4	2.8	2.49
Office Paper	4.3	2.85	2.90
Telephone books	2.7	2.66	2.97
Dimensional lumber	0.21	2.46	NA[d]
Mixed Plastics[e]	1.2	1.52	1.63

[a] All units are in $MTCO_2E$/ton of material
[b] WARM = Waste Reduction Model
[c] GGCWM = Greenhouse Gases Calculator for Waste Management
[d] The GGCWM did not report a value for dimensional lumber.[5]
[e] The mixed plastics average assumes a mix of 71% PET and 29% HDPE (Ref. 27).

3.7.1 Inorganic materials

The inorganic materials (e.g. aluminum, steel, etc.) are generally consistent with the WARM and GGCWM models, however, the wood-based organic materials vary in many cases (Table 12). For example, the magazines/3rd class mail category varies by an order of magnitude between this method and WARM.

3.7.1.1 Aluminum

The calculated process and transportations emissions for aluminum were 14.0 $MTCO_2E$/ton (Table 8) in this method and 13.67 $MTCO_2E$/ton in WARM (value after multiplying by the R_{use} variable)[4]. The overestimate of emissions in this method compared to WARM may be due to the nature of the emission factors employed in the study. The GGCWM model uses a Canadian electricity emission factor which is much lower than the United States electricity emission factor, which leads to a lower emission value.[5]

The RERF for aluminum was also compared to other aluminum studies. A recent paper by McMillan and Keoleian indicated that a global average emission factor for aluminum production in 2005 was 13.3 $MTCO_2E$/ton primary ingot, which is comparable to this method.[7] A study completed in China found that aluminum process emissions were 19.6 $MTCO_2E$/ton for China, which were about 70% higher than the global average of 11.5 $MTCO_2E$/ton (value is dependent on electricity mix).[58] Another study on the Indian aluminum industry indicated that their average emissions are on the order of 20.4 $MTCO_2E$/ton.[59]

3.7.1.2 Steel

The RERF for steel is consistent with the factors from WARM and GGCWM (Table 12). Small discrepancies in the overall values can be attributed to the emission factors used and the electricity mix used in this method. An evaluation of the steel-making capacity in Russia indicates that it requires about 3.4 $MTCO_2E$/ton of steel production.[60] While this value is higher than the RERF, the discrepancy may be due to higher emission factors for electricity use and different, less efficient steel-making mechanisms in Russia. A study by Gorgolewski (2006) indicates that 600 kg of coal/tonne is avoided by recycling steel (544 kg/ton).[61] Using an aggregate emission factor for coal,[22] this equates to an emission reduction of 1.1 $MTCO_2$/ton.[61]

3.7.1.3 Glass

The RERF generated in this method is consistent with WARM and GGCWM (Table 12). A paper that evaluated the energy inputs needed to make a 200 g glass jar indicated that it took about 73 g CO_2E/200 g glass jar. Assuming there are 4536 glass jars in a short ton, the total manufacturing emissions are 0.33 $MTCO_2E$/ton.[62] This is comparable to the results from this method for the emissions associated with producing a ton of glass from virgin materials (Table 8).

3.7.1.4 High Density Polyethylene (HDPE)

The RERF for HDPE is lower by about a factor of 2 when compared to the WARM and GGCWM studies, respectively (Table 12). This rather large discrepancy may have occurred due to the data source availability. The data used in this method for the energy process and transportation emissions for virgin production is consistent with a study completed by Franklin and Associates assigns a value of 1.34 $MTCO_2E$/ton of material to the emissions from virgin HDPE resin production (for comparison, see Table 8, 1.6 $MTCO_2E$/ton of material).[63] The results from this method are also consistent with a study completed by Boustead.[64] This study, funded by PlasticsEurope, indicated that the GHG emissions associated with producing one ton HDPE resin was 1.45 $MTCO_2E$.[64] Other studies by PlasticsEurope indicate the emissions for HDPE are higher as greater production is involved. For example, the production of HDPE bottles is 2.36 $MTCO_2E$/ton, indicating that the boundaries assumed in this method and WARM may vary.[4]

3.7.1.5 Polyethylene Terephthalate (PET)

The PET RERF is consistent with WARM, but underestimated by a factor 2 when compared to GGCWM (Table 12). The study from FAL (2007)[65] indicates that emissions for PET are 2.3 $MTCO_2E$/ton for virgin material production, which is consistent with this method (Table 8, 2.4 $MTCO_2E$/ton of material). The PlasticsEurope study uses an average of PET amorphous (2.54 $MTCO_2E$/ton) and PET bottle-grade (2.63 $MTCO_2E$/ton) resin to generate a total of 2.50 $MTCO_2E$/ton, which is slightly higher.[65,66] When compared to PET bottle production, the emissions are 3.72 $MTCO_2E$.[67]

3.7.2 Wood-based organic materials

Unlike the materials discussed above, the wood-based organic materials RERF include a forest carbon sequestration component. The forest carbon sequestration factor accounts for the incremental carbon sequestered in a tree that would not have occurred if the tree would have been harvested. The comparisons below reflect the existing literature for wood-based organic materials.

3.7.2.1 Corrugated cardboard

The RERF for corrugated cardboard is about 1.7 times higher in this method compared to WARM and GGCWM (Table 12). The discrepancy occurs in the manufacturing stage emissions (a difference of ~1.3 $MTCO_2E$/ton) and the forest carbon sequestration (a difference of ~1.2 $MTCO_2E$). According to WARM,[4] the manufacturing stage emissions for corrugated cardboard is ~ 0. This is in contrast to this method (Table 8) which calculates an emissions benefit of 1.3 $MTCO_2E$/ton. Additional information on this issue can be viewed in the Supplemental Spreadsheet. The manufacturing emissions from corrugated cardboard were also calculated by the Paper Task Force (2002).[36] In this study,[36] the manufacturing emissions were 1.4 $MTCO_2E$ (relative to recycling), which is consistent with this method.

WARM assigns a forest carbon sequestration value for corrugated cardboard of 3.0 $MTCO_2E$/ton.[4] While the WARM value is slightly different than this method (Table 12), the method used to calculate the forest carbon sequestration is markedly different. While this method employs a microscale, single tree approach, the USEPA(2006)[4] study uses a macroscale, stock change approach that is consistent with other methods utilized at the national level.[68]

3.7.2.2 Magazines/3rd Class Mail

The RERF for magazines/3rd class mail was only 0.3 $MTCO_2E$/ton in this method, compared to a much higher values in the WARM model (Table 12). The discrepancy in values is mainly due to the forest carbon sequestration factor. According to a manuscript by USEPA,[9] magazines only use 10% of recycled material in recycled magazine paper. The remaining 90% comes from primary groundwood fiber. For this reason, 90% of the weight of virgin wood (Table 5) for magazines/3rd class mail was subtracted out of the forest carbon sequestration factor. Because of the different methods used by WARM[4] in their determination of the forest carbon sequestration factor, this method has a much lower value for this product.

3.7.2.3 Newspaper

The newspaper RERF is slightly higher in this method compared to WARM and GGCWM (Table 12). The manufacturing emissions in the WARM model are 0.7 $MTCO_2E$[4] compared to 1.0 $MTCO_2E$ in this method (Table 8). Research from the Paper Task Force (2002)[36] indicates that the upstream energy emissions are 2.7 $MTCO_2E$/ton. Additionally, the forest carbon sequestration value is also higher in this method than WARM.[4] The tree equivalents used in this method are consistent with a calculation performed for *Recycled Papers: The Essential Guide*.[53]

3.7.2.4 Office Paper

The office paper RERF in this method is higher than WARM and GGCWM (Table 11). The forest carbon sequestration factor is consistent with WARM,[4] but the manufacturing emissions are much higher than WARM (2.4 $MTCO_2E$/ton in this method vs. -0.20 $MTCO_2E$/ton in WARM). The reason for this large discrepancy may be due to an added assumption that was not made in this study but assumed in WARM.[4]

Two previous studies have evaluated the upstream energy benefits of recycling office paper. The Paper Task Force[36] determined the upstream energy emissions from recycling to be 1.36 $MTCO_2E$/ton, which is an intermediate value between WARM and this method. Additionally, Counsell and Allwood[8] calculated a value of 4.4 $MTCO_2E$/ton. This value was determined by summing together the avoided emissions associated with forestry, pulping and landfilling. After completing this review, it is evident the upstream emission benefits from recycling office paper have a wide range. The results range from positive emissions to over 4 $MTCO_2E$/ton of benefits.

3.7.2.5 Telephone Books

The RERF value for this method is consistent with existing studies (Table 12). Both the upstream energy and forest carbon sequestration component are similar to WARM.[4]

3.7.2.6 Dimensional Lumber

The RERF value for this method is not similar to the WARM study (Table 12). The difference is due to the methods used to determine the value. In the WARM study, it was assumed that recycled dimensional lumber was remanufactured into more lumber while in this method, it is assumed that lumber is chipped and used at biomass facility.

4. SUMMARY

This method estimates recycling emission reduction factors for various recyclable materials. The recycling factors are based on the emission benefit of using recycled material over virgin inputs in the manufacturing stage, forest carbon sequestration, the transportation associated with moving the recycled material to the point of remanufacturing and the recycling efficiency. The data sources relied upon in the study are well-documented and the methods used are clearly defined. This method does not evaluate the associated avoided landfill methane (CH_4) benefits of recycling. Fugitive CH_4 emissions are accounted for separately as part of the California greenhouse gas inventory.[17]

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19. The closed loop approach utilizes the best data available for each material in this study. Open loop recycling, the recycling of one material to be remanufactured into another is also prevalent in recycling markets. However, sufficient data is not available to evaluate the materials in this study by an open loop process.
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