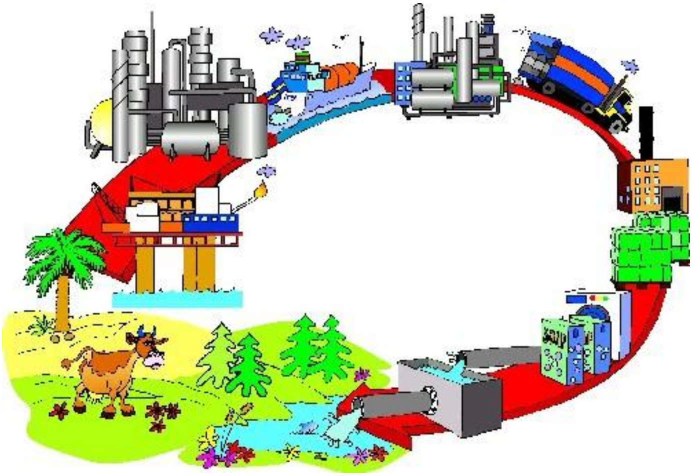
Environmental Life Cycle Assessment
PSE 476/WPS 576/WPS 595-005

Lecture 12: Global Warming and Carbon Footprinting

Richard Venditti



Fall 2012

Richard A. Venditti
Forest Biomaterials
North Carolina State University
Raleigh, NC 27695-8005

Richard_Venditti@ncsu.edu
Go.ncsu.edu/venditti

Introduction to Global Warming and Carbon Footprinting

Dr. Richard Venditti

Forest Biomaterials

North Carolina State University

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This Summary for Policymakers should be cited as:

IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Global Warming Changes

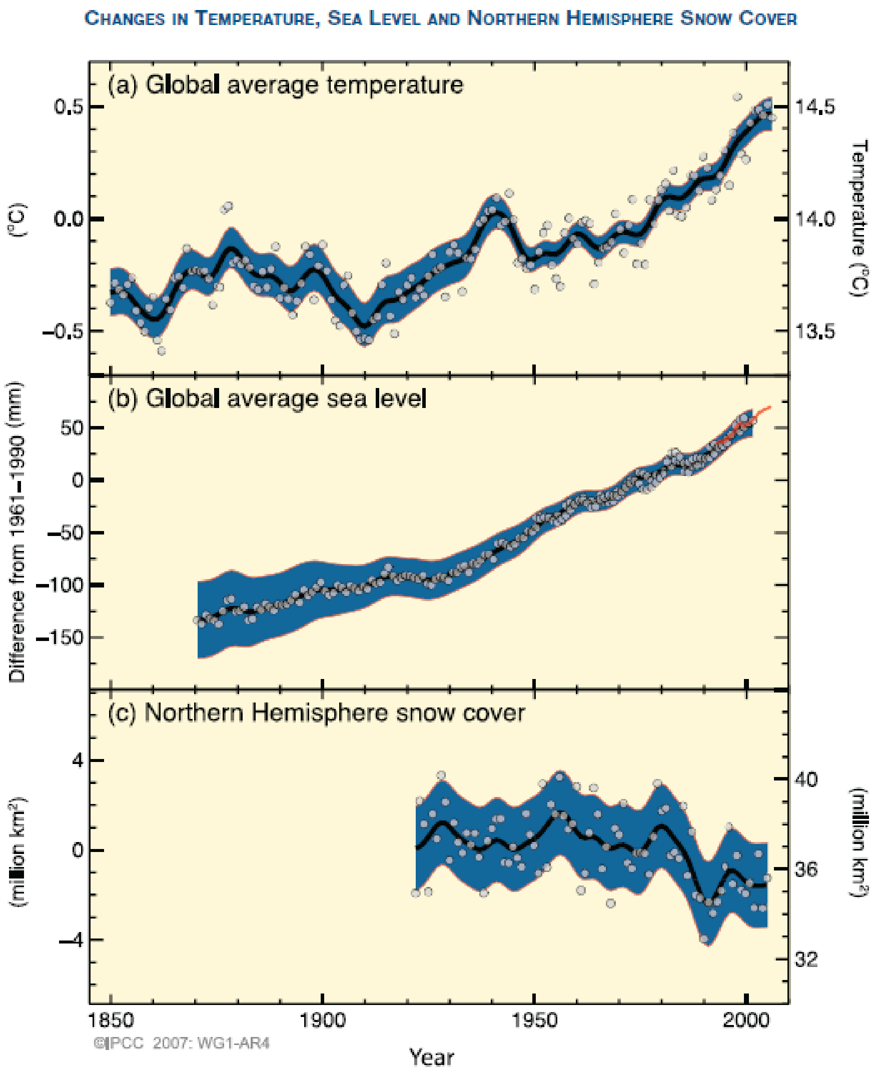
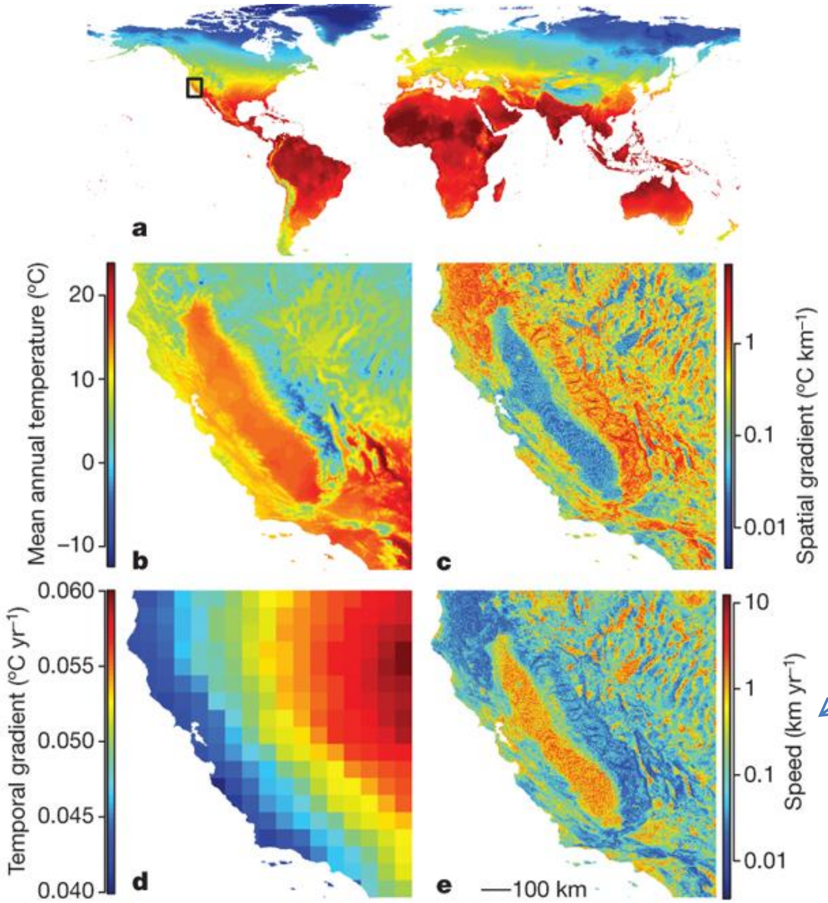


Figure SPM.3. *Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c). {FAQ 3.1, Figure 1, Figure 4.2, Figure 5.13}*

Global Carbon Cycle

- ***The velocity of climate change may have more impact than the absolute value of the changes***

Changing temperature in California.



Velocity of climate change

SR Loarie *et al.* *Nature* **462**, 1052-1055 (2009) doi:10.1038/nature08649

nature

Global Warming Predictions

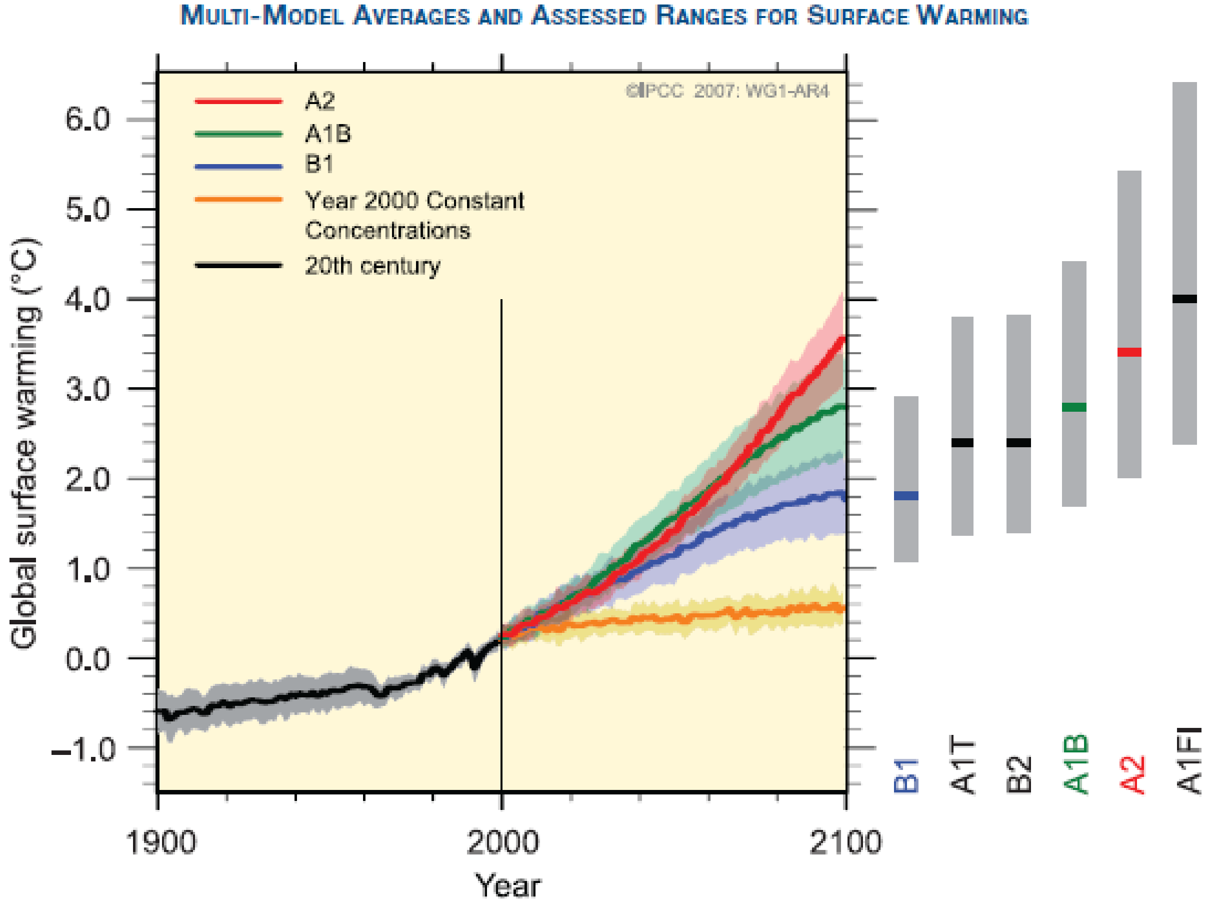


Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the* ***likely*** *range assessed for the six SRES marker scenarios. The assessment of the best estimate and* ***likely*** *ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. {Figures 10.4 and 10.29}*

Changes in GHGs

- **Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750**
- **Now far exceed pre-industrial values determined from ice cores spanning many thousands of years**
- **The global increases in**
  - **carbon dioxide concentration are due primarily to fossil fuel use and land use change,**
  - **Methane and nitrous oxide are primarily due to agriculture.**

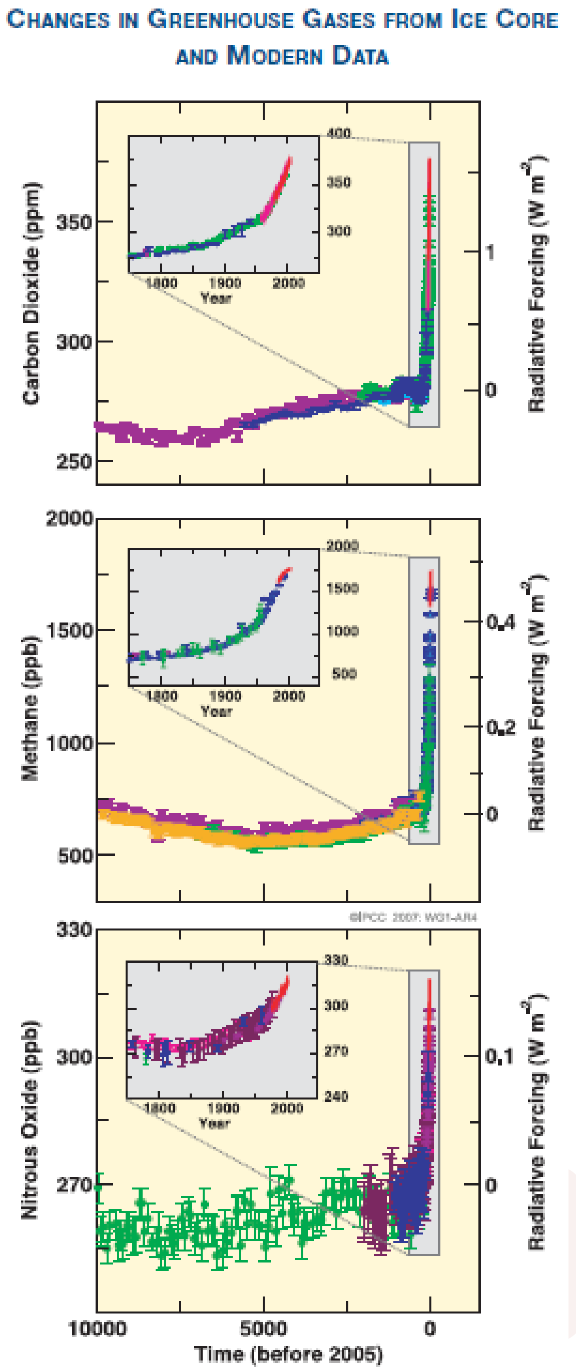


Figure SPM.1. *Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding radiative forcings are shown on the right hand axes of the large panels. {Figure 6.4}*

Global Carbon Cycle

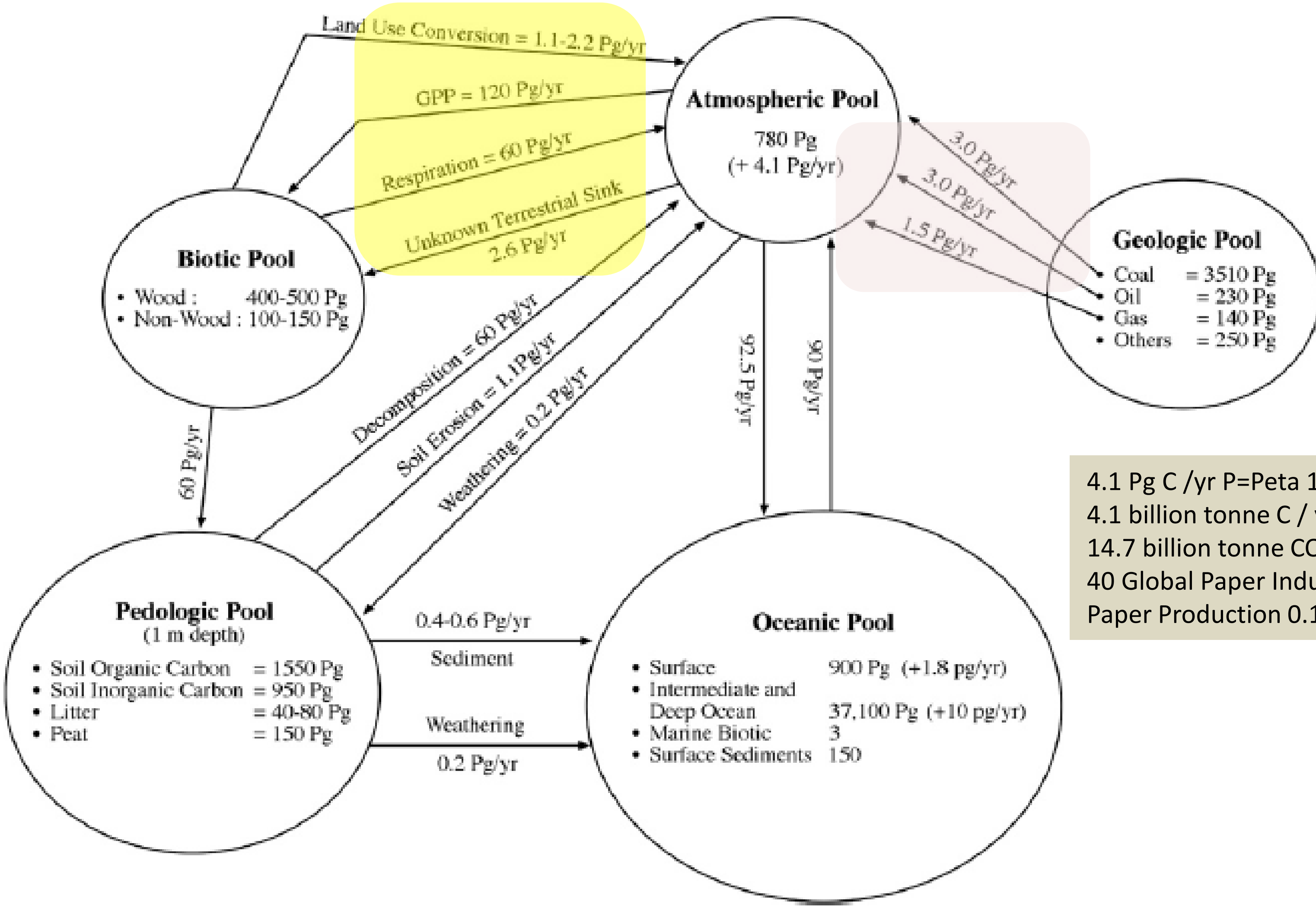


Fig. 1 Estimates of the global pools and fluxes between them.[1,4,5,7,152]

4.1 Pg C /yr P=Peta 10^15
4.1 billion tonne C / yr
14.7 billion tonne CO2 / yr
40 Global Paper Industries
Paper Production 0.15 billion tonne C/yr

Global Warming

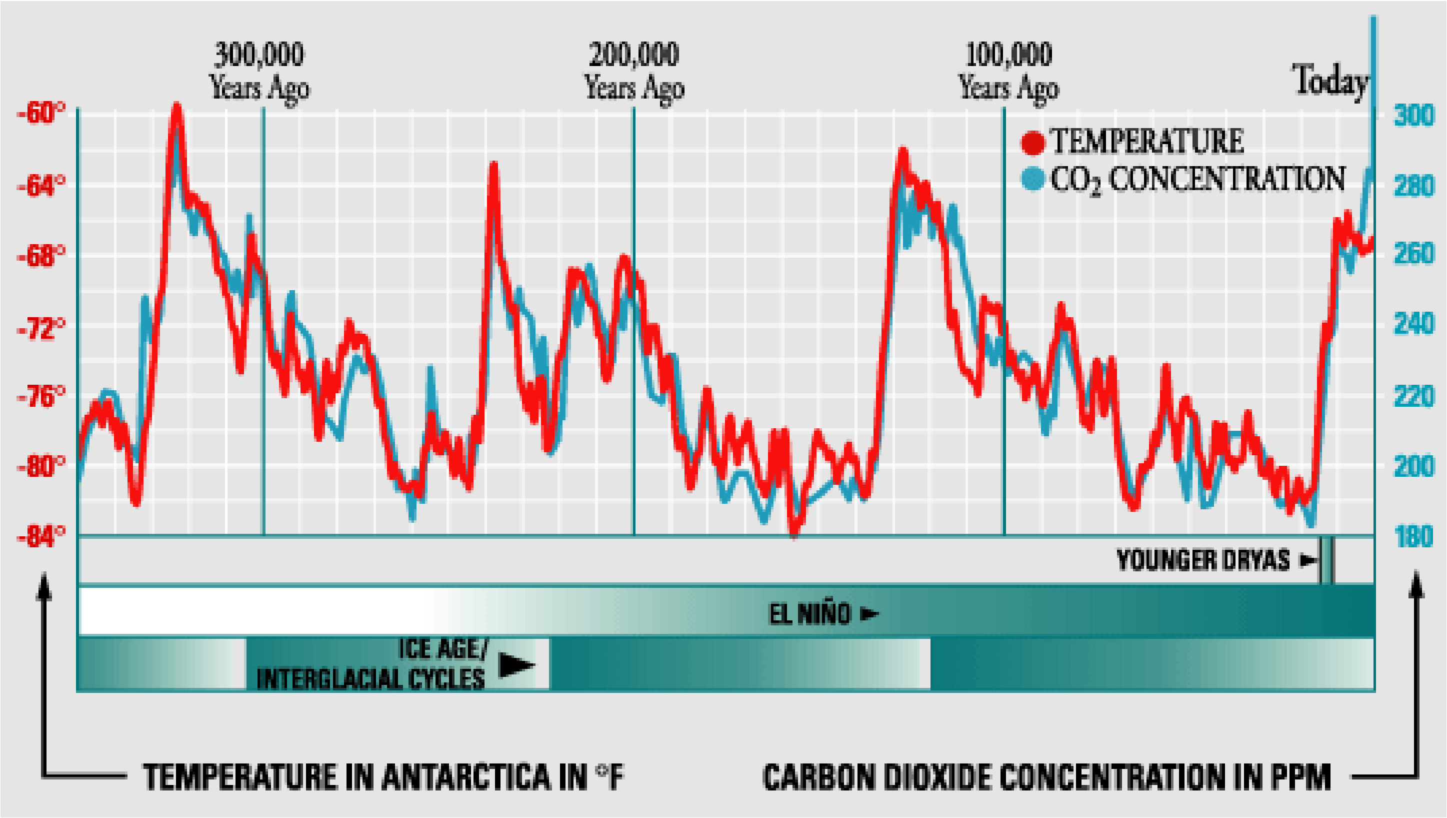


Figure 2. Ice core record from Vostok, Antarctica, showing the near-simultaneous rise and fall of Antarctic temperature and CO2 levels through the last 350,00 years, spanning three ice age cycles. However, there is a lag of several centuries between the time the temperature increases and when the CO2 starts to increase. Image credit: Siegenthalter et al., 2005, Science

Global Warming Potential (GWP)

- relative measure of how much heat a greenhouse gas traps in the atmosphere.
- compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide.
- commonly determined over a span of 20, 100 or 500 years.
- GWP is expressed as a factor of carbon dioxide (whose GWP is standardized to 1).

Radiative Forcing Capacity (RF) and GWP

- RF = the amount of energy per unit area, per unit time, absorbed by the greenhouse gas, that would otherwise be lost to space
- GWP is the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas

$$GWP_i \equiv \frac{\int_0^{TH} RF_i(t)\,dt}{\int_0^{TH} RF_r(t)\,dt} = \frac{\int_0^{TH} a_i \cdot [C_i(t)]\,dt}{\int_0^{TH} a_r \cdot [C_r(t)]\,dt}$$

- where *TH* is the time horizon,
- *RFi* is the global mean RF of
- component *i*,
- *ai* is the RF per unit mass increase in atmospheric abundance of component *i* (radiative effi ciency),
- [*Ci*(*t*)] is the time-dependent abundance of *i*,
- and the corresponding quantities
- for the reference gas (*r*) in the denominator.

Global Warming Potential Values

Table 2.14. *Lifetimes, radiative efficiencies and direct (except for CH_4) GWPs relative to CO_2. For ozone-depleting substances and their replacements, data are taken from IPCC/TEAP (2005) unless otherwise indicated.*

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency ($W\ m^{-2}\ ppb^{-1}$)	Global Warming Potential for Given Time Horizon			
				SAR‡ (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]1.4×10^{-5}	1	1	1	1
Methane[c]	CH_4	12[c]	3.7×10^{-4}	21	72	25	7.6
Nitrous oxide	N_2O	114	3.03×10^{-3}	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435
Methyl bromide	CH_3Br	0.7	0.01		17	5	1
Methyl chloroform	CH_3CCl_3	5	0.06		506	146	45
HCFC-22	$CHClF_2$	12	0.2	1,500	5,160	1,810	549
HCFC-123	$CHCl_2CF_3$	1.3	0.14	90	273	77	24
HCFC-124	$CHClFCF_3$	5.8	0.22	470	2,070	609	185
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181
Hydrofluorocarbons							
HFC-23	CHF_3	270	0.19	11,700	12,000	14,800	12,200
HFC-32	CH_2F_2	4.9	0.11	650	2,330	675	205
HFC-125	CHF_2CF_3	29	0.23	2,800	6,350	3,500	1,100

Global Warming Potential Values

Table: Global Warming Potential Values from the IPCC for some key GHGs

	Lifetime (years)	GWP time horizon		
		20 years	100 years	500 years
Carbon dioxide	Complex	1 1 1	1 1 1	1 1 1
Methane	12 12 12	72 62 56	25 23 21	7.6 7 6.5
Nitrous oxide	114 114 120	289 275 280	298 296 310	153 156 170
HFC-23	270 260 264	12,000 9,400 9,100	14,800 12,000 11,700	12,200 10,000 9,800
HFC-134a	14 13.8 13.8	3,830 3,300 3,400	1,430 1,300 1,300	435 400 420
CF_4 (PFC)	50,000 50,000 50,000	5,210 3,900 4,400	7,390 5,700 6,500	11,200 8,900 10,000
Sulfur hexafluoride	3,200 3,200 3,200	16,300 15,100 16,300	22,800 22,200 23,900	32,600 32,400 34,900

Row 1: 2007 IPCC AR4 (See Chapter 2 of Working Group I report)

Row 2: 2001 IPCC TAR (See Chapter 6 of Working Group I report)

Row 3: 1996 IPCC SAR (See Chapter 2 of the Working Group I report)

http://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/

Global Warming Potential Values

There are three key factors that determine the GWP value of a GHG:

- the gases absorption of infrared radiation,
- where along the electromagnetic spectrum (i.e., what wavelengths) the gas absorbs radiation, and
- the atmospheric lifetime of the gas.

We typically only use GWP values for gases that have a long atmospheric lifetime (i.e., in years). Because only these gases last long enough in the atmosphere to mix evenly and spread throughout the atmosphere to form a relatively uniform concentration. GWP values are meant to be "global," as the name implies. So if a gas is short-lived and does not have a global concentration because it is destroyed quickly and emitted in different amounts in different places, then it can't really have a GWP.

Specifically, the gases with relatively long atmospheric lifetimes that tend to be evenly distributed throughout the atmosphere, and therefore have global average concentrations, are CO2, CH4, N2O, HFCs, PFCs, and SF6. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NOx, and NMVOCs), and tropospheric aerosols (e.g., SO2 products and black carbon) vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts.

Some GWP values may also account for indirect as well as direct effects. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas(es) that is/are also a greenhouse gas, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases.

In sum, the higher the GWP value the more infrared radiation the gas will tend to absorb over its lifetime in the atmosphere. Now, there are three more complications to this story.

The first is that gases will absorb certain wavelengths of radiation. GHGs each absorb in a given "window" of the spectrum. The more that window is filled up, the less there is to absorb. So, as concentrations of certain gases increase they can saturate that wavelength, leaving no more radiation for additional concentrations of gas in the atmosphere to absorb.

The second complication is one that occasionally trips people up. Remember above when we defined GWP by saying "cumulative radiative forcing…integrated over a period of time"? Well, that means that we have to define a time period for the integration to occur. You have to know what the integration period is to make sure you are using the correct GWP. The typical periods that the IPCC publishes are 20, 100, and 500 years.

Now, to be clear, everyone pretty much universally uses 100 year GWP values, so you often never see the time period even cited. But occasionally, someone will use something different, not realizing that they are breaking convention. It is also possible to compute an infinite time horizon GWP value, which would basically mean that accounted for every bit of radiative forcing of every molecule of gas as long as it existed in the atmosphere.

The last complication relates to the fact that the IPCC keeps updating its GWP values with each of its major scientific assessment reports. It makes sense to update GWP values as our scientific understanding improves. However, the problem is that people are using and making commitments based on GWP values while these revisions are taking place. So, say a company or a country says it will reduce its emissions by 10% and achieves that goal. Then all of a sudden GWP values change and now they no longer make the goal if new GWP values are used (due to the mix of different GHGs they emit and reduce). It would be like moving the net after you already kicked the ball towards the goal.

For this reason, the Kyoto Protocol fixed the use of GWP values published by the IPCC in 1996 in its Second Assessment Report. Since then the IPCC has updated its GWP values twice, once in 2001, and again in 2007. The result has been a proliferation of GWP values out there that leads to a lot of confusion.

Specifically, the Parties to the UNFCCC said:

In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons. (FCCC/CP/1996/15/Add.1)

The major causes for the IPCC's updates to GWP values involved new laboratory or radiative transfer results, improved atmospheric lifetime estimates, and improved calculations of CO2 radiative forcing and CO2 response function. When the radiative forcing of CO2 is updated, then the GWPs of the other gases relative to CO2 also change.

The result of the varying time periods and the regular updates by the IPCC is a complicated state of affairs. This table presents GWP values for the most common GHGs (there are many more if we listed all the HFCs, PFCs and other trace gases). As you can see in this table, each gas has number of GWP values that you could chose.

But the truth is, contrary to what a lay person might expect, we typically only use values over a 100 year time period, even though some gases have lifetimes of thousands of years. And we use the old SAR values so all the climate change programs and policies around the world, including the Kyoto Protocol, are consistent in their emissions accounting (these GWP values are highlighted in red in the table).

http://ghginstitute.org/2010/06/28/what-is-a-global-warming-potential/

Radiative Forcing

- rate of energy change per unit area of the globe as measured at the top of the atmosphere
- expressed in units of Watts per square metre

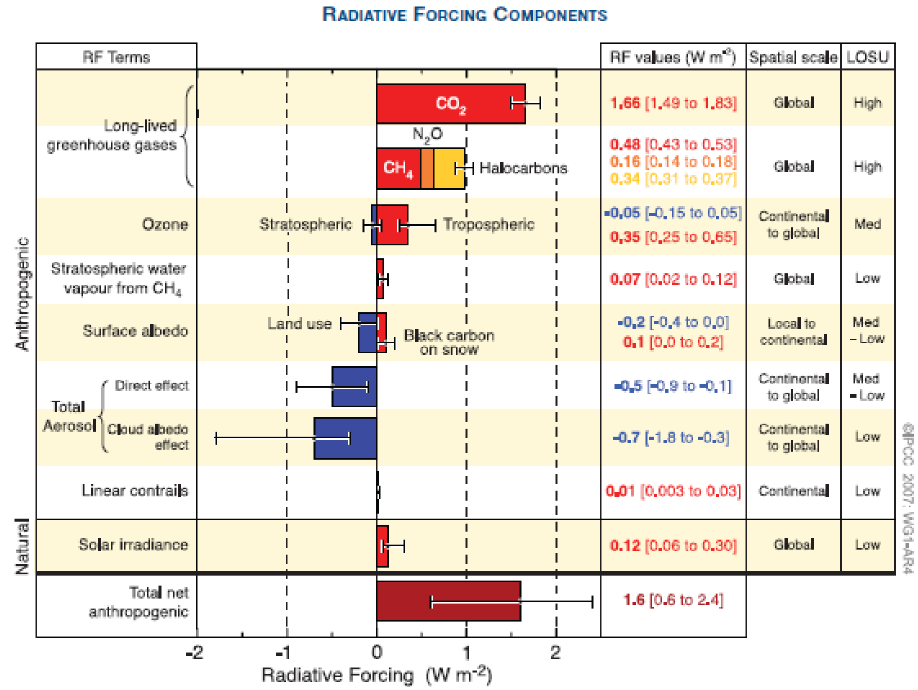


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. {2.9, Figure 2.20}*

Carbon Footprint: Impact Assessment Method

- **Partial life cycle analysis**

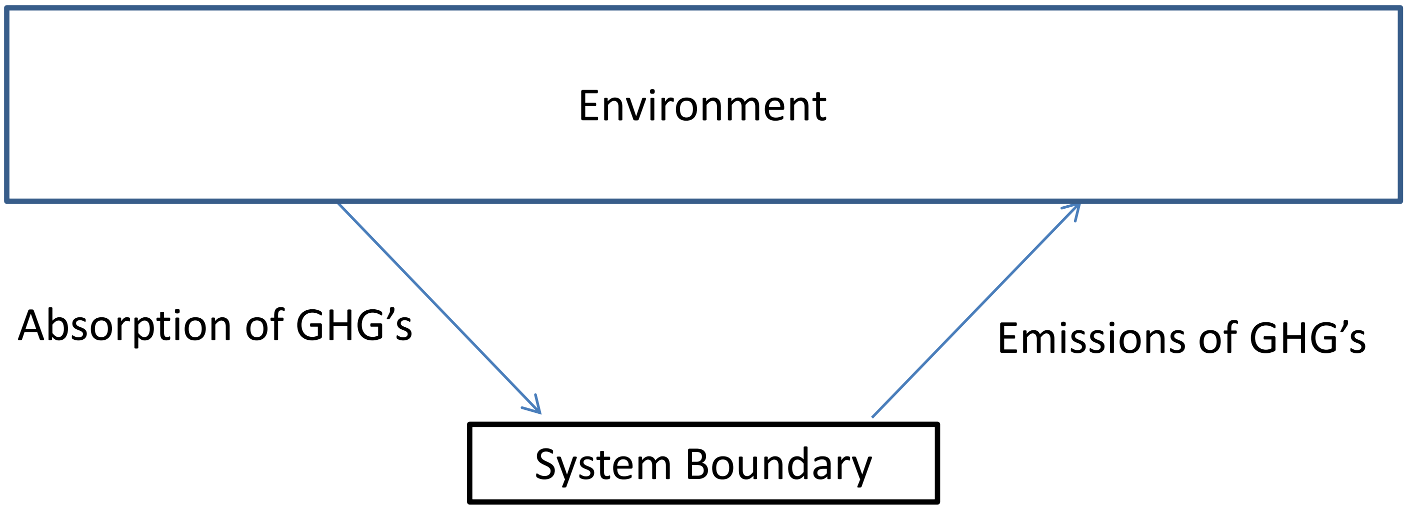
- **Historicially**: the total set of greenhouse gas (GHG) emissions caused by an organization, event, product or person (UK Carbon Trust, 2009)
- **Practically:** A measure of the total amount of carbon dioxide (CO_2) and methane (CH_4) emissions of a defined population, system or activity, considering all relevant sources, sinks and storage within the spatial and temporal boundary of the population, system or activity of interest. Calculated as carbon dioxide equivalent (CO_2e) using the relevant 100-year global warming potential (GWP100) (Wright etal, Carbon Mgmt, 2011)

Carbon Footprint:
Impact Assessment Method

- **IPCC is the leading authority in evaluating the science behind GWP**

Revision Year	CO_2 equivalents for CH_4	CO_2 equivalents for N_2O
1996	21	310
2001	23	296
2006	25	298

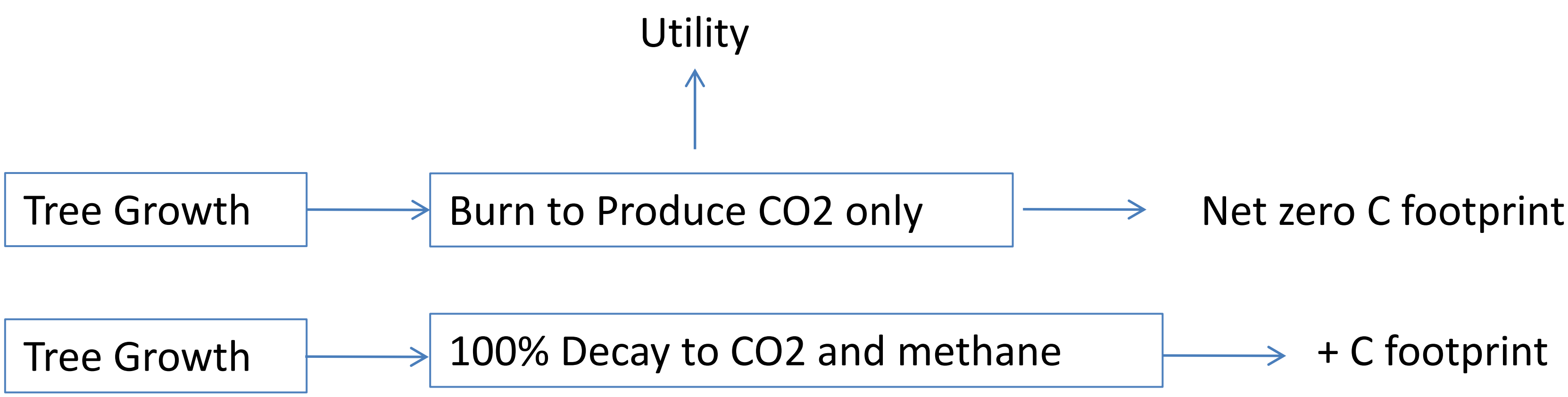
Carbon Footprint:
A Material Balance of GHG's



Carbon footprint = Emissions- Absorption (kg CO2 equivalents)

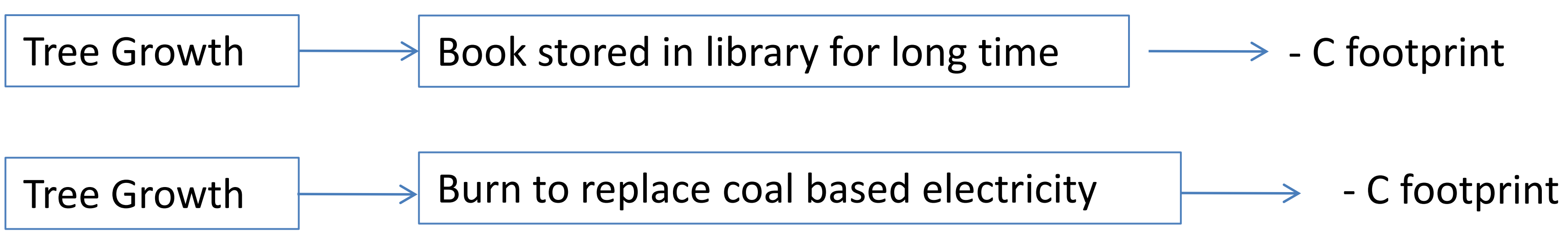
Carbon Footprint:
Impact Assessment Method

- **Typically, a carbon footprint does not consider biogenic (from living processes) carbon nor does it consider CO_2 emissions from the burning or decay of the biogenic material (they balance each other)**
- **Biogenic material decay/burning that produces methane or N_2O must be considered**



Carbon Footprint:
Impact Assessment Method

- **Non renewable resources (coal, oil) are considered since they have been formed over very long time scales and are not being formed over time scales of interest**
- **Materials, transportation, energy often have associated with them carbon emissions**
- **Long term storage of carbon away from the atmosphere is considered a negative C footprint contribution**
- **When one product with a lower C footprint replaces another with larger C footprint, an avoided C input to the atmosphere is claimed, a negative C footprint contribution**



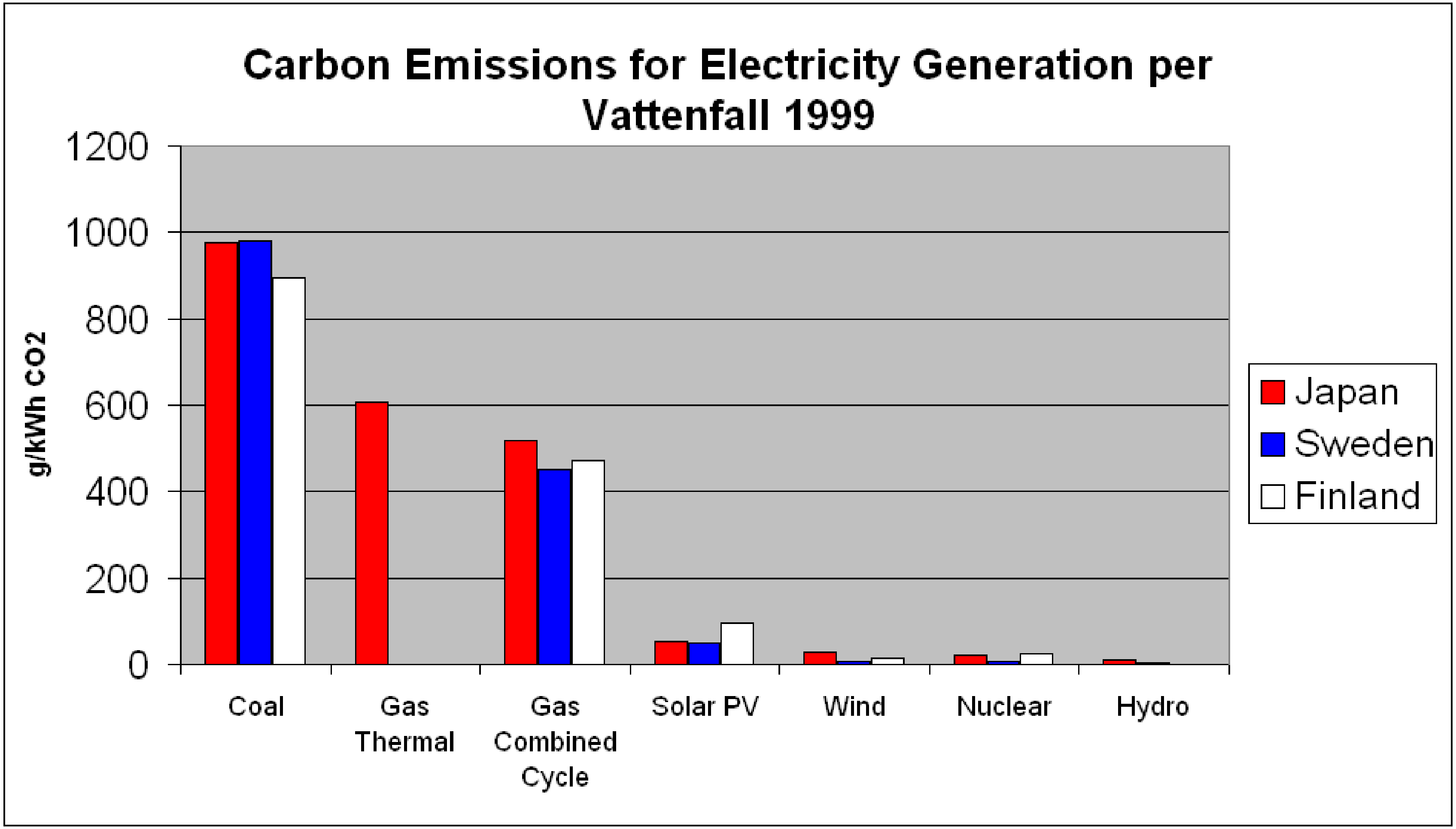
Carbon Footprint: CO2 list.org

This list may confirm what you know, or may surprise you.
CO_2 is not caused by others, it is caused by our choices: Heating & cooling; Buying products; Red meat versus chicken and grain; Cars and

CO2LIST.ORG Home **Bold** shows some interesting items	KILOS OF CO2 (includes effect of other greenhouse gases)	POUNDS OF CO_2	UNITS OF MEASURE FOR EACH ITEM (We and most others measure CO_2 by weight. Its size varies, so it can't be measured in volume. For other items we pick appropriate units, shown below.)		What is the answer? Solutions are discussed at http://Your.CO2List.org Complete sources and calculations are at xls.CO2List.org Data from US, except when the following symbols appear: ‡ Data are from UK † Data are from Australia France has data (in English) for many items, not yet incorporated here. Contact us 16 March 2012
CO_2 POUNDS RELEASED WHILE MAKING PRODUCTS					
1 - FOOD	**KILOS OF CO2**	**POUNDS OF CO2**		**Pounds of CO_2 per 500 Calories** (this is 1/4 of a daily 2,000-Calorie diet)	Sweden labels individual food items
Red meat	**22**	**22**	Pounds CO_2 per pound of product, or Kilos of CO2 per kilo of product	12	92% from production of animals & their feed, including N2O & methane. Remainder is transport of inputs & meat, and selling. (interesting article by former Texas Ag Commissioner http://jimhightower.com/node/6901)
Chicken, fish, eggs	**6**	**6**		4	81% from production of feed & meat
Dairy	4	4		6	91% from production of feed & animals
Cereals, carbohydrates	3	3		1.5	75% from production of crops
Fruit, vegetables	**2**	**2**		4	74% from production of crops
Oils, sweets, condiments	2	2		0.5	74% from production of crops
Balanced Diet				1.7	USDA Food Guide: 53% carbohydrate, 29% oils, 18% protein (here protein is chicken, fish, eggs) http://www.cnpp.usda.gov/Publications/DietaryGuidelines/2005/2005
	Source: Weber & Matthews 2008 "Food-Miles and the Relative Climate Farm products (food, cloth, leather, biofuels) release greenhouse gases from and Crutzen et al. 2008 "N_2O Release...") (d) methane (CH_4) created in animal stomachs and intestines, (e) 2009 report on Biofuels, particularly chapters 6 on land use and 5 on				http://pubs.acs.org/doi/full/10.1021/es702969f http://www.iea.org/textbase/nppdf/free/2004/biofuels2004.pdf http://www.atmos-chem-phys.net/8/389/2008/acp-8-389-2008.html http://icsu.org/ http://cip.cornell.edu/biofuels/
Potato chips‡	2	2	pounds CO_2 per pound of product kilos CO_2 per kilo of product		Mostly from growing crops: N_2O from nitrogen-fixing bacteria, fuel The figures in the section above are larger, and come from a much more complete methodology.
Orange juice	0.9-1.4	0.9-1.4			
Bottled smoothie‡	1.1	1.1			
Organic new potato‡	0.29	0.29			
Potato, not organic‡	0.24	0.24			
	Sources: Carbon Trust, a UK nonprofit, has a summary and Report CTC744. Orange juice is from a Pepsico study reported in the *NY Times*.				http://www.carbon-label.com/individuals/product.html http://www.carbontrust.co.uk/Publicsites/cScape.CT.PublicationsOrd id=CTC744 http://www.nytimes.com/2009/01/22/business/22pepsi.html/

Carbon Footprint:

Japan's Central Research Institute of the Electric Power Industry's

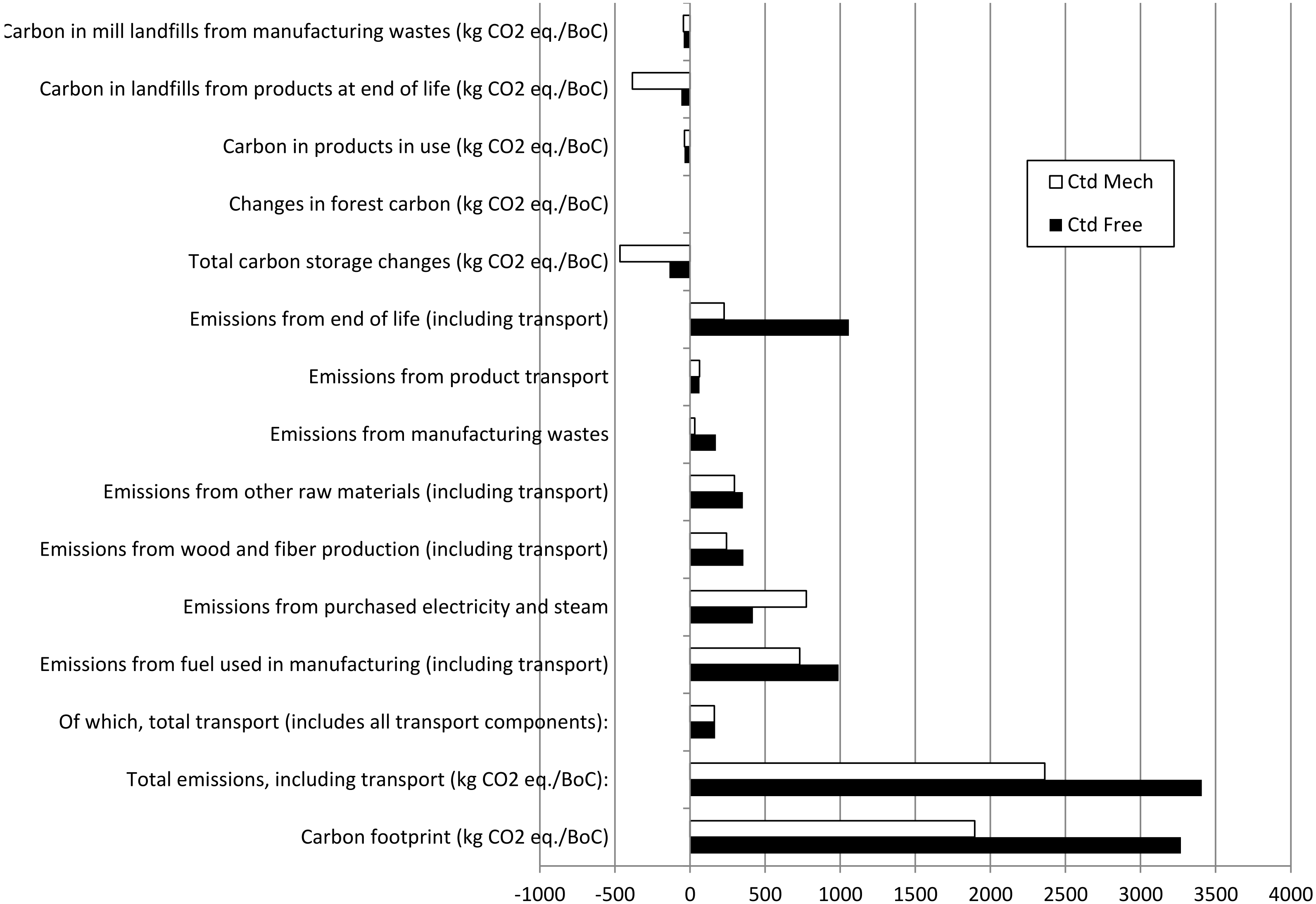


Carbon Footprint Example: Coated Paper (Catalog)

Data and Graphs from NCASI LCA P&W Grades, 2010
Software used from NCASI, FEFPRO

NCASI LCA NA P&W Grades, 2010

Life Cycle Analysis of Paper: Carbon Footprint Results



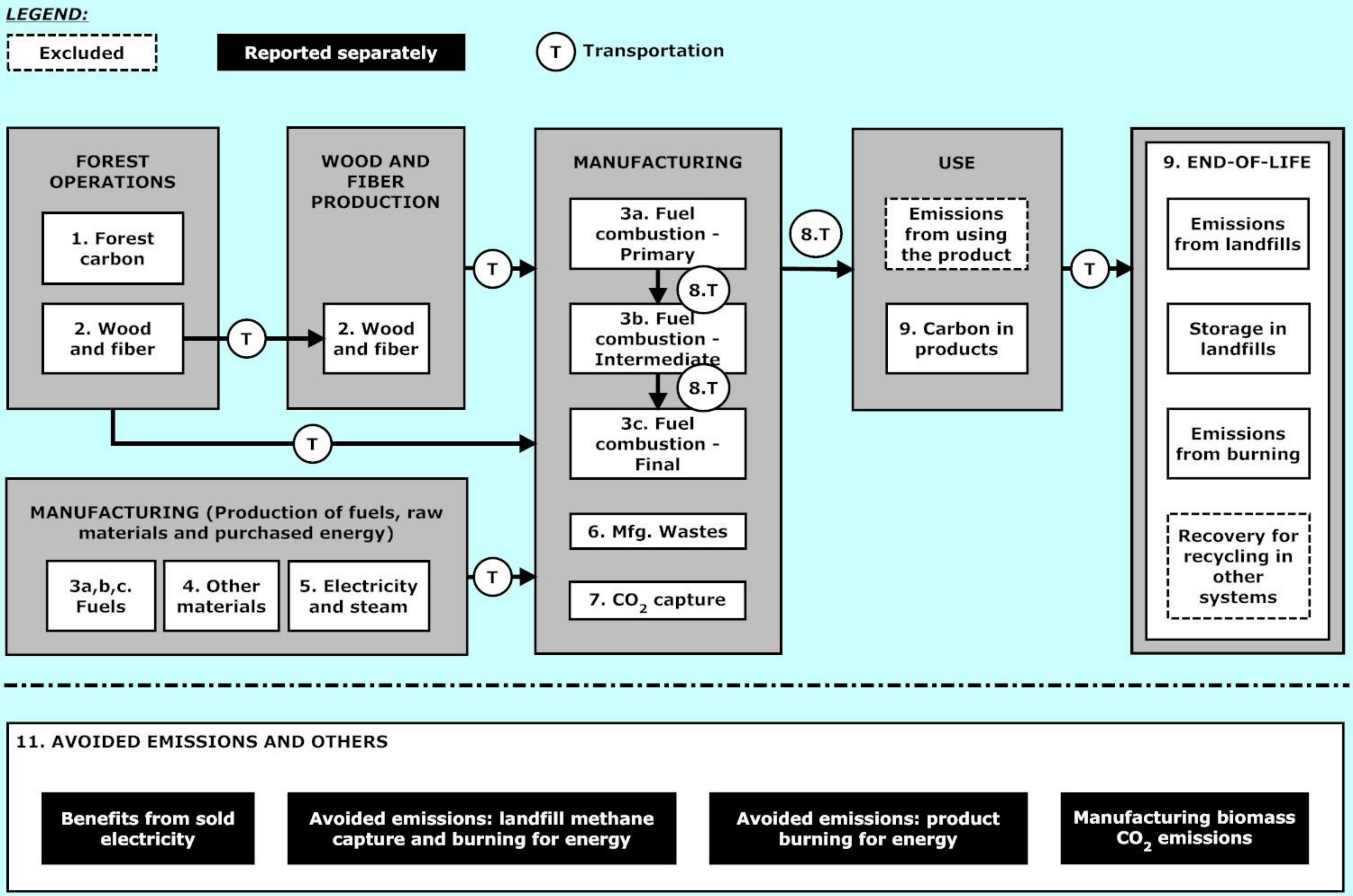
Go.ncsu.edu/venditti (downloads)

Basic Steps of the Carbon Footprint

- Define the footprint boundary
- Define the scope
- Define the Basis of Calculation
- Begin to complete the Life Cycle Inventory
  - Forest Carbon Changes
  - Wood and Fiber
  - Fuels from Mfg
  - Other Materials
  - Electricity and Steam
  - Mfg waste
  - Product Transport
  - End of Life
- Evaluate Results, Interpret, Report

Define the footprint boundary

- Cradle to Grave of catalog paper, coated free sheet
- 100 years



Define the scope

- 100 years

- Scope 1: all direct GHG emissions from owned production;
- Scope 2: indirect GHG emissions from consumption of purchased electricity, heat or steam; and
- Scope 3: indirect GHG emission from systems such as extraction and production of purchased materials and fuels, transportation in *non-owned* vehicles, or production facilities operated by parties other than the user.

Define the Basis of Calculation

- Basis of Calculation (BoC) is the metric upon which all of the data input, calculations, and result output are based. For example, a BoC of 1000 kg of product (one metric tonne) means that data input such as quantity of raw material consumed is entered per 1000 kg of production (e.g., a BoC of 1000 kg and log input of 2000 kg means that 2 tonnes of logs are consumed in the production of 1 tonne of product).

Name of this footprint	Coated Freesheet NCASI Number of Uses Cradle to Grave
Product Name	Coated Freesheet
Product Type	coated woodfree
Footprint Boundaries	Cradle to Grave only in this version
Description of a single product	1 mdst (5% water)
Basis of Calculation (BoC)	1 machine-dry short ton (5% water)
Basis of calculation (BoC) expressed as mass (dry kg)	861.82556

Life Cycle Inventory: Forest Carbon Changes

- Must understand if the land that is being used to provide the amount of wood needed to make paper is being changed such that the net carbon stock on the land for 100 years is changing over many harvests
- Not commonly known, but can be important
- In developed countries, significant proportion is harvested sustainably and many certified

Forest name	Method of determining carbon stock changes	Change in carbon stocks (kg carbon/BoC)	
		Default value	Selected value
Generic Forest	*Constant Stock*	*0*	0.00

Life Cycle Inventory: Wood and Fiber

- Wood and Fiber inputs into manufacturing
- Northern Hardwood chips example, but most cases have multiple inputs

		Proposed defaults	From owned operations	From non-owned operations
Quantity (kg/BoC, dry basis)		*No default*		261
Moisture content as received (fraction between zero and one)		*No default*		0.5
Emissions for this fiber source (kg CO2 eq./kg dry)	Scope 1	*0.130*		0
	Scope 2	*0.090*		0
	Scope 3	*0.010*		0.230
Wet tonnes			0	0.522
Total shipped tonnes			0.522	

	kg CO_2 eq./BoC		
	Scope 1	**Scope 2**	**Scope 3**
Emissions for this fiber source	0	0	50.028364
Truck, owned	0		0
Truck, non-owned			4.394349
Rail, owned	0		0
Rail, non-owned			0.1841231
Water inland, owned	0		0
Water inland, non-owned			0
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***0***	***0***	***54.606836***
Transport only	***0***		***4.5784721***

Life Cycle Inventory: Fuels Consumed

- Coal, example

		Proposed defaults	Burned in owned operations	Burned in non-owned operations
Quantity (GJ HHV/BoC, dry basis)		*No default*	5.56	
Moisture content as received (fraction between zero and one)		0.1	0.1	
Emissions for this fuel (kg CO_2 eq./GJ HHV)	Combustion	90.32	90.32	N/A
	Pre-combustion	5.382	5.382	N/A
	Total	95.702	95.702	
		Transported tons	0.196744515	0
		Total transported tons	0.196744515	

	kg CO_2 eq./BoC		
	Scope 1	**Scope 2**	**Scope 3**
Fuel-related emissions	425.8628		25.376366
Truck, owned	0		0
Truck, non-owned			0.0453493
Rail, owned	0		0
Rail, non-owned			2.3267772
Water inland, owned	0		0
Water inland, non-owned			0.0545282
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***425.8628***		***27.80302***
Transport only	***0***		***2.4266546***

Life Cycle Inventory: Fuels Consumed

- Black liquor, organic material byproduct of making paper

		Proposed defaults	Burned in owned operations	Burned in non-owned operations
Quantity (GJ HHV/BoC, dry basis)		*No default*	9.1	
Moisture content as received (fraction between zero and one)		0.35	0.35	
Emissions for this fuel ($kg\ CO_2$ eq./GJ HHV)	Combustion	0.637	0.637	N/A
	Pre-combustion	0	0	N/A
	Total	0.637	0.637	
Transported tons			1	0
Total transported tons			1	

	kg CO_2 eq./BoC		
	Scope 1	Scope 2	Scope 3
Fuel-related emissions	4.830908		0
Truck, owned	0		0
Truck, non-owned			0
Rail, owned	0		0
Rail, non-owned			0
Water inland, owned	0		0
Water inland, non-owned			0
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***4.830908***		***0***
Transport only	***0***		***0***

Life Cycle Inventory: Other Materials

- Example Latex coating material

	Proposed defaults	User entry
Quantity (kg/BoC, dry basis)	*25.85*	25.85
Moisture content as received (fraction between zero and one)	*0*	0
Upstream emissions for this raw material (kg CO_2 eq./kg dry)	*2.628*	2.628
Total received tonnes (wet)	0.02585	

	kg CO_2 eq./BoC		
	Scope 1	**Scope 2**	**Scope 3**
Upstream Emissions			57.60986
Truck, owned	0		0
Truck, non-owned			0.533979
Rail, owned	0		0
Rail, non-owned			0.079094
Water inland, owned	0		0
Water inland, non-owned			0
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***0***		***58.22294***
Transport only	***0***		***0.613073***

Life Cycle Inventory: Electricity and Steam

- Need to know quantities and location of electricity

Quantity (MWh/BoC)	Region supplying the electricity	Default emission factor (kg CO_2 eq./MWh)		Selected emission factor (kg CO_2 eq./MWh)		
		Scope 2	Scope 3	Scope 2	Scope 3	Used for
0.0183	Alabama	711.0	18.2	711.0000	18.2000	Combined operations
0.0518	Kentucky	1045.4	25.3	1045.4000	25.3000	Combined operations
0.0157	Maryland	711.5	18.2	711.5000	18.2000	Combined operations
0.0306	Maine	393.6	11.5	393.6000	11.5000	Combined operations
0.0515	Michigan	738.2	18.8	738.2000	18.8000	Combined operations

kg CO_2 eq./BoC		
Scope 1	Scope 2	Scope 3
	11.03396573	0.282444692
	45.92225396	1.111376531
	9.472955502	0.242315938
	10.21380252	0.298421568
	32.23979045	0.821062125

Life Cycle Inventory: Electricity and Steam

- For steam used a proxy:

Quantity (GJ/BoC)	Steam supplier/Source of emission factor	Default emission factor (kg CO_2 eq./MGJ)	Selected emission factor (kg CO_2 eq./GJ)
		Scope3	Scope 3
0.0434	*used natural gas EF*	*No default*	63.324

Life Cycle Inventory: Manufacturing Wastes

- On site landfill that decays

	Proposed default	Selected value
Quantity of manufacturing wastes placed in industry landfills (dry kg/BoC)	43.09	83.50
Fraction of carbon in wastes	0.275	0.275
Fraction of carbon in wastes permanently stored	0.50	0.50
Fraction of wastes from owned operations	*No default*	1.00

Results

	Scope 1	Scope 3
Mass of methane emitted from mill landfills (kg CO_2 eq./BoC)	172.21875	0
Mass of carbon permanently stored in mill landfills (kg CO_2 eq./BoC)	42.09791667	
Scope 1 Biogenic CO_2 emitted (kg CO_2 eq./BoC)	23.1538542	

Life Cycle Inventory: Product Transport

- All transport steps involved, default emmission data used

Product descriptor:	# T23 Code 293 USDOT 99,04 and USEPA 06 (printer to customer) 91%
Product transported:	Advertising material, commercial or trade catalogues, and similar printed products
Quantity (dry kg/BoC):	784.26
Moisture content:	0.08

Mode	**Proposed defaults**		**Owned transportation**		**Non-owned transportation**	
	Fraction of quantity transported	**Distance, km**	**Fraction of quantity transported**	**Distance, km**	**Fraction of quantity transported**	**Distance, km**
Truck	1	403.9			1	403.9
Rail	0	0				
Freshwater (inland) shipping	0	0				
Marine (ocean) shipping	0	0				

	kg CO_2 eq./BoC		
	Scope 1	**Scope 2**	**Scope 3**
Truck	0		32.19272
Rail	0		0
Marine (ocean) shipping	0		0
Inland (freshwater) shipping	0		0
Total	***0***		***32.19272***

Life Cycle Inventory: Product Transport

- All transport steps involved, default emmission data used

Transportation mode	(kg CO_2 / km*tonne)		
	Combustion	**Precombustion**	**Total**
Truck	0.0805	0.013	0.0935
Rail	0.0191	0.0031	0.0222
Marine (ocean)	0.0163	0.0022	0.0185
Inland (freshwater)	0.0288	0.0046	0.0334
Small truck (EOL)			1.26

Life Cycle Inventory: End of Life: Carbon in Products

- How much carbon exists in products. Needed for end of life and carbon storage in products.
- Half life, number of years for the existing paper in use to half
- C permanently stored (in landfills)

Product	Carbon content (fraction)	Half-life (years)	Carbon permanently stored (fraction)
bleached kraft board	0.50	2.54	0.12
bleached kraft paper (packaging & industrial)	0.48	2.54	0.61
coated mechanical	0.50	2.54	0.85
coated woodfree	0.50	2.54	0.12
average containerboard	0.50	2.54	0.55
newsprint	0.46	2.54	0.85
recycled boxboard	0.50	2.54	0.55
recycled corrugating medium	0.50	2.54	0.55

Life Cycle Inventory: End of Life

- Define the amount recycled
- Define the amount burned for energy and landfilled
- Built in data about landfill emissions

The final product is probably used and disposed of in: U.S.

Disposition	Fractions: Proposed defaults	Fractions: User Selection	Transport distances, km: Proposed defaults	Transport distances, km: User Selection
Recycling	0.4210	0.388	32.18	32.18
Landfill	0.4696	0.498	32.18	32.18
Burning w/ energy recovery	0.1094	0.114	32.18	32.18

Burning assumptions:
- GHG emissions are mainly N_2O.

Landfill assumptions:
- Landfills are assumed to be completely anaerobic.

- Fraction of gas transformed to methane:	50%
- Fraction of methane oxidized to CO_2 in landfill covers	10%

Life Cycle Inventory: End of Life

Mass of product remaining in use after 100 years (kg/BoC)	31.58112712
Mass product landfilled (kg product/BoC)	413.46172757
Mass carbon landfilled (kg C/BoC)	133.54813801
Mass carbon permanently stored (kg C/BoC)	16.02577656
Mass if carbon transformed to gas (kg C/BoC)	117.52236145
Mass of carbon transformed into methane (kg C/BoC)	58.76118072
Mass of carbon in methane not oxidized in landfill covers (kg C/BoC)	52.88506265
Mass of carbon transformed into CO_2 (kg C/BoC)	5.87611807
Mass of carbon in methane burned for energy recovery (kg C/BoC)	23.26942757
Mass of methane emitted (kg CH_4/BoC)	39.48751345
Landfill methane (kg CO_2 eq./BoC)	987.1878361
Burning GHGs (kg CO_2 eq./BoC)	0.946478653
Transport GHGs (kg CO_2 eq./BoC)	69.88853723
Total EOL (scope 3) GHG emissions (kg CO_2 eq./BoC)	***1058.022852***
Carbon storage (kg CO_2 eq./BoC)	***58.76118072***

Life Cycle Inventory: Analysis

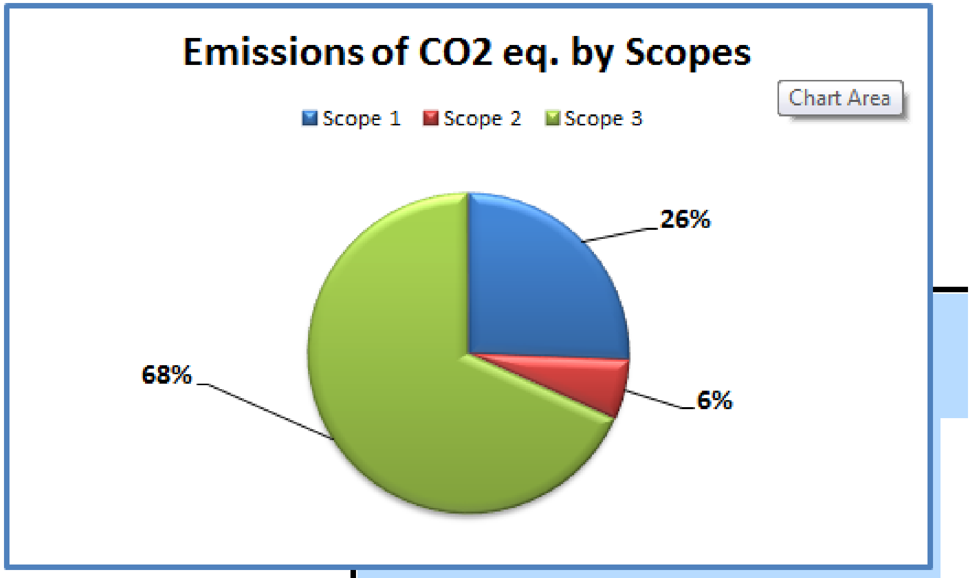
- Check for completeness, consistency, errors…..
- Interpret….

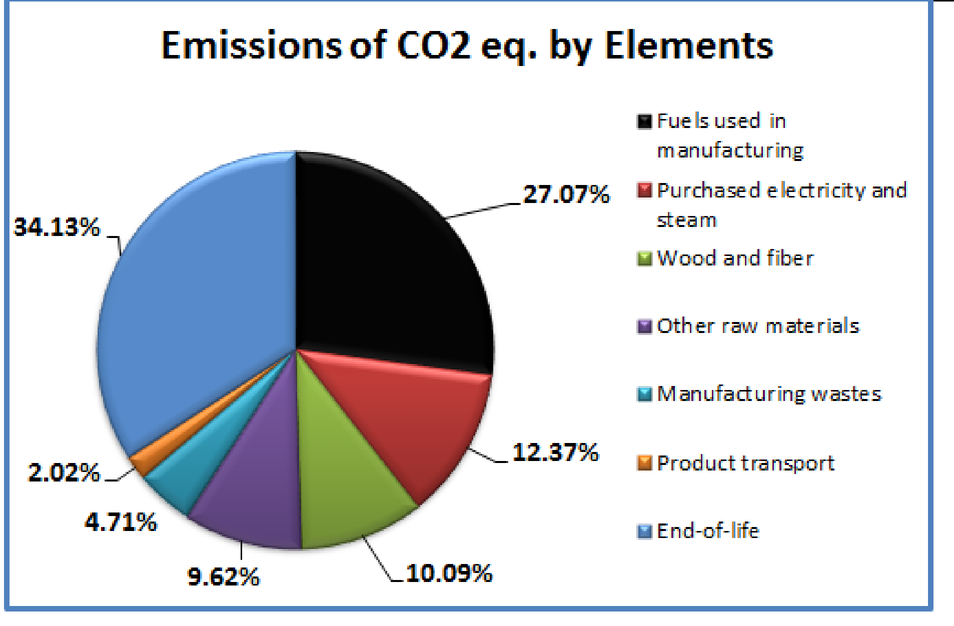
	Total	Scope 1	Scope 2	Scope 3
Basis of calculation (BoC, kg)	*861.82556*			
Total emissions, including transport (kg CO_2 eq./BoC):	*3100*	*793.5*	*188.6*	*2118*
Of which, total transport (includes all transport components):	*161.2*	*0*	*0*	*161.2*
Emissions from fuel used in manufacturing (including transport)	*839.2*	*647.5*	*0*	*191.7*
Emissions from purchased electricity and steam	*383.5*	*0*	*188.6*	*194.9*
Emissions from wood and fiber production (including transport)	*312.9*	*0*	*0*	*312.9*
Emissions from other raw materials (including transport)	*298.1*	*0*	*0*	*298.1*
Emissions from manufacturing wastes	*146*	*146*		*0*
Emissions from product transport	*62.53*	*0*	*0*	*62.53*
Emissions from end of life (including transport)	*1058*			*1058*
Total carbon storage changes (kg CO_2 eq./BoC)	*138.3*			
Changes in forest carbon (kg CO_2 eq./BoC)	*0*			
Carbon in products in use (kg CO_2 eq./BoC)	*37.4*			
Carbon in landfills from products at end of life (kg CO_2 eq./BoC)	*58.76*			
Carbon in mill landfills from manufacturing wastes (kg CO_2 eq./BoC)	*42.1*			

Method used to estimate amount of product in use: *Weighted avg first order*

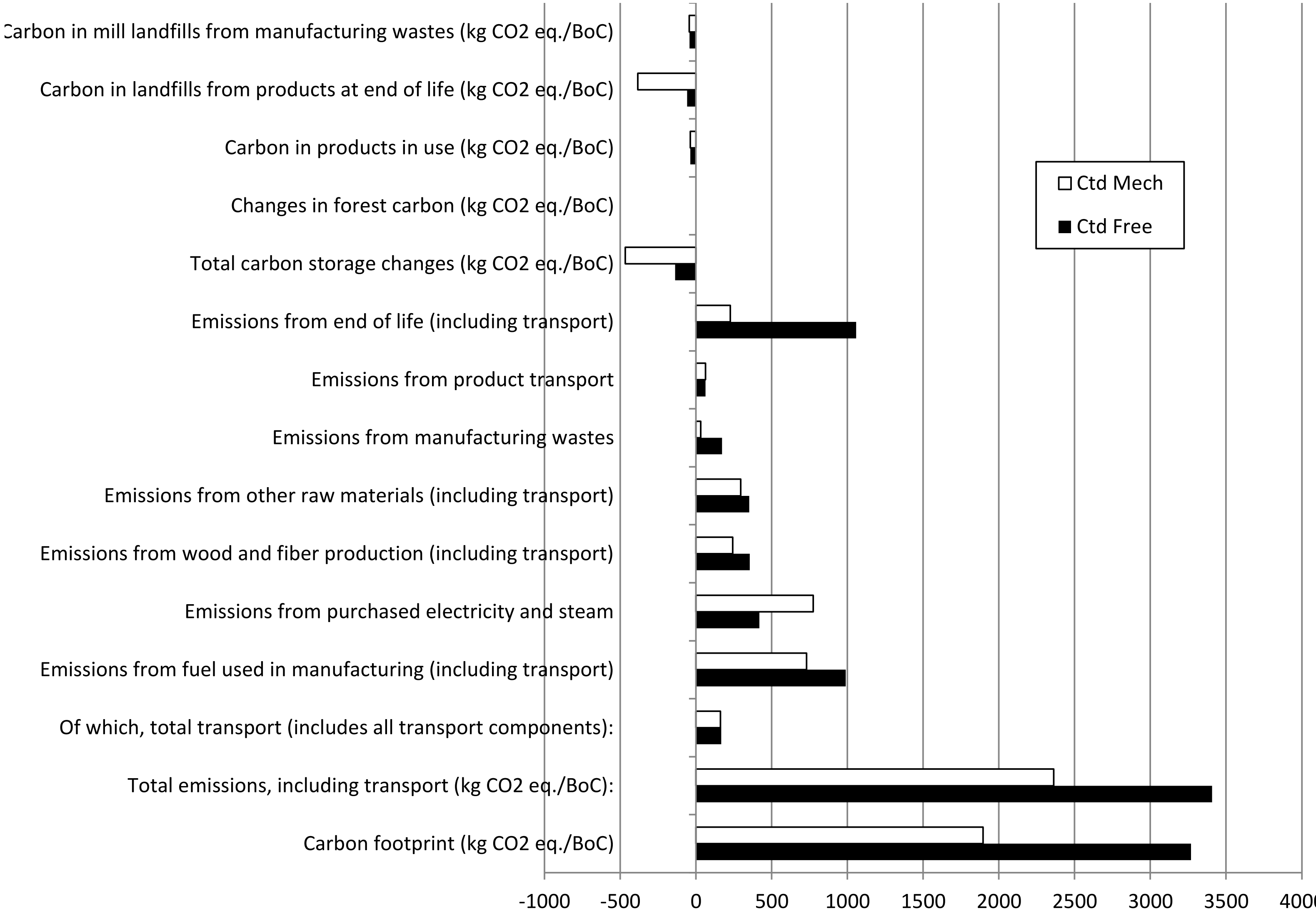
Life Cycle Inventory: Analysis

- Check for completeness, consistency, errors…..
- Interpret….



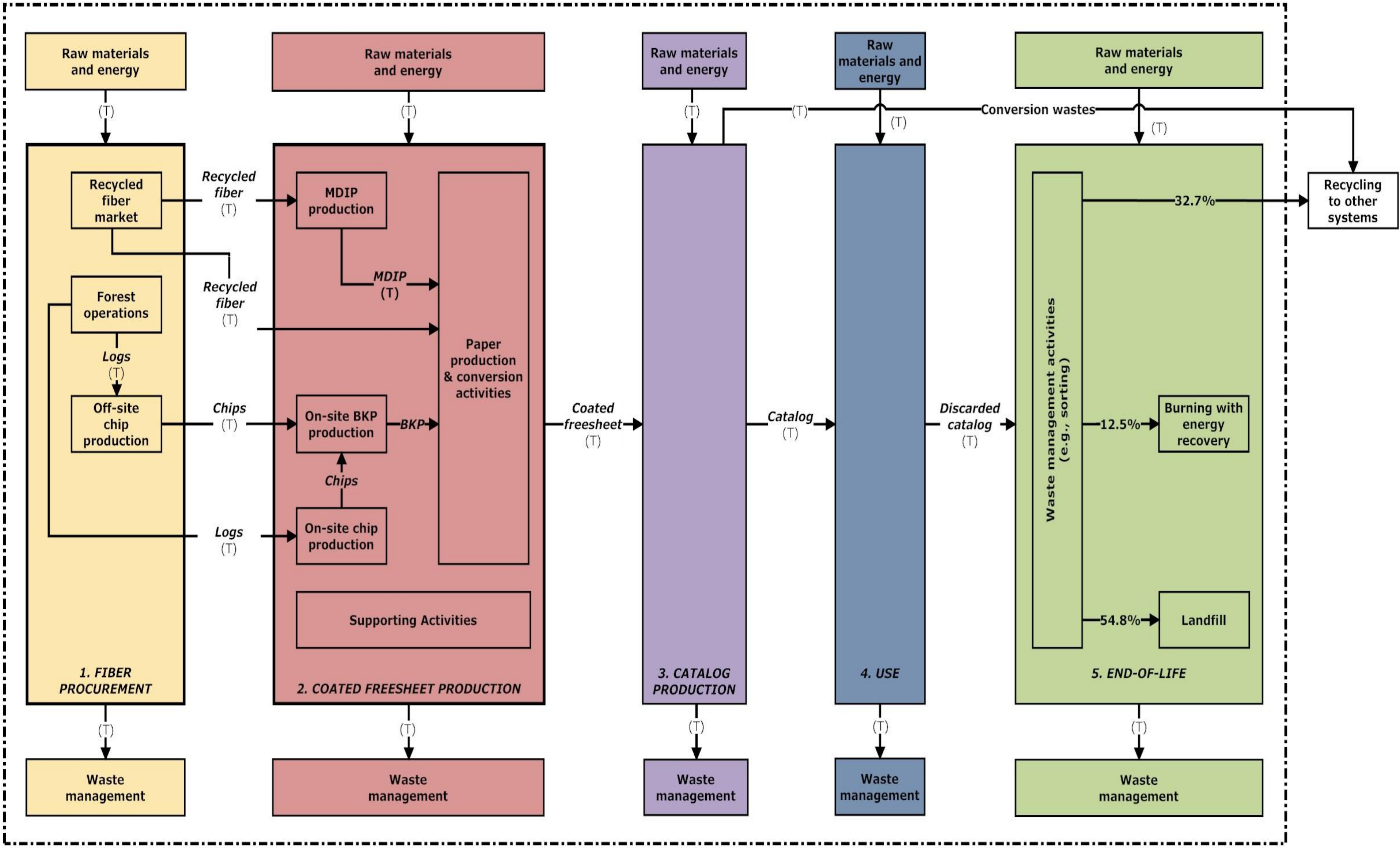


Life Cycle Analysis of Paper: Carbon Footprint Results



Go.ncsu.edu/venditti (downloads)

Life Cycle Analysis of Paper: Catalog System Boundary



NCASI LCA NA P&W Grades, 2010

Full Life Cycle Analysis of Paper: Carbon Footprint Results

Table ES-6. LCIA Results – Catalog, Coated Freesheet

Impact category	Unit	Total (unit/ catalog)	1- Fiber procurement	2- Coated freesheet production	3- Production of catalogs	4- Transport and use	5- End-of-life	Storage in use and landfill
Global Warming (GW)	kg CO_2 eq.	4.89E-01	5.4%	43.6%	15.7%	1.2%	37.7%	-3.4%
Acidification (AC)	H^+ moles eq.	1.67E-01	7.6%	67.4%	21.1%	1.1%	2.9%	N/A
Respiratory effects (RES)	kg $PM_{2.5}$ eq.	6.52E-04	3.5%	77.9%	15.6%	0.3%	2.6%	
Eutrophication (EU)	kg N eq.	8.85E-04	1.9%	19.0%	6.2%	0.2%	72.8%	
Ozone depletion (OD)	kg CFC-11 eq.	2.63E-08	6%	53%	31%	4%	7%	
Smog (SM)	kg NOx eq.	2.10E-03	7.7%	36.4%	48.7%	1.8%	5.3%	
Fossil fuel depletion (FF)	MJ surplus	3.94E-01	9.3%	52.4%	29.8%	2.6%	5.9%	

[1] Results obtained using the *ecoinvent* database only (see Section 9.3.1.2 for more details)

National Council for Air and Stream Improvement, Inc. (NCASI). 2010. *Life cycle assessment of North American printing and writing paper products*. Unpublished Report. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

Summary

- GHG concentrations are rising abruptly
- From a scientific viewpoint these are expected to increase radiative forcing and global warming
- A carbon footprint of a service is a method to gauge the net GWP
  - Includes emissions
  - Includes storage
- The carbon footprint is a partial life cycle analysis and as should not be considered in isolation
  - Often there is a tradeoff between carbon footprint and other environmental impacts that should be considered

Summary

- Global Carbon Cycle
- Global Warming Potential
- Radiative Forcing
- Carbon Footprint