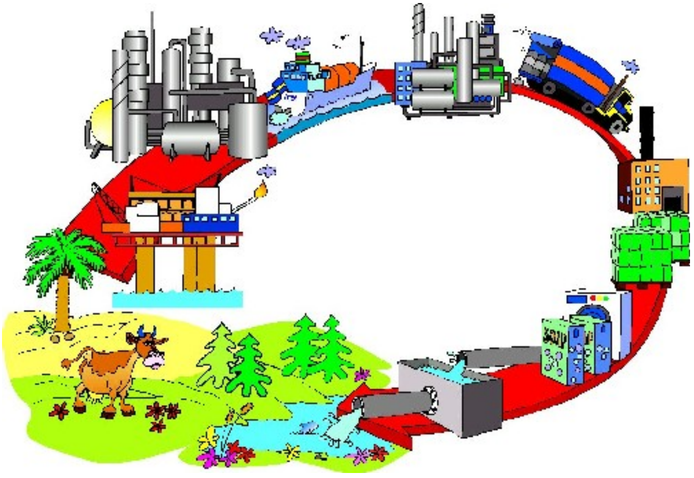
Environmental Life Cycle Assessment
PSE 476/FB 576

Lecture 13: Global Warming and Carbon Footprinting

Richard Venditti



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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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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

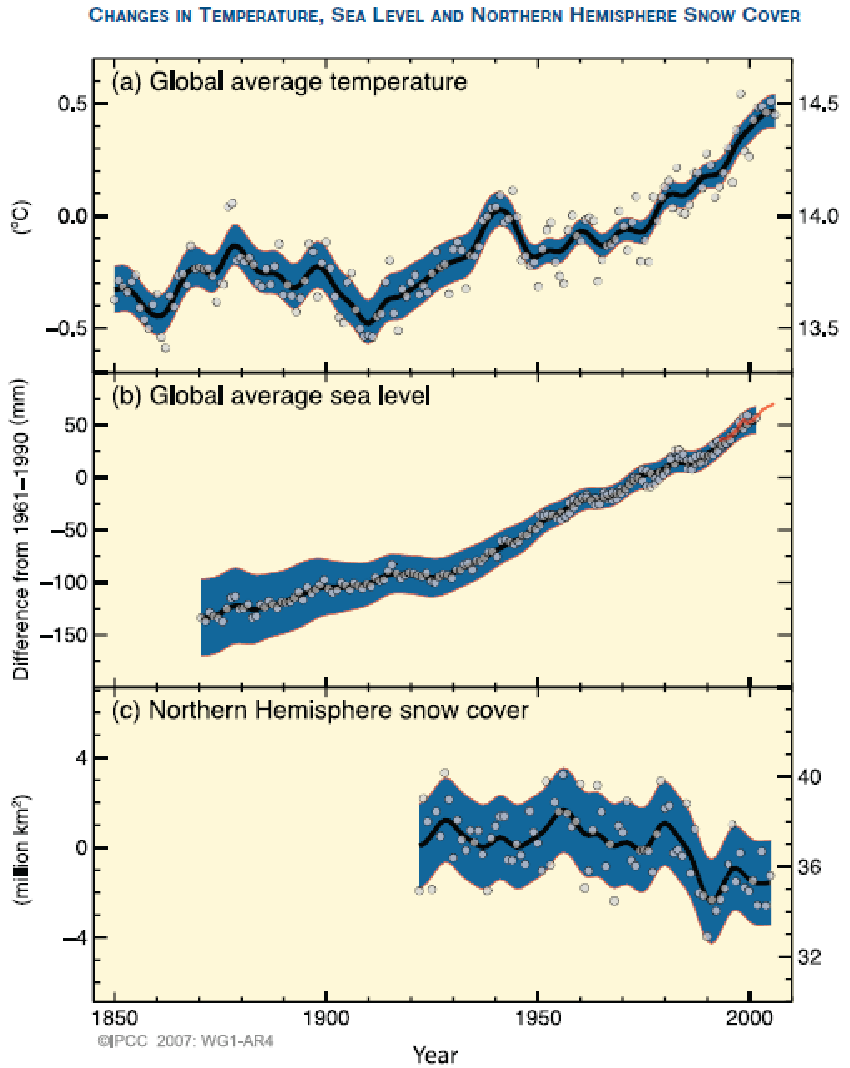
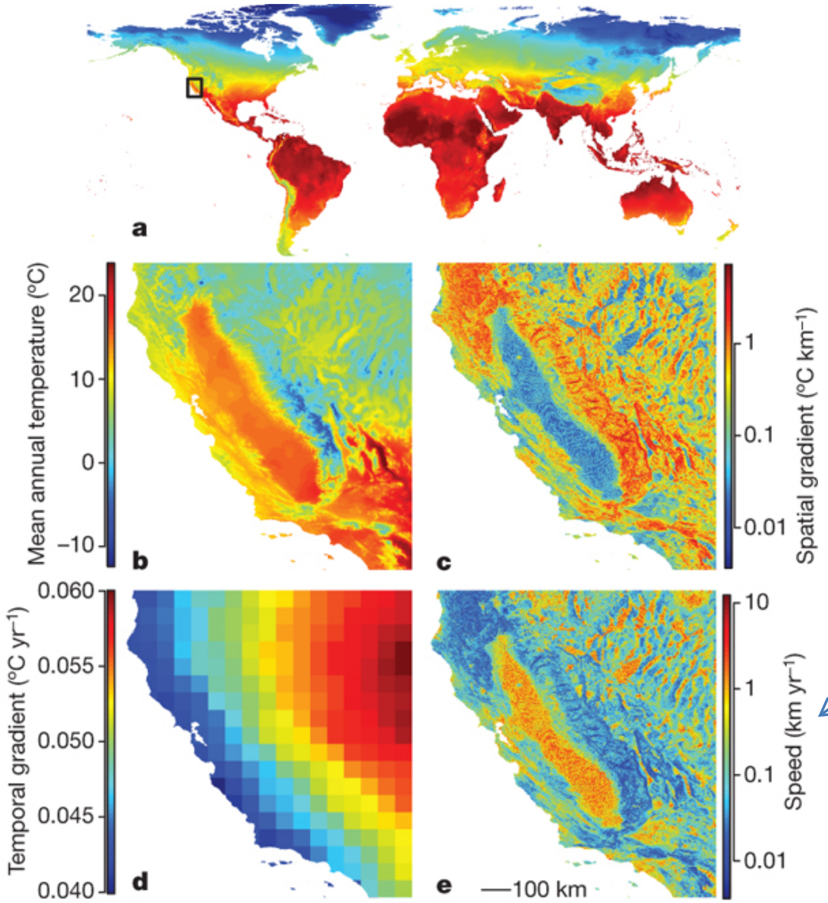


Figure SPM.3. *Observed changes in (a) global average surface temperature, (b) global average sea level from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961–1990. Smoothed curves 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: Uncertainty

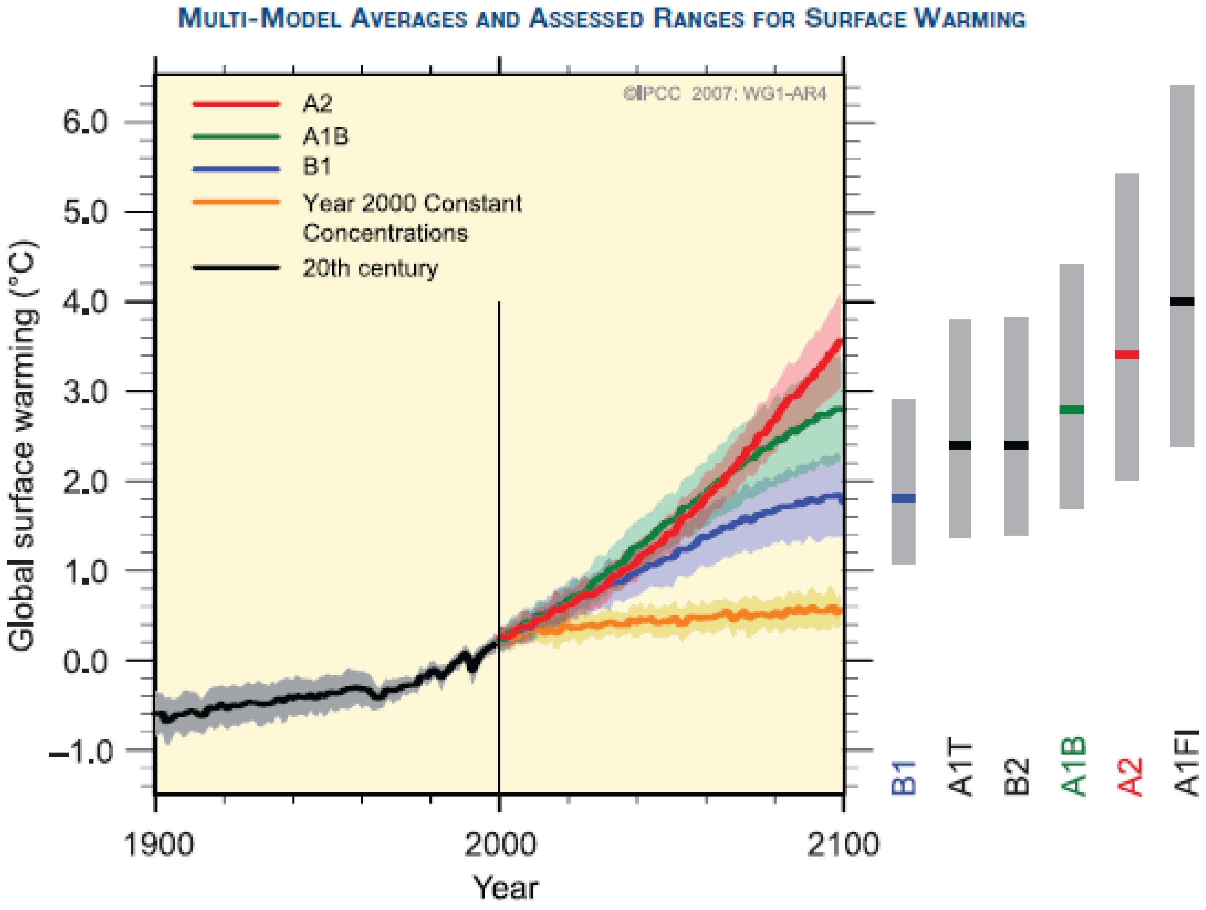


Figure SPM.5. *Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the 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.

Changes in Greenhouse Gases from Ice Core and Modern Data

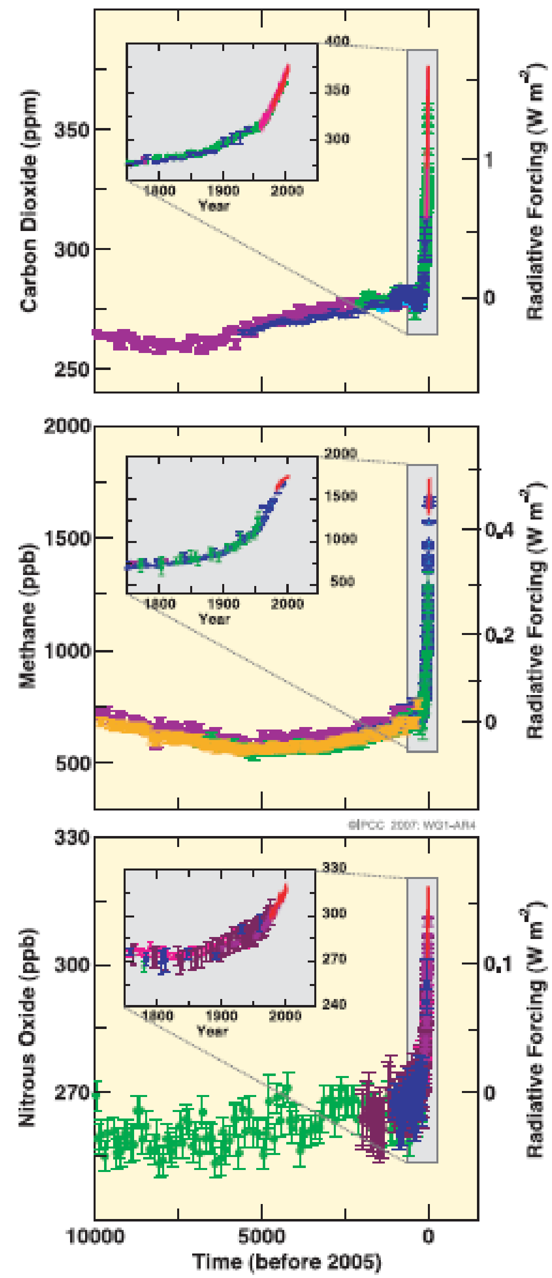
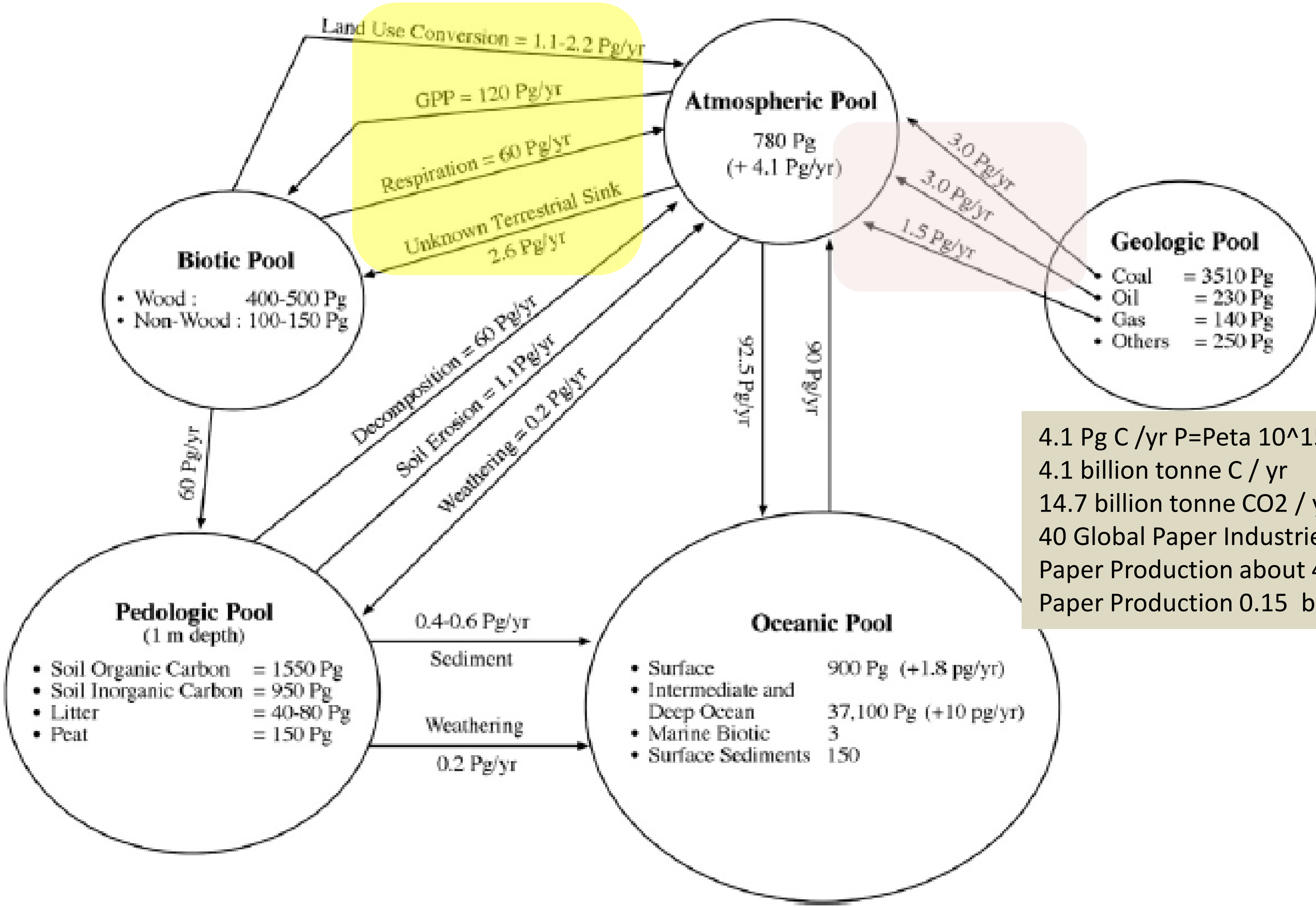


Figure SPM.1. *Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (inset panels). Measurements are shown from ice cores (symbols with different colours for different studies) and atmospheric samples (red lines). The corresponding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

Global Carbon Cycle



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 about 400 million tonne/yr paper
Paper Production 0.15 billion tonne C/yr

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

Global Warming

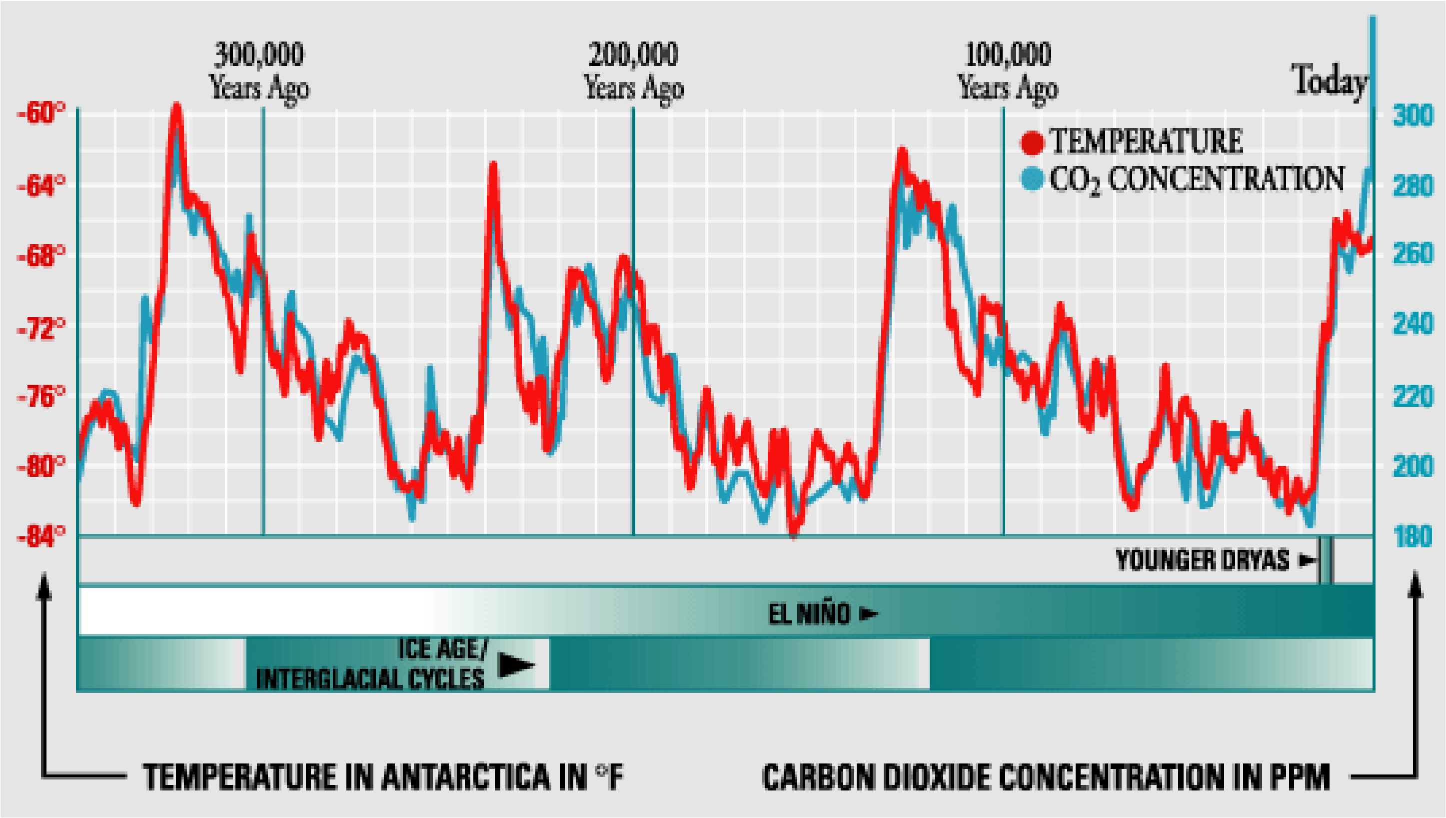


Figure 2. Ice core record from Vostok, Antarctica, showing the near-simultaneous rise and fall of Antarctic temperature and CO2 levels through the last 350,00 years, spanning three ice age cycles. However, there is a lag of several centuries between the time the temperature increases and when the CO2 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).

How do we calculate the global warming potential?

How we measure the warming effect of greenhouse gases

- The warming effect of greenhouse gases depends on the **quantity of the green house gas present in the atmosphere**
- GHGs decay over time **at different rates**

CO_2 Decay Function

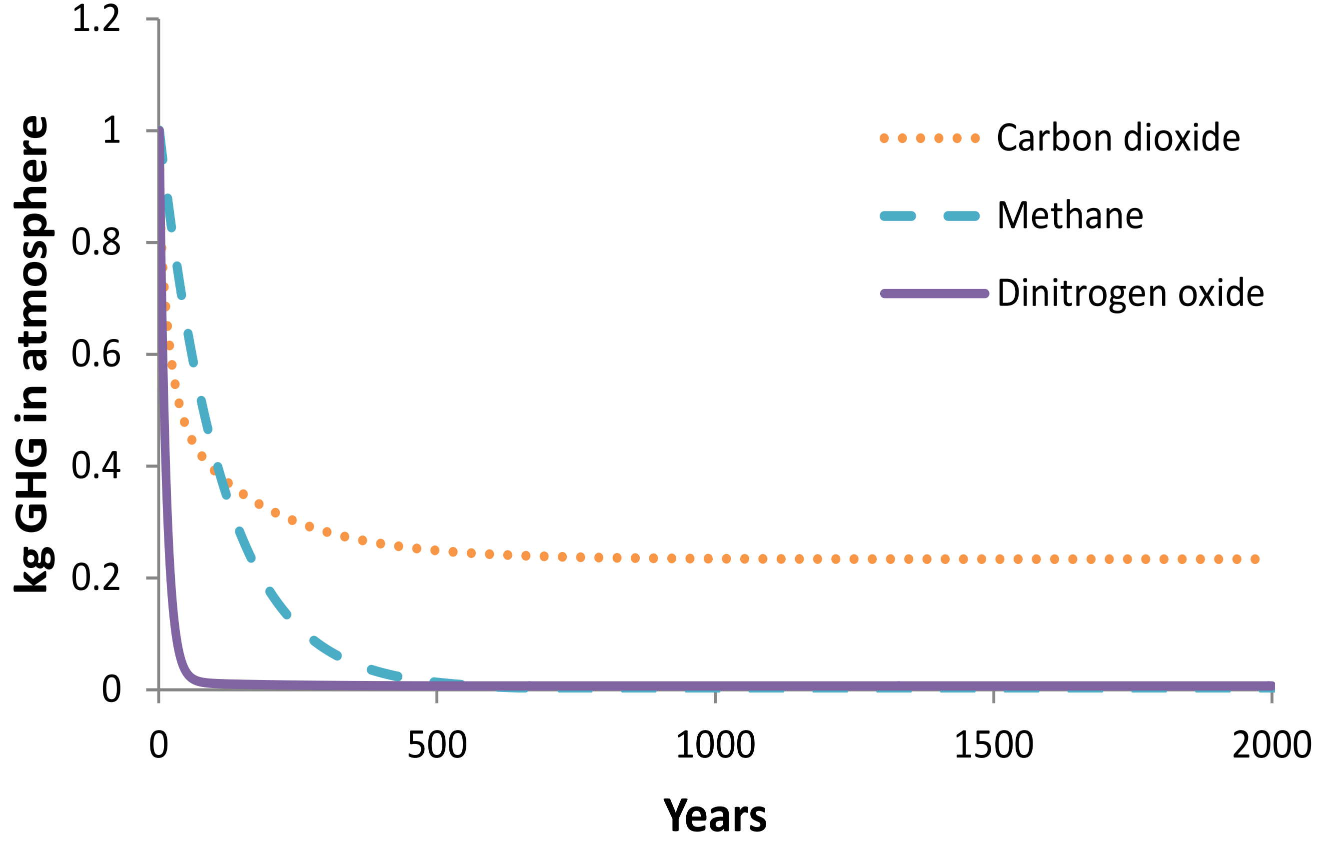
$$C(t) = a_0 + \sum_{i=1}^{3} a_i e^{-1/\tau_i} \qquad \textbf{(7-1)}$$

a_o=0.217, a_1=0.259, a2=0.338, a_3=0.186 τ_1=172.9 years, τ_2 =18.51 years, τ_3 =1.186 years

Other GHGs Decay Function

$$C(t) = e^{-1/\tau}$$

Decomposition of GHG Gasses in Atmosphere



Global Warming Potential Calculation

$$GWP_i^{TH} = \frac{\int_0^{TH} \alpha_i C_i(t)dt}{\int_0^{TH} \alpha_{CO2} C_{CO2}(t)dt} \qquad \textbf{(7-4)}$$

$$GWP_i^{TH} = \frac{\text{Warming due to gas of interest}}{\text{Warming of } CO_2}$$

α_i represents the radiative efficiency for a species of gas and C_i represents the decay function for the species of gas as a function of time.

Global Warming Potential Calculations
Carbon Dioxide (CO2)
Methane (CH4) and Dinitrogen Oxide (N2O)

Year	Carbon dioxide		Methane			Dinitrogen oxide		
	Instantaneous impact $W.m^{-2}$	Cumulative impact $W.m^{-2}$	Instantaneous impact $W.m^{-2}$	Cumulative impact $W.m^{-2}$	GWP (t) kg CO_2 eq	Instantaneous impact $W.m^{-2}$	Cumulative impact $W.m^{-2}$	GWP (t) kg CO_2 eq
1	1.69E-15	1.69E-15	1.75E-13	1.75E-13	103	3.87E-13	3.87E-13	229
2	1.53E-15	3.22E-15	1.61E-13	3.35E-13	104	3.84E-13	7.71E-13	240
3	1.44E-15	4.65E-15	1.48E-13	4.84E-13	104	3.81E-13	1.15E-12	247
4	1.38E-15	6.04E-15	1.37E-13	6.21E-13	103	3.77E-13	1.53E-12	253
5	1.34E-15	7.38E-15	1.26E-13	7.47E-13	101	3.74E-13	1.90E-12	258
6	1.31E-15	8.69E-15	1.16E-13	8.63E-13	99	3.71E-13	2.27E-12	262
7	1.28E-15	9.97E-15	1.07E-13	9.70E-13	97	3.67E-13	2.64E-12	265
8	1.26E-15	1.12E-14	9.90E-14	1.07E-12	95	3.64E-13	3.01E-12	268
9	1.23E-15	1.25E-14	9.14E-14	1.16E-12	93	3.61E-13	3.37E-12	270
10	1.21E-15	1.37E-14	8.43E-14	1.25E-12	91	3.58E-13	3.72E-12	272

Radiative Forcing Capacity (RF) and GWP

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

- 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
- 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*,
- r stands for reference gas

Global Warming Potential Values
Time horizons: 20, 100, and 500 years

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

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

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)

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 meter
- LOSU : level of scientific understanding

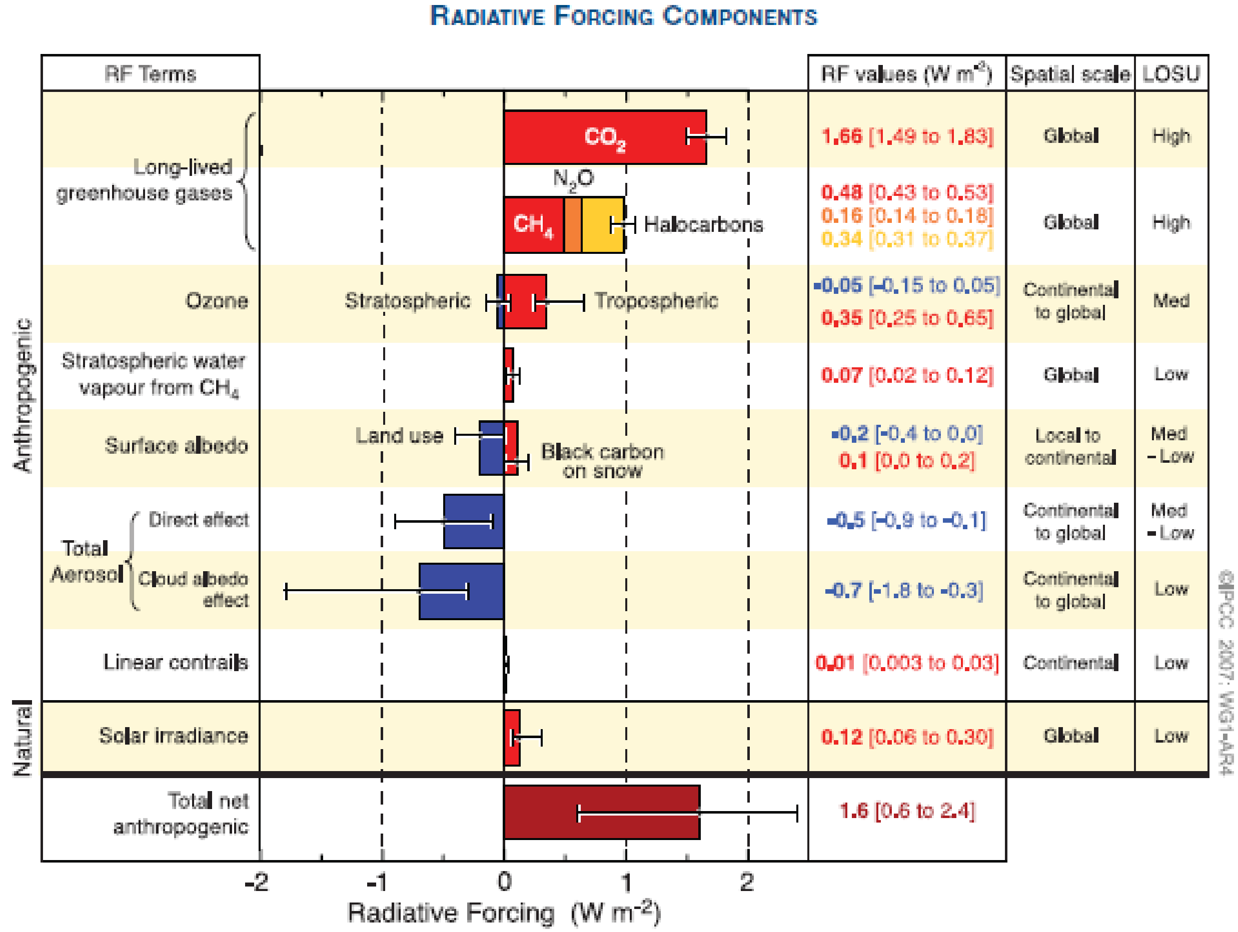


Figure SPM.2. *Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level 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}*

Lecture 13 (cont.) 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)
- "How much net GWP gasses go into the atmosphere"
- **(often there are trade offs not considered when doing just a carbon balance)**

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

INTERGOVERNMENTAL PANEL ON climate change

Carbon Footprint: Impact Assessment Method

- **Often products and flows are specified as having a certain carbon content**

- **To convert the carbon content to CO_2, must multiply by the conversion factor:**
  - **44 kg CO_2 / 12 kg Carbon**

Carbon Footprint:
Impact Assessment Method

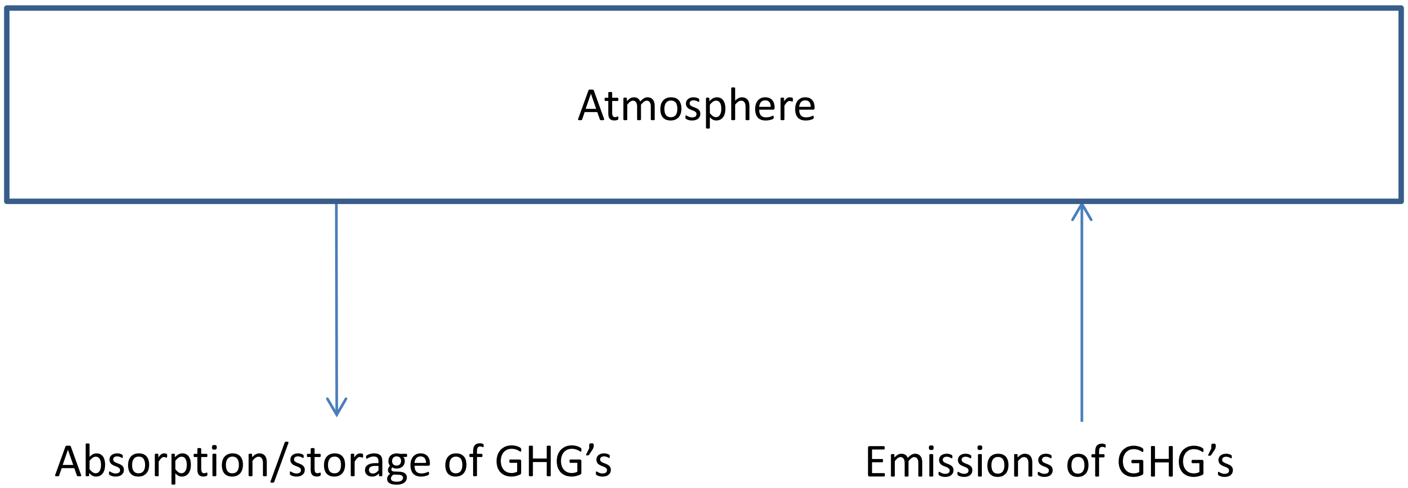
- **Example 400 kg of a charcoal filter cartridge is put in a landfill. The cartridge is 10% metal and 90% carbon filter. The carbon filter has a carbon content of 98% and does not degrade.**
- **What is the amount of carbon that goes into the landfill in terms of CO_2?**

Carbon Footprint: Impact Assessment Method

- **Example: loblolly pine grows at 17 dry tonne per hectare per year. What is the amount of CO_2 take up for 1 hectares of pine if the pine has a % carbon of 52%?**

- **Repeat for unmanaged hardwoods with a growth of 2.2 dry tonne per hectare per year and a carbon content of 50%?**

Carbon Footprint: Accounting for GHG’s in the atmosphere



Carbon footprint = ΣGHG’s flowing IN - Σ GHG flowing OUT

(in kg CO2 equivalents)

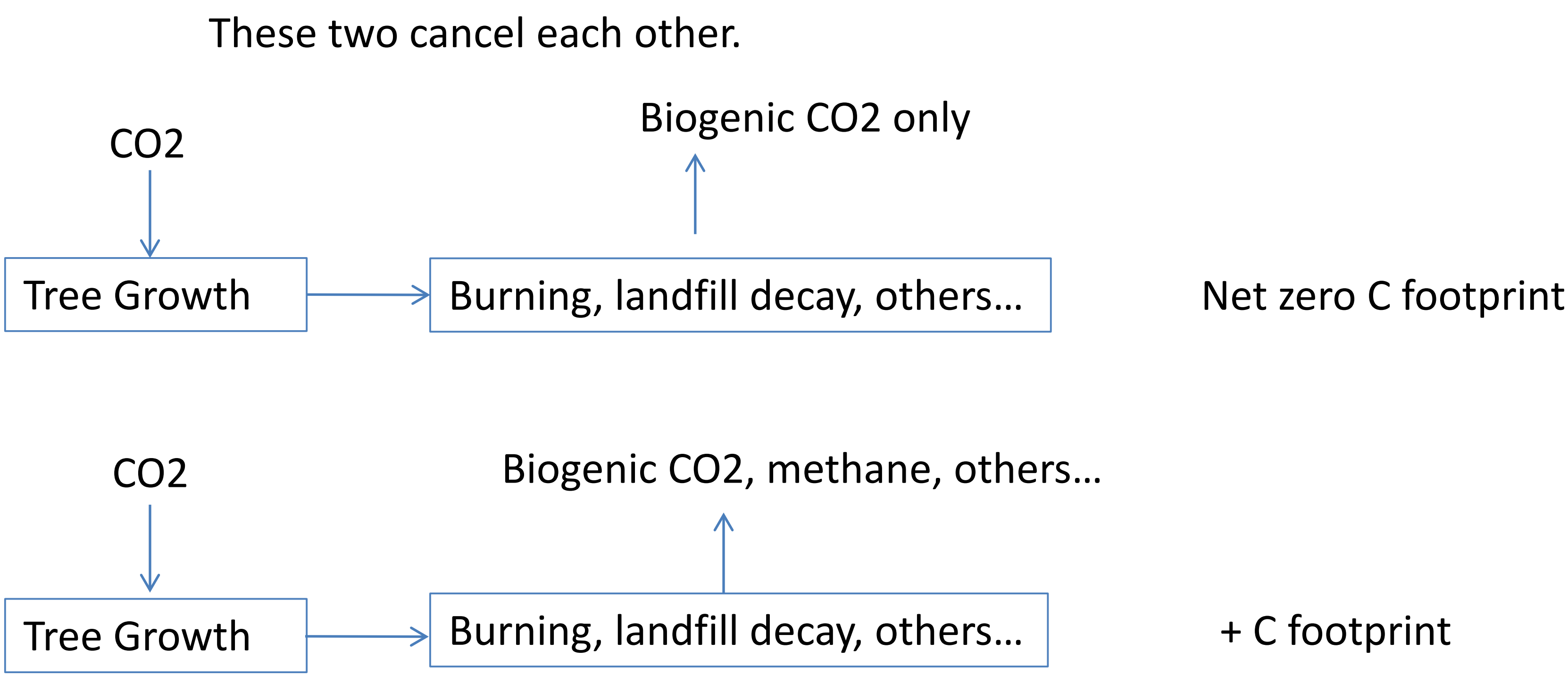
Carbon Footprint: Impact Assessment Method

- Ignore the CO_2 taken from atmosphere into plants. If this is done then ignore all biogenic CO_2 emitted. Take credit for CO_2 storage over the GWP time horizon. **(ignore biogenic flows, more popular)**

- Take a credit for CO_2 taken in from plants. If this is done then take into account all biogenic CO_2 emitted. Do not take credit for CO_2 storage, as this would be double counting CO_2 removed from the atmosphere. **(consider biogenic flows, less popular, harder to track, but shows C flows more explicitly)**

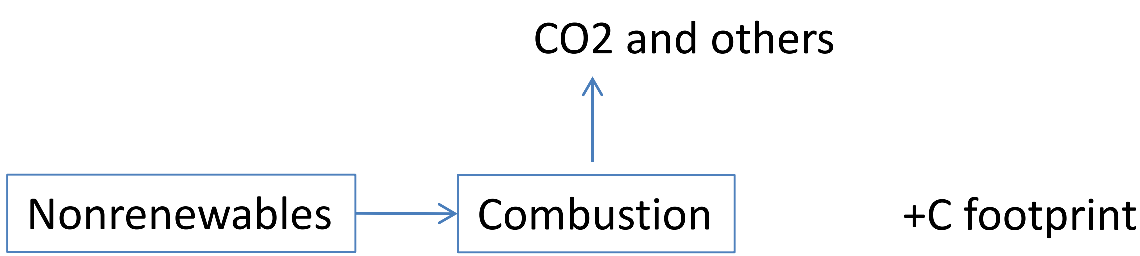
Carbon Footprint:
Impact Assessment Method

- Biogenic material decay/burning that produces methane or N2O must be considered



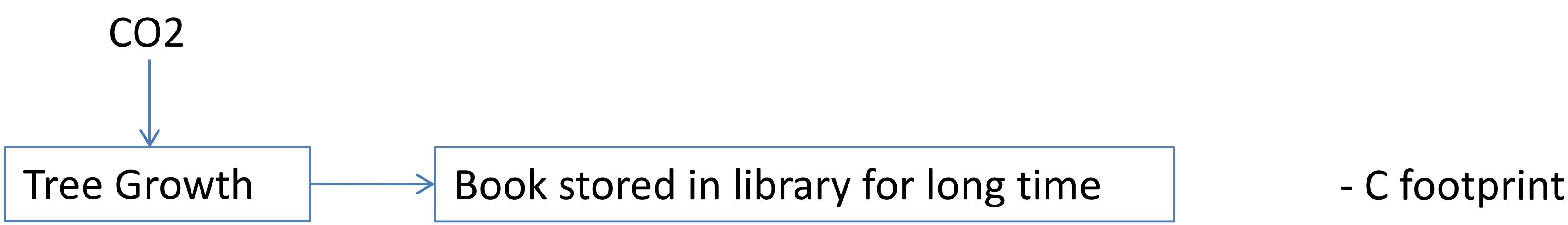
Carbon Footprint:
Impact Assessment Method

- 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



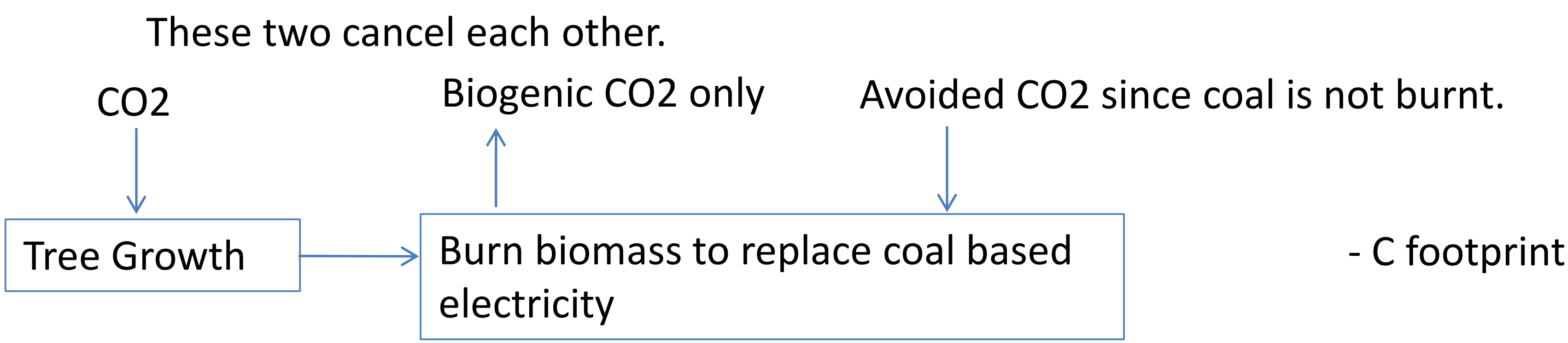
Carbon Footprint: Impact Assessment Method

- Long term storage of carbon away from the atmosphere is considered a negative C footprint contribution if a credit was not taken for plant growth



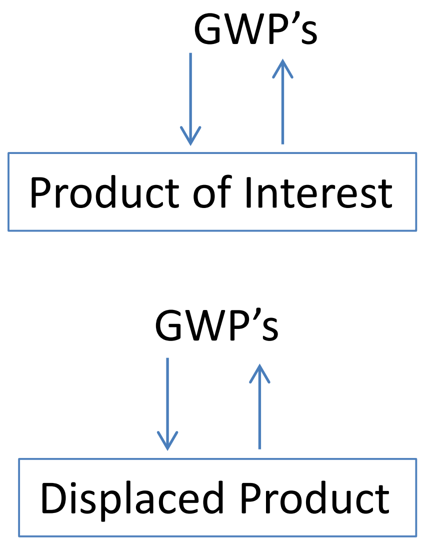
Carbon Footprint:
Impact Assessment Method

- When one product with a lower C footprint replaces another with larger C footprint, and thus the larger C footprint is not used, then an avoided C input to the atmosphere is claimed, a negative C footprint contribution: termed displacement
- ***Example 1,*** *replace non-renewable with renewable biomass that only emits biogenic CO2 in this case:*



Carbon Footprint: Impact Assessment Method

- When one product with a lower C footprint replaces another with larger C footprint, and thus the larger C footprint is not used, then an avoided C input to the atmosphere is claimed, a negative C footprint contribution: termed *displacement* ***Example 2, replace non-renewable (displaced product) with lower footprint non-renewable (product of interest):***



Y = C footprint

Z = C footprint

Net carbon footprint is Y-Z .

Carbon footprint exercise (1)

- A factory typically burns coal to produce electricity. The factory requires 114 MWh of electrical energy per week and the emission factor for the coal based electricity is 710 kg CO_2(eq)/MWh. What is the carbon footprint of displacing the coal electricity with a biofuel that has an emission factor of 24 CO_2(eq)/MWh? (The emission factor accounts for all of the non biogenic CO2 emissions from using the biofuel).

Carbon footprint exercise (2)

- It is found that the final fate of Sports Illustrated magazines is that 10% is stored in houses and libraries for over 100 years. The remaining 90% is sent to landfills. In the landfills, 85% of the magazine never decomposes. Of the part of the magazine that does decompose, 50% by weight decomposes to methane and is lost to atmosphere and 50% decomposes to CO_2. The biogenic carbon content of the magazine is 50%. If the magazine weighs 0.3 kg, what is the carbon footprint (using a 100 year time horizon) per one magazine for its end-of-life stage only?
- The GWP of CO_2 is 1 kg CO_2(eq)/kg.
- The GWP of methane is 25 kg CO_2(eq)/kg.
- The GWP of N_2O is 298 kg CO_2(eq)/kg.
- Formula weight of Carbon =12
- Formula weight of Carbon Dioxide = 44

Basic Steps of the Carbon Footprint

- Define the Goal and Scope:
  - Define the goal
  - Define the scope
    - Functional unit (and ref flows or basis of calculation)
    - System boundary: Operations included, life cycle stages included
    - Time Scale
    - Characterization factor source
    - Others……
- Complete the Life Cycle Inventory:
  - Emissions of GHG's
  - Storage of Carbon
- Perform the life cycle assessment
  - Apply appropriate characterization factors for emissions
    - CO_2 = 1
    - CH_4 = 25
    - N_2O= 298
    - Etc……..
  - Carbon footprint = Sum of the emissions (+) and storage (-)
- Evaluate Results, Interpret, Report
  - Hot spots
  - Comparison of alternatives

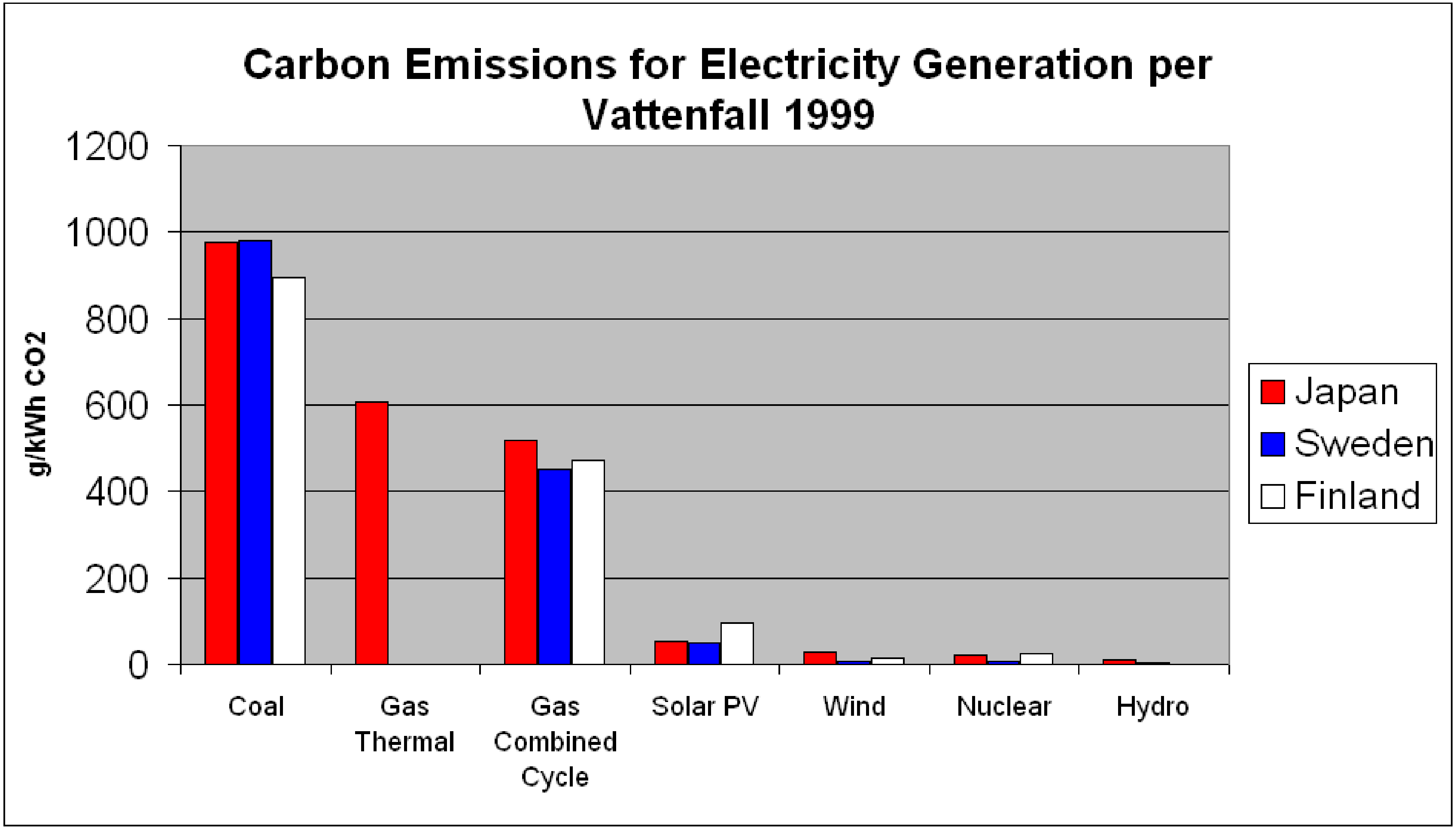
Carbon Footprint: CO2 list.org

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	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
(includes effect of other greenhouse gases)					
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



Scopes within a carbon footprint

- Businesses keep track of who is in control of emissions/storage

- 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.

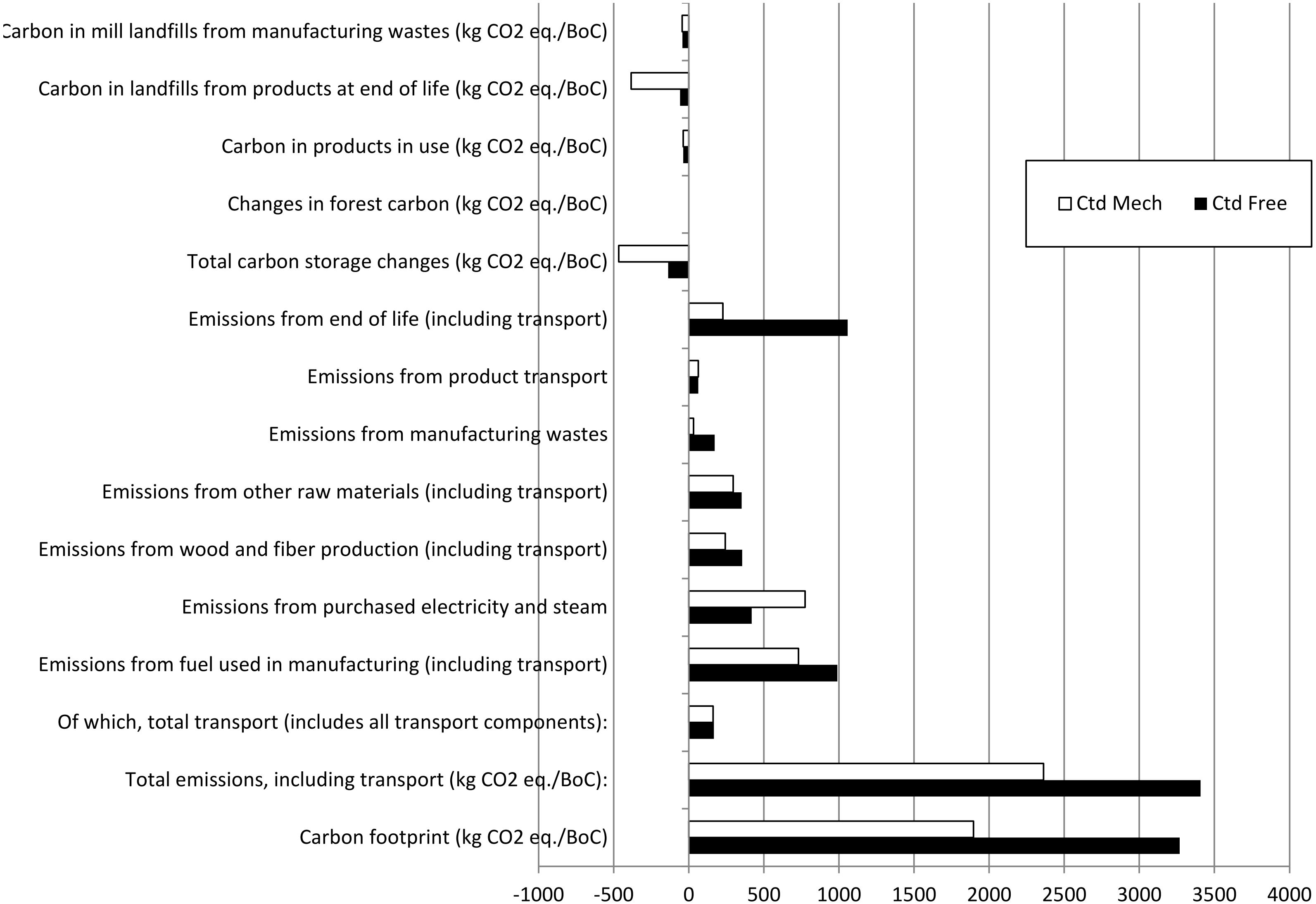
Life Cycle Inventory: Interpretation

- 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 Analysis of Paper: Carbon Footprint Results



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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

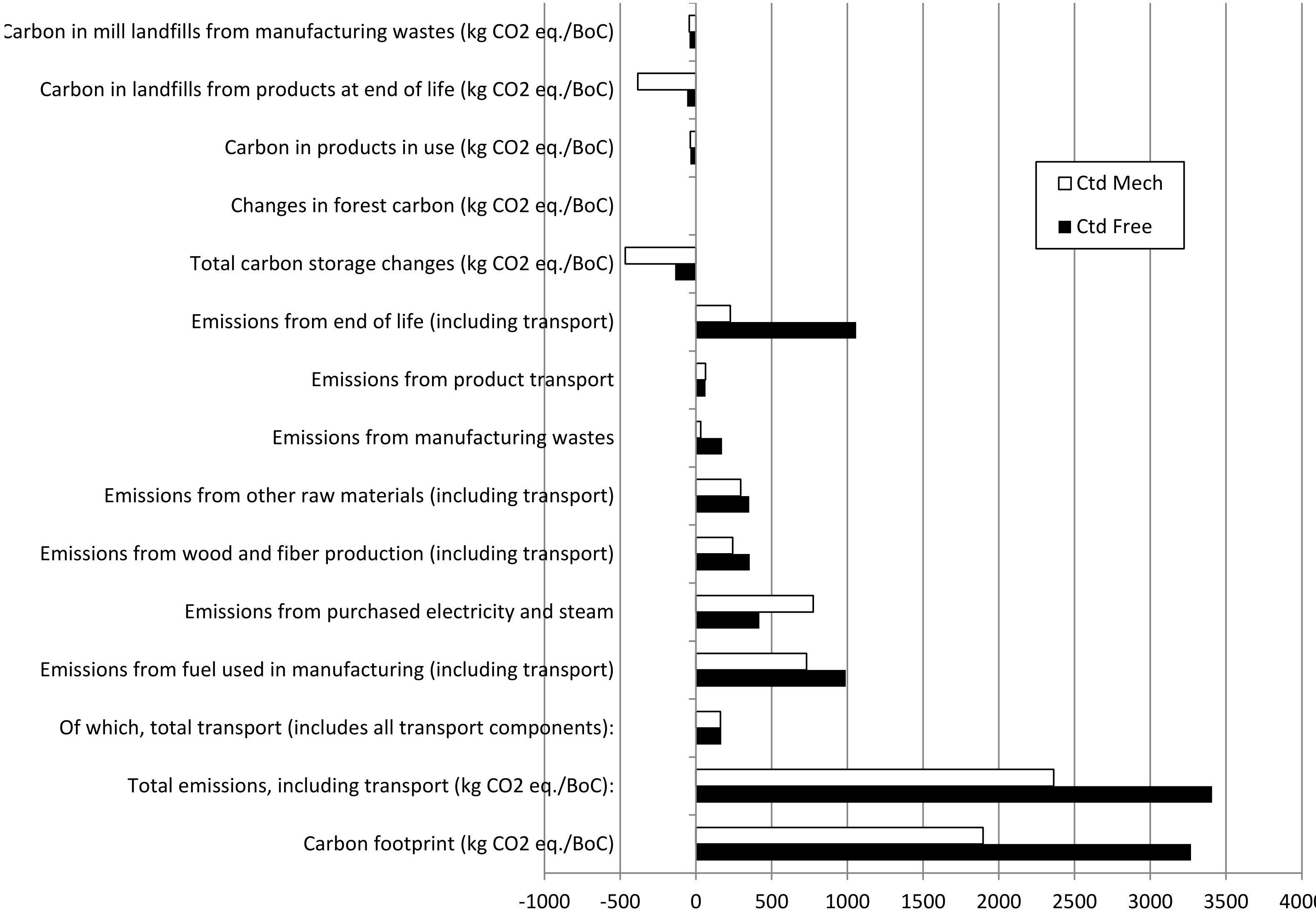
- Global Carbon Cycle
- Global Warming Potential
- CO_2 equivalent
- Radiative Forcing
- Time Horizon
- Carbon Footprint
- IPCC: International panel on climate change (www.ipcc.ch)
- Storage of carbon
- Emissions
- Displacement
- LOSU
- Basis of calculation: also known as the reference flow(s)
- Scope 1 Emissions
- Scope 2 Emissions
- Scope 3 Emissions

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



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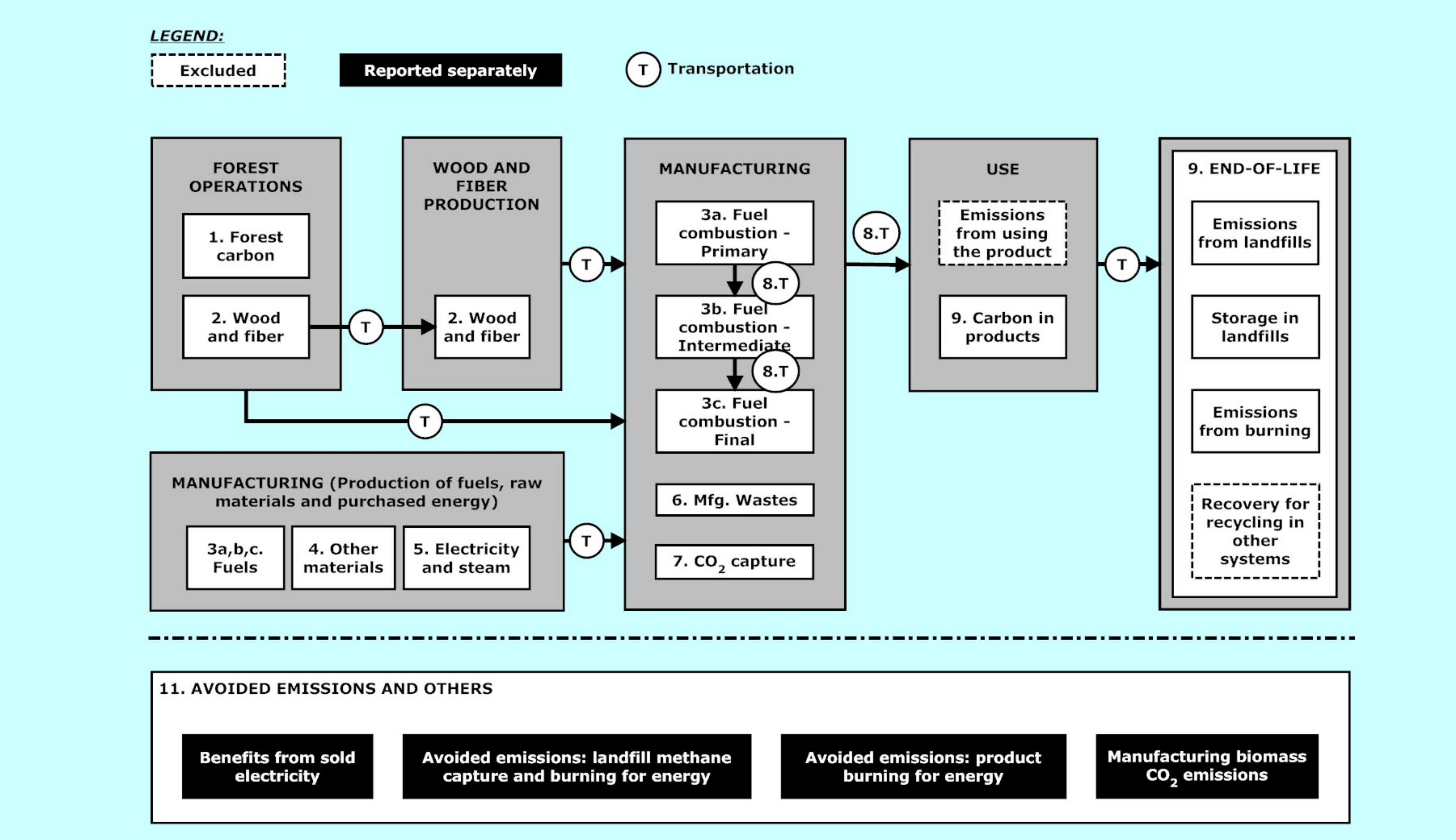
Basic Steps of the Carbon Footprint

- Define the Goal and Scope:
  - Define the goal
  - Define the scope
    - Functional unit (and ref flows or basis of calculation)
    - System boundary: Operations included, life cycle stages included
    - Time Scale
    - Characterization factor source
    - Others……
- Complete the Life Cycle Inventory:
  - Emissions of GHG's
  - Storage of Carbon
- Perform the life cycle assessment
  - Apply appropriate characterization factors for emissions
    - CO_2 = 1
    - CH_4 = 25
    - N_2O= 298
    - Etc……..
  - Carbon footprint = Sum of the emissions (+) and storage (-)
- Evaluate Results, Interpret, Report
  - Hot spots
  - Comparison of alternatives

Define the system 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;
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- 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).

SETUP

Name of this footprint	Coated Freesheet Cut off NCASI 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	60.03
Truck, owned	0		0
Truck, non-owned			5.2728642
Rail, owned	0		0
Rail, non-owned			0.2209328
Water inland, owned	0		0
Water inland, non-owned			0
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***0***	***0***	***65.523797***
Transport only	***0***		***5.4937971***

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	502.1792		29.92392
Truck, owned	0		0
Truck, non-owned			0.053476
Rail, owned	0		0
Rail, non-owned			2.7437457
Water inland, owned	0		0
Water inland, non-owned			0.0642998
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***502.1792***		***32.785442***
Transport only	***0***		***2.8615216***

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	5.7967		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	***5.7967***		***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			67.9338
Truck, owned	0		0
Truck, non-owned			0.62967
Rail, owned	0		0
Rail, non-owned			0.093268
Water inland, owned	0		0
Water inland, non-owned			0
Water ocean, owned	0		0
Water ocean, non-owned			0
Total	***0***		***68.65674***
Transport only	***0***		***0.722939***

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 2	Scope 3
13.0113	0.33306
54.15172	1.31054
11.17055	0.28574
12.04416	0.3519
38.0173	0.9682

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		Transport distances, km	
	Proposed defaults	User Selection	Proposed defaults	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: Interpretation

- 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*
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Total carbon storage changes (kg CO_2 eq./BoC)	*138.3*			
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Method used to estimate amount of product in use: *Weighted avg first order*

Life Cycle Inventory: Interpretation

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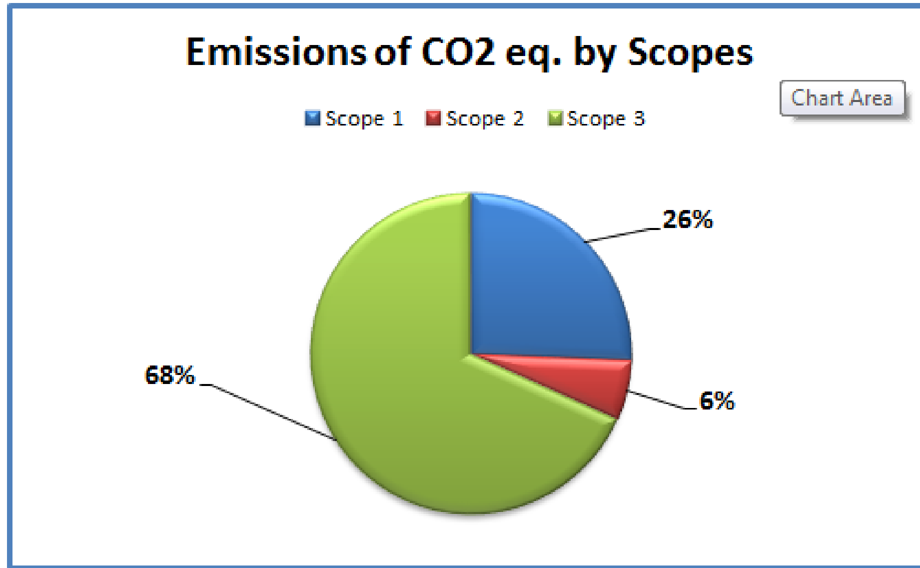
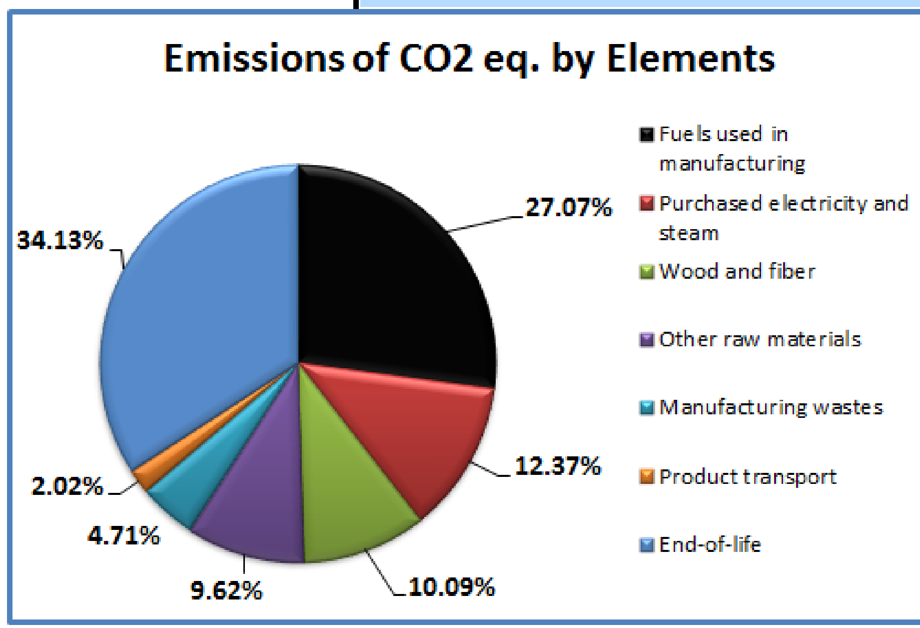
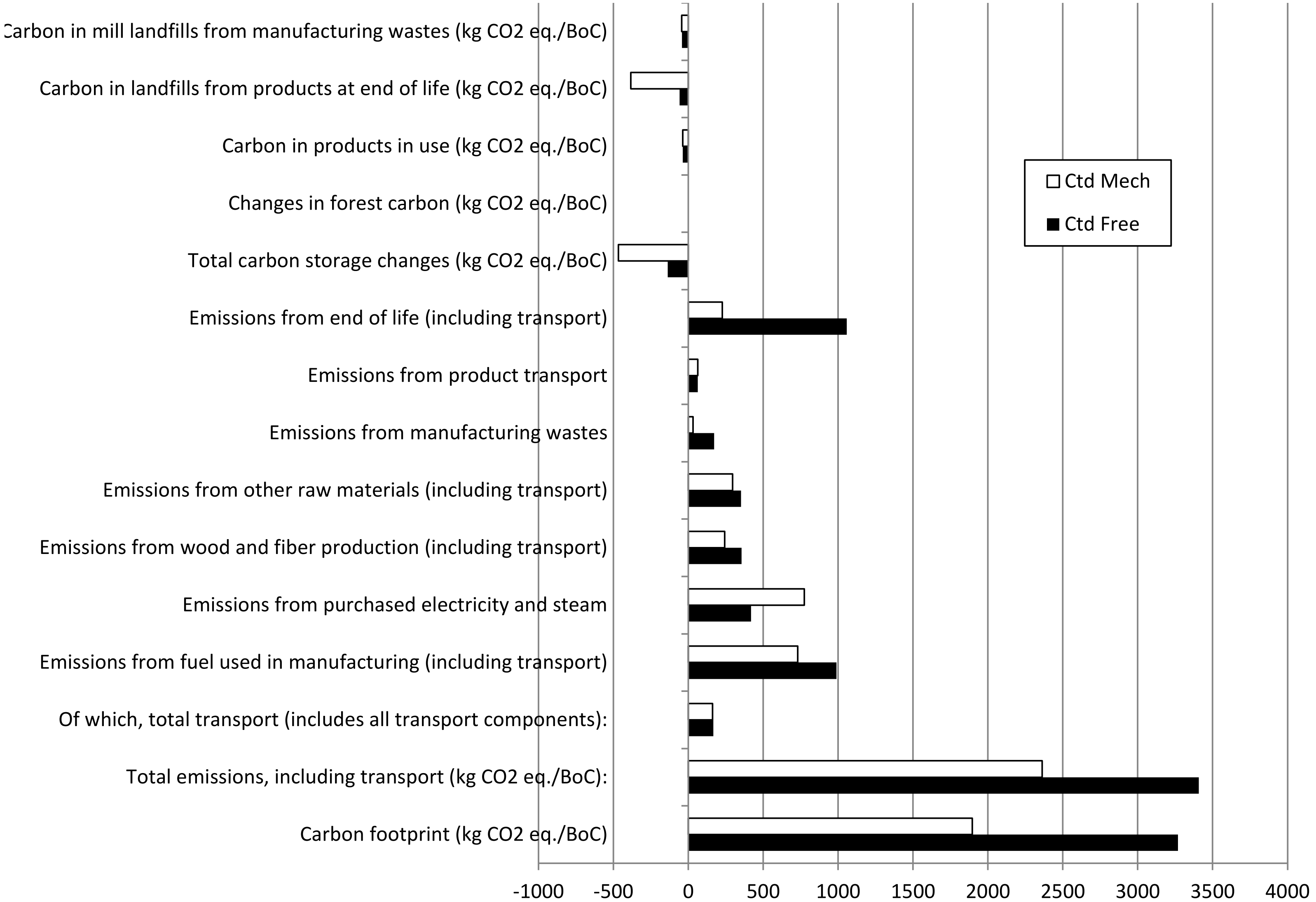
- Interpret....





Life Cycle Analysis of Paper: Carbon Footprint Interpretation



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Full Life Cycle Analysis of Paper: Carbon Footprint Interpretation

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.

Catalog weight is .135 kg, so GWP per tonne is 3620 kgCO2e

Summary

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