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Carbon footprint: current methods of estimation

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Abstract Increasing greenhouse gaseous concentration in the atmosphere is perturbing the environment to cause grievous global warming and associated consequences. Following the rule that only measurable is manageable, mensuration of greenhouse gas intensiveness of different products, bodies, and processes is going on worldwide, expressed as their carbon footprints. The methodologies for carbon footprint calculations are still evolving and it is emerging as an important tool for greenhouse gas management. The concept of carbon footprinting has permeated and is being commercialized in all the areas of life and economy, but there is little coherence in definitions and calculations of carbon footprints among the studies. There are disagreements in the selection of gases, and the order of emissions to be covered in footprint calculations. Standards of greenhouse gas accounting are the common resources used in footprint calculations, although there is no mandatory provision of footprint verification. Carbon footprinting is intended to be a tool to guide the relevant emission cuts and verifications, its standardization at international level are therefore necessary. Present review describes the prevailing carbon footprinting methods and raises the related issues.

Keywords Carbon footprint · Direct emissions · Embodied emissions · Greenhouse gases

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Introduction

The Intergovernmental Panel on Climate Change (IPCC) in its fourth assessment report has strongly recommended to limit the increase in global temperature below 2°C as compared to pre-industrial level (i.e., measured from 1750) to avoid serious ecological and economic threats. A rise in temperature by 0.74°C has already been recorded and hence climate scientists are focusing on an urgent action to curb global warming (IPCC 2007; Kerr 2007). The imbalances caused in natural systems due to warming are already being signaled in the form of extreme weather events and climate change. The mountainous snow cover, permafrost, and glaciers are melting and Greenland, Antarctic, and Arctic ice packs are experiencing a negative mass balance causing the sea level to rise at a rate of 3 mm $year^{-1}$ (Kerr 2006; Rignot and Kanagaratnam 2006; IPCC 2007). Owing to such complex changes in natural phenomena, it has been projected that 1–2 billion additional people will be under water stress, crop productivity in mid-latitudes will suffer loss, and wildlife and biodiversity will be threatened (Kerr 2007). On social forefront, developing and poor countries are at immediate and disproportionately high risk of being adversely affected by global warming and thus the "MILLENNIUM development goal" of eradicating poverty may be compromised (UNDP 2007). "The world is running short of time and option" at social and economic front in view of high risks related with global warming and climate change (Stern 2006). Strong and immediate local to international actions are thus needed to stabilize emissions in a justified manner. As the understanding of the science and consequences of global warming grew, the concern for preventing disastrous climate change led to a substantive action in the form of endorsement of "Kyoto protocol" in 1997 which requires developed economies or economies in transition listed in its annexure I to reduce their collective emissions of six important greenhouse gases (GHGs) namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), set of perfluorocarbons, and hydrofluorocarbons by at least 5.2% as compared to 1990 level during the period 2008–2012 (UN 1998). The gases covered under Kyoto protocol are referred collectively as "Kyoto gases" (WRI/WBCSD 2004). This protocol, however, has not received equal support from all the nations and some did not ratify it giving reasons that their economies may suffer loss. However, a critical review over impacts of acting or not acting against climate change carried out by Stern (2006) led to the conclusion that "the benefits of strong early action considerably outweigh the costs." It was predicted that not acting immediately will cost at least 5% of global gross domestic product (GDP) loss annually while annual investment equivalent to 1% of global GDP may help in limiting temperature rise below 2°C. Otherwise it would be impossible to revert the changes. Emissions of Kyoto gases need to be cut by 25% below the current level by 2050 so that the growth of countries is not compromised.

Greenhouse gas sources

Rapid rise in global temperature is due to the "enhanced greenhouse effect" (i.e., the greenhouse effect additional to the natural) due to human induced release of GHGs into the atmosphere. Not all GHGs have equal capacity to cause warming but their strengths depend on radiative forcing it causes and the average time for which that gas molecule stays in the atmosphere. Considering these two together, the average warming it can cause, known as 'global warming potential' (GWP), is calculated mathematically and is expressed relative to that of CO_2. Therefore, unit of GWP is carbon dioxide equivalent (CO_2-e).

Important contributors to global warming are Kyoto gases, whose emissions increased by 70% during 1970–2004 (IPCC 2007). In addition to these six gases, the members of chlorofluorocarbons family bear very high GWP, but since their emissions have been controlled successfully under Montreal protocol, they are no longer a problem. Tropospheric ozone and black carbon have also been found to warm the troposphere. The rates of increment in GHG concentrations are extraordinarily high, far exceeding the natural range as evident from geological and ice core studies (IPCC 2007). The biggest share of these GHGs comes from fossil fuel combustions in the form of CO_2 (58.6%). Next come CH_4 and N_2O contributing to 14.3% and 7.9%, respectively, to total collective CO_2-e. Major sources of these two gases are the agricultural systems (IPCC 2007).

In order to comply with 2°C target, the atmospheric stock of GHGs needs to be stabilized below 550 ppm in terms of carbon dioxide equivalents, of which 430 ppm has been attained in 2007 (Page 2008). Therefore GHG inventories are going on all over the world and every possible method to control them are being recognized and evaluated. As the climate change issues became prominent on political and corporate agenda, general public especially in developed countries started recognizing their responsibility towards taking action against global warming (Goodall 2007). These concerns and media have provided tremendous popularity to quantification of the contribution of various activities to global warming usually represented in terms of "carbon footprint". However, information available on carbon footprinting beset with uncertainty and inconsistency (Schiermeier 2006; Wiedmann and Minx 2007; Kenny and Gray 2008; Padgett et al. 2008). The objective of the present review is to systematically analyze the relevant available information on global warming, GHG emissions and characteristics, carbon footprinting concepts, calculation of carbon footprints, methodology followed for estimation, and uses of this by general public, corporate sector, industries, and governments.

Concept of carbon footprint

Origin of carbon footprint can be traced back to as a subset of "ecological footprint" proposed by Wackernagel and Rees (1996). Ecological footprint refers to the biologically productive land and sea area required to sustain a given human population expressed as global hectares. According to this concept, carbon footprint refers to the land area required to assimilate the entire CO_2 produced by the mankind during its lifetime. In due course of time as the global warming issue took prominence in the world environmental agenda, use of carbon footprint became common independently, although in a modified form (East 2008). The concept of carbon footprinting has been in use since several decades but known differently as life cycle impact category indicator global warming potential (Finkbeiner 2009). Therefore, the present form of carbon footprint may be viewed as a hybrid, deriving its name from "ecological footprint", and conceptually being a global warming potential indicator. There are few studies that report carbon footprint in terms of global hectares notwithstanding the modern nexus about it (Browne et al. 2009). Besides its widespread favorable public reputation as an indicator of contribution of an entity to the global warming, there are confusions over what it exactly means (Wiedmann and Minx 2007; East 2008; Finkbeiner 2009; Peters 2010). It is also remarked that the scientific literature on the subject is scarce and the most studies have been carried out by private organizations and companies predominantly due to their business sense rather than their environmental responsibility (Kleiner 2007; Wiedmann and Minx 2007; East 2008). Other terms used associated or sometimes as a synonym of carbon footprint in the available literature are embodied carbon, carbon content, embedded carbon, carbon flows, virtual carbon, GHG footprint, and climate footprint (Wiedmann and Minx 2007; Courchene and Allan 2008; Edgar and Peters 2009; Peters 2010). There is little uniformity in the definitions of carbon footprint within the available literature and studies (Wiedmann and Minx 2007). Based on their survey, Wiedmann and Minx (2007) defined that the carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product. A new term "climate footprint" was proposed as a comprehensive GHG indicator, i.e., if all the GHGs originating from within the boundary are quantified. However, new studies and methods followed for carbon footprint calculation, suggest including other GHGs as well, apart from only CO_2 (Office of sustainability and environment, City of Seattle 2002; Kelly et al. 2009; Eshel and Martin 2006; Bokowski et al. 2007; Ferris et al. 2007; T C Chan Center for Building Simulation & Energy Studies/Penn Praxis 2007; Garg and Dornfeld 2008; Good Company 2008; Johnson 2008, Edgar and Peters 2009; Browne et al. 2009).

There is a lack of uniformity over the selection of direct and embodied emissions. Direct emissions are those that are made directly during the progress of a process. As an example, CO_2 released during combustion in a gasoline fired industrial boiler is a direct emission. On the other hand in electrically heated boiler, no direct emissions will be observed. But if the electricity used in the boiler was generated in a thermal power plant, the amount of CO_2 released in generation and transmission of the units of electricity consumed in the boiler is referred as the embodied or indirect emission. It becomes complex to include all possible emissions and thus most studies report only direct or first order indirect emissions (Carbon Trust 2007b; Wiedmann and Minx 2007; Matthews et al. 2008b). In absence of consistencies among selection of characteristic properties of carbon footprint viz. gases selected and boundaries drawn for the carbon footprint calculations by different organizations vary significantly (Wiedmann and Minx 2007; Kenny and Gray 2008; Padgett et al. 2008). Since carbon footprint is associated with money transactions in form of taxes, carbon offsets, or increase/decrease in consumer choices, consistent carbon footprint calculations are essential to facilitate comparisons. In spite of prevailing differences among the calculations, the CO_2 equivalent (CO_2-e) mass based on 100 years global warming potential has been accepted as reporting unit of carbon footprint (WRI/WBCSD 2004; Carbon Trust 2007b; BSI 2008). Hammond (2007) and Global Footprint Network (2007) hold the opinion that “footprints are spatial indicators”. Hence, the term commonly called as carbon footprint should precisely be called as “carbon weight” or “carbon mass” (Jarvis 2007). But CO_2-e mass has been promoted as unit of carbon footprint due to convenient calculations and wide acceptance (Lynas 2007). Therefore carbon footprint may be defined as, “the quantity of GHGs expressed in terms of CO_2-e, emitted into the atmosphere by an individual, organization, process, product, or event from within a specified boundary”. The set of GHGs and boundaries are defined in accordance with the methodology adopted and the objective of carbon footprinting as discussed later in this review.

Importance of carbon footprinting

Carbon footprint, being a quantitative expression of GHG emissions from an activity helps in emission management and evaluation of mitigation measures (Carbon Trust 2007b). Having quantified the emissions, the important sources of emissions can be identified and areas of emission reductions and increasing efficiencies can be prioritized. This provides the opportunity for environmental efficiencies and cost reductions. Reporting of carbon footprint to the third party or disclosure to the public is needed in response to legislative requirements, or carbon trading or as a part of corporate social responsibility, or for improving the brand’s image (Carbon Trust 2007b; L.E.K. Consulting LLP 2007).

Legislative actions have been taken to quantify and reduce carbon footprint of cities and organizations and it is playing an important role in policy making (Office of sustainability and environment, City of Seattle 2002; Courchene and Allan 2008; Good Company 2008). USA has made it mandatory to keep register of emissions from firms and companies under ‘Consolidated Appropriations Act, 2008’ (Rich 2008). EU has also taken lead in formulating legal bindings for reduction in emissions embodied in aviation. California capped

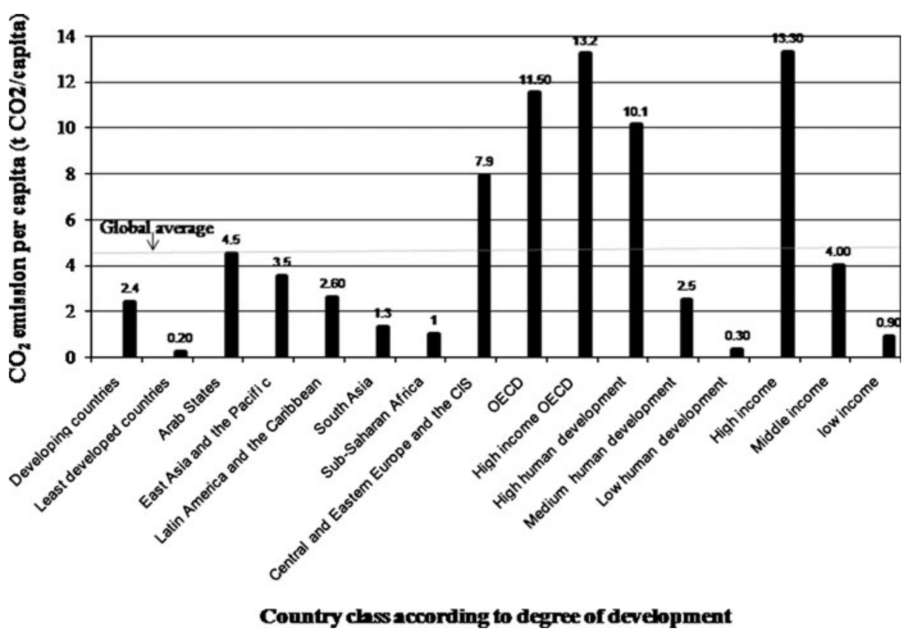


Fig. 1 Carbon footprint per capita in different classes on countries based on degree of development (based on UNDP 2007)

Table 1 Carbon footprints of some entities and the tiers covered

S. no.	Event/product/organisation	Entity/activity	Carbon footprint (ton CO_2-e)	Reference
1	World's per capita	Based on emissions from fossil fuel consumption, gas flaring, and cement production	4.5 in 2004	UNDP (2007)
2	Per capita national footprint	Based on emissions embodied in construction, shelter, food, clothing, manufactured products, mobility, service, and trade	In 2001 USA: 2.86 × 10 Brazil: 4.1 France: 1.31 × 10 India: 1.8 China: 3.1 Malaysia: 4.2 Zimbabwe: 2.0	Edgar and Peters (2009)
3	United Nations Climate Change Conference, 2008 in Poznań (an estimate carried out by the Polish government)	Tier I: air travel and local transport Tier II and III (no clear demarcation between the tiers available): hotels, meeting rooms	Approx. 1.3×10^4	UNFCCC (2008), http://unfccc.int
4	The World Bank's energy portfolio Assumption: all reserves activated with the World Bank assistance will be extracted and burned and projects operate at full capacity for a lifetime of 20 years. All end use emissions are calculated Methodology adopted: IPCC tier I approach (i.e., using a default emissions factor)	Fossil fuel-based extraction, production, and energy generation projects supported by The World Bank Excluded: other emissions-intensive sectors, transport, infrastructure, and industry, or additional emissions from fossil fuel production, like gas flaring, transmission lines for electricity, projects, and specific fossil fuel projects for which data have not been disclosed publicly	5.353×10^9 in 2001 8.23×10^8 in 2008	Craeynest and Streatfeild (2008)
5	University of British Columbia (Point grey campus)	Tier I: heat, commuter traffics, transit, and flights Tier II: emissions embodied in electricity	8.2750×10^4	Ferris et al. (2007)
6	University of Pennsylvania	Tier I: natural gas and transportation Tier II: energy consumption through the use of steam, chilled water, and electricity Tier III: agriculture, solid waste disposal, and refrigerant	3.0×10^5	TC Chan center for building simulation/ Penn Praxis (2007)
7	Books and documents in engineering library, University of California Berkeley	Tier I: travel of labors and business trips Tier II: embodied GHGs in energy, electronic equipments, and books Tier III: not defined	5.8526×10^9 year^{-1}	Garg and Dornfeld (2008)

Table 1 (continued)

S. no.	Event/product/organisation	Entity/activity	Carbon footprint (ton CO_2-e)	Reference
8	Hawaii	Tier I: ground and air transportation Tier II: electric utilities Tier III: not covered	2.154×10^7 in year 2005	USDoE (2005)
9	The City of Vancouver, Canada	Tier I: vehicle fleet, diesel and natural gas consumption, and refrigerants Tier II: electricity Tier III: all other indirect sources of greenhouse gas emissions that may result from city activities or originate from sources owned or controlled by others, such as from the production of goods purchased by the city, emissions from land-filled solid waste, and employee's personal commuting habits	4.1983×10^7 in year 2006 4.1013×10^7 in year 2007	Good company (2008)
10	The city of Seattle, USA	Tier I: fuel consumption associated with transportation, electricity generation, and city heating Tier II: significant embodied GHG emissions in electricity, infrastructure, and city heating Tier III: all other emissions those are under direct influence or control of the Mayor	7.013×10^6 in year 2000	Office of Sustainability and Environment, City of Seattle (2002)
11	Average household in UK	Tier I: CO_2 embodied in fuel use in houses and personal vehicles Tier II and III: CO_2 embodied in personal aviation, goods and services	Approx. 5.5×10^2	Druckman and Jackson (2009)
12	Household in UK under reduced consumption scenarios	Tier I: fuel use in houses and personal transportation Tier II and III: personal aviation, goods, and services	Couple parents with four children: approx. 3.5×10, couple parents with one child: approx. 2.125×10, single pensioner: approx. 7.5	Druckman and Jackson (2010)
13	Wildfires in the continental USA, excluding Washington D.C. each year	(Tiers cannot be defined well) Based on CO_2 released during forest fires in US continent averaged over 2002–2006	2.93×10^8	Wiedinmyer and Neff (2007)

Table 1 (continued)

S. no.	Event/product/organisation	Entity/activity	Carbon footprint (ton CO_2-e)	Reference
14	Hurricane Katrina on US gulf coast	(Tiers cannot be defined well) Based on CO_2 released due to biomass loss due to hurricane	3.85×10^8	Chambers et al. (2007)
15	FIFA world Cup 2006	Tier I: onsite fuel consumption related to construction of stadiums, travel within the country, and temporary facilities Tier II: electricity consumption at the stadiums, temporary facilities and those used for accommodating visitors Tier III: not defined	1.0×10^5	Bellassen and Leguet (2007)
16	Road freight transport in Britain forecast (based on CO_2 only)	Tier I: fuel consumption, projected change in fuel efficiency, projected change in carbon intensity of fuel, loading factor, road quality	1.93×10^7 business-as-usual forecast for 2020: 1.74×10^7	Piecyk and McKinnon (2009)
17	Per capita carbon footprint of metropolitan cities	Tier I: transportation systems. Emissions from commercial buildings, industry, and other modes of transportation such as planes, transit, and trains have been omitted Tiers II and III: not clear but urban morphology and policy interventions have been included	Average of 100 metropolitan cities: 2.24 for 2005 US average 2.6 for 2005	Brown et al. (2009)
18	Chlor alkali plant	Tier I: fuel consumption in boiler and transportation of raw materials Tier II: electricity consumption Tier III: not undertaken	4.358×10^3 per month	Tjan et al. (2010)
19	Tongkat Ali extract production	Tier I: fuel consumption in boiler and transportation of raw materials Tier II: electricity consumption Tier III: not undertaken	1.37×10 per month	Tjan et al. (2010)
20	Average balanced diet in India	Tier I: fuel consumption in cooking Tier II: transportation Tier III: raw material production (agricultural practices), processing	Vegetarian adult male: 7.23×10^{-4} Vegetarian adult female: 5.83×10^{-4} Non vegetarian adult male: 1.031×10^{-3} Non vegetarian adult female: 8.918×10^{-4}	Pathak et al. (2010)

Table 1 (continued)

S. no.	Event/product/organisation	Entity/activity	Carbon footprint (ton CO_2-e)	Reference
21	Reduction in carbon footprint of surgical scrub through change in tap design in an average hospital	Tier I: not applicable Tier II: electricity consumption in water heater Tier III: tap design, scrubbing time, and temperature of water	1.4×10^4/year	Somner et al. (2008)

the GHG emissions from major industries and put a moratorium on import of non-conventional vehicular fuels unless its carbon footprint is less than that of petroleum-derived fuel (Courchene and Allan 2008). California Global Warming Solution Act, 2006 is aimed at bringing the emissions of California to the level of 1990 by 2020 (Capoor and Ambrosi 2009). The UK Government through the Low Carbon Transition Plan, 2009 instigates households to contribute towards building a low carbon future (Department of Energy and Climate Change 2010). Most of the organizations and almost all personal carbon footprinting attempts have been observed to head towards reducing the emissions or offsetting the footprints through buying carbon credits, or other control measures. Besides policy matters, carbon footprint has got an enormous importance for business. The corporate world has sensed a carbon constrained economy in near future (Kleiner 2007). Hence a rush to calculate the carbon footprint and to cut down the emissions has begun worldwide so as to take competitive advantage (Kleiner 2007). It is proved by the fact that number of companies participating in CDP increased from 383 in 2008 to 409 in 2009 (CDP 2009). In a survey conducted by L.E.K. Consulting LLP (2007), it was found that 44% consumers preferred to buy the products, which provided the information about their carbon footprints, while 43% were willing to pay more for the products with relatively low carbon footprint. Hence the corporate sector has responded in a big way. With growing awareness regarding climate change, a remarkable concern has grown in individuals over their responsibility of contributing to the emissions of GHGs. This has led to the surge of personal carbon footprinting facilities (consultancies and online calculators) particularly in developed countries (Padgett et al. 2008; Kenny and Gray 2008). After footprint calculation, they offer to offset the footprint by tree plantation, supporting forestation, and renewable energy resources (Murray and Day 2009) and for this reason, a dramatic growth in voluntary carbon market has been reported since 1989 (Hamilton et al. 2007). Decrease in fossil-fueled transport systems can be achieved through propensity to walk and use bicycles as a behavioral change in individuals (Frank et al. 2010).

In addition to its business importance, carbon footprint has been used as an indicator of the impact of lifestyle of a citizen of a country on carbon emissions. The UNDP (2007) and Edgar and Peters (2009) published country wise per capita carbon footprint, a convenient way to compare contributions of countries, cities, and sectors towards global warming. Figure 1 represents per capita carbon footprint for different classes of countries based on the degree of development. It is clear that high income countries leave the biggest footprint while it is substantially low for developing countries. Carbon footprints are now used as an important indicator of event management (London 2012 Sustainability Plan 2007). Studies on the impact of natural and semi-natural systems quantitatively in terms of carbon footprint are reported (Chambers et al. 2007). It may help to compare natural verses anthropogenic impacts on the environment. Hence we see that hardly there may be any entity which cannot be a candidate to carbon footprinting. Table 1 shows some of the entities for which carbon footprint has been calculated.

Calculation of carbon footprint

For calculating carbon footprint, the amount of GHGs emitted/removed or embodied in life cycle of the product has to be estimated and added. Life cycle includes all the stages involved for a product such as its manufacture right from bringing of raw material to final packaging, distribution, consumption/use, and to the final stages of disposal. Analysis of life cycle therefore is also called as 'cradle to grave analyses'. Life cycle assessment (LCA) produces complete picture of inputs and outputs with respect to generation of air pollutants, water use and wastewater generation, energy consumption, GHGs emitted, or any other similar parameter of interest and cost–benefit initiatives. This assessment is often called as environmental LCA. For carbon footprinting purpose, LCA estimates the GHGs emitted/embodied at each identified step of the product's life cycle, technically known as GHG accounting. Standards and guidance are available for GHG accounting. Common resources are:

1. GHG protocol of World Resource Institute (WRI)/World Business Council on Sustainable Development (WBCSD): there are two standards, (1) A Product Life Cycle Accounting and Reporting Standard, and (2) Corporate Accounting and Reporting Standard: Guidelines for Value Chain (tier III) Accounting and Reporting. It provides sector-specific and general calculation tools and deals with quantification of GHG reductions resulting due to adoption of mitigation methods in its Project protocol. It forms basis for most GHG accounting guidelines including ISO 14064 (parts 1 and 2) (WRI/WBCSD 2004, 2005).
2. ISO 14064 (parts 1 and 2): it is an international standard for determination of boundaries, quantification of GHG emissions, and removal. It also provides standard for designing of GHG mitigation projects (ISO 2006a, b).
3. Publicly Available Specifications-2050 (PAS 2050) of British Standard Institution (BSI): it specifies the requirements for assessing the life cycle GHG emissions of goods and services (BSI 2008).
4. 2006 IPCC guidelines for National Greenhouse Gas inventories: all anthropogenic sources of GHG emissions are classified into four sectors—energy, industrial process and product use, agriculture, forestry and other land use, and waste. 2006 guidelines are an updated version of earlier 1996 guidelines. All countries that are signatory to UNFCCC and committed to prepare, update, and communicate their national GHG emissions/removal inventories following these guidelines. Therefore emission/removal inventories of the countries are comparable. UNFCCC however has not yet made it compulsory to use 2006 guidelines and hence most of the nations are still following 1996 guidelines.
5. ISO 14025: it is a standard for carrying out LCA.
6. ISO 14067: a standard on carbon footprinting of products is under development.

Some countries have developed their own GHG accounting guidelines such as Department of Food and Rural Affair (DEFRA) and Carbon trust in United Kingdom and Environmental Protection Agency (EPA) in USA. Registries and consultancies like World Wildlife Fund Climate Servers, California Climate Registry (USA), The Climate Registry (USA), etc. have formulated their own methodologies based on these guidelines. Almost all of these newly developed guidelines and standards direct accounting for the GHGs emitted during the manufacture, use and disposal of the product, entity, or event and referred to as complete LCA.

Life cycle assessment

Each stage of the life cycle of any product or event is linked to other secondary stages, each of which may further be linked to others and so on. Covering all the associated steps, the boundary may go on expanding to become too complex to be analyzed. Selection cradle and grave should therefore be done appropriately depending on the objective of the assessment as well as on the availability of data.

Approaches to perform LCA for GHG estimation are (1) "Bottom up" or "process analysis

(PA)"; and (2) "top down" or "input–output analysis (IO)" (Wiedmann and Minx 2007; Matthews et al. 2008a). In bottom up approach, the emission sources are broken down into different categories for convenient quantification. This method is more accurate for small entities, but it becomes too complex for large firms which cover more than second order emissions thus underestimating the actual footprint (Lenzen 2001; Wiedmann and Minx 2007). It is useful in identification of area of process improvement (Green Design Initiative 2008).

Top down approach makes use of economic input–output (EIO) model extended to accept and perform operations on environmental variables for calculations of carbon footprint (Green Design Initiative 2008). Inputs and outputs are represented in the form of matrix, with inputs required to produce a unit product represented in respective row. The inputs–outputs matrix can be represented in the form of following equation (Miller and Blair 1985):

$$x = (I + A + A \times A + A \times A \times A + \ldots)$$
$$y = (I - A)^{-1}\, y,$$

where I is identity matrix, y is vector of desired outputs, A, $A \times A$, $A \times A \times A$, ... are the first, second, and so on level supply chains to produce product y. In this mathematical procedure, extension of boundary is easy and chances of double counting are minimized. Basic algebraic operations can clearly indicate the changes in outputs corresponding to changes in one or more variables. Entire economic system can be put as a boundary. Hence there is an opportunity to include small emissions and intersectoral transactions. This technique has been used to calculate emissions related with exports and imports, and is technically termed as 'multiregional input–output analysis' (Robbie et al. 2009). Uncertainties, however, may accumulate as sectors are aggregated (Green Design Initiative 2008; Matthews et al. 2008b). The micro level implementation of EIO-LCA is limited (Wiedmann and Minx 2007).

An integration of PA-LCA and EIO-LCA, called EIO-LCA hybrid, is emerging as the state of art technique in LCA. In this hybrid method, small emissions are covered by PA-LCA, while rest is taken up by EIO-LCA. This preserves robustness of EIO-LCA model and provides accuracy to PA-LCA, thus increasing completeness, flexibility, and reliability of estimates.

Greenhouse gas accounting

In order to keep account of the emissions along the life cycle, the following structured framework is suggested (WRI/WBCSD 2004; Carbon Trust 2007a, b; BSI 2008):

1. Selection of GHGs
2. Setting boundary
3. Collection of GHG emission data

Selection of GHGs

Selection of the set of GHGs covered in calculation depends on the guideline followed, the need of carbon footprint calculation, and on the type of activity for which carbon footprinting is being done. For example, in a thermal power plant, where CO_2 is a predominant emission and other gases are almost negligibly emitted, only CO_2 emission measurement will be feasible whereas for a cattle farm, CH_4, CO_2, and N_2O emissions may be significant. Although some studies include only CO_2 emissions in carbon footprint calculations (Patel 2006; BP 2007; Wiedmann and Minx 2007; Craeynest and Streatfeild 2008) others include the six Kyoto gases (Bokowski et al. 2007; Energetics 2007; T C Chan Center for Building Simulation & Energy Studies/Penn Praxis 2007; Garg and Dornfeld 2008; Good Company 2008; Matthews et al. 2008b). All the guidance and standards also direct to include all the long-lived GHGs and not only CO_2. Kelly et al. (2009) calculated carbon footprints of Indianapolis city in USA based on only two gases, CO_2 and CH_4, which were measured. If carbon footprint is viewed in context of climate change, Peters (2010) argues that it must cover black carbon also.

Setting boundary

Boundary refers to an imaginary line drawn around the activities that will be used for calculating carbon footprint. It depends on the objective of footprinting and characteristics of the entity for which footprinting will be done. Boundary must be selected so as to represent the organization based on legal, financial, or business control. In case of joint ventures, the organization may take responsibility of the fraction of the emissions for which it is responsible, technically called as 'equity share' or may consider all the emission sources which are under its direct control, depending on the need of carbon footprinting. Once the organizational boundary has been established, operational boundary is to be selected. Operational boundary refers to the selection of the direct and indirect emissions, which will be accounted for. To facilitate convenient accounting, tiers or scopes have been suggested (WRI/WBCSD 2004; Carbon Trust 2007b; BSI 2008):

1. All direct emissions, i.e., onsite emissions
2. Embodied emissions in purchased energy
3. All indirect emissions, such as those associated with transport of purchased goods, sold products, business travels, energy activities, disposal of products etc., not included in tiers I and II (WRI/WBCSD 2004; Carbon Trust 2007a, b; BSI 2008; CDP 2008; Matthews et al. 2008a, b; Strutt et al. 2008).

Figure 2 illustrates the three tiers in carbon footprint estimation. The tiers II and III both include indirect emissions, but tier II refers to the emissions embodied in energy production or (and) purchase, transmission, and distribution caused by the entity under consideration, but end user emissions are out of scope of tier II. Tier III tends to cover all the embodied emissions within the specified boundary. But tier III has vaguely been defined and the most carbon footprint studies limit up to tier II as it becomes too complex to estimate carbon footprint beyond tier II with accuracy (CDP 2008; Dada et al. 2008; Matthews et al. 2008a, b). Also, it is important to be ascertained that to what extent responsibility and control over emissions can be made beyond tier II (Lenzen 2001). For this reason most GHG accounting standards (PAS-2050, GHG protocol, and other registries and consultancies based on these) have kept tier III optional. Advancement

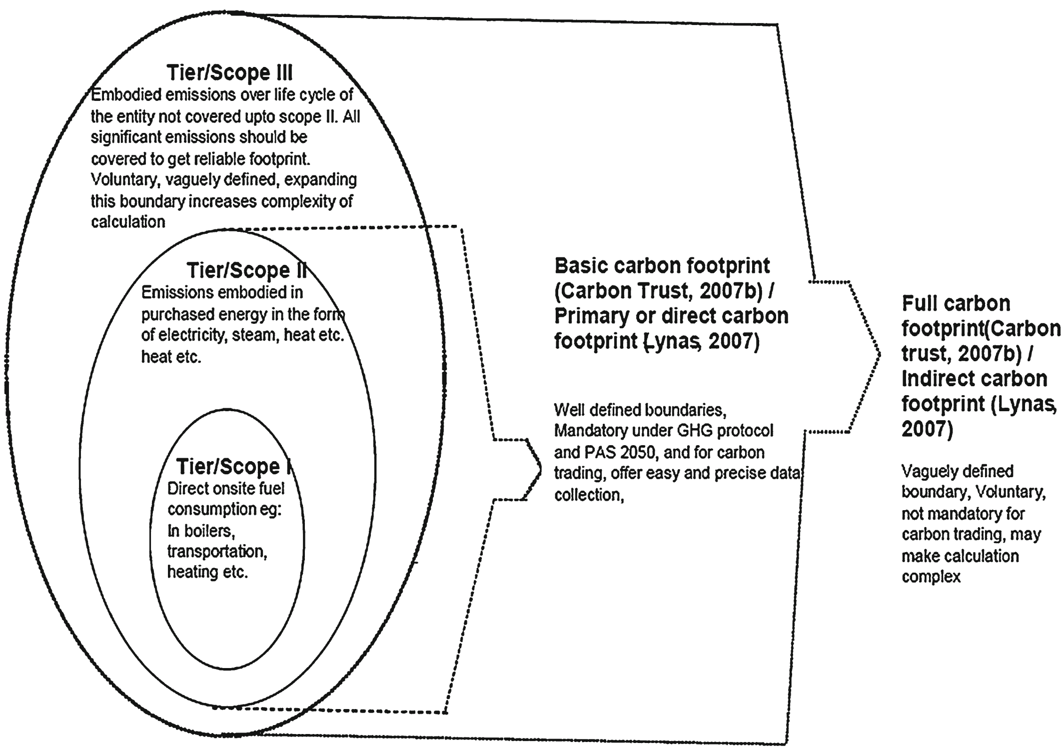


Fig. 2 Boundaries for calculation of carbon footprint

in the tracking and management of emissions in the supply chain is expected to promote tier III accounting and reporting (Matthews et al. 2008b; CDP 2009). Based on order of emissions covered, carbon footprint has two components namely "basic" or "primary" referring to carbon footprint calculated from direct emissions and emissions embodied in energy purchase, and "full carbon footprint" when all direct and indirect emissions are included (Carbon Trust 2007b; Lynas 2007). Among 500 companies inquired worldwide, 72% of the respondents report their GHG emissions up to tier II (CDP 2008). But in many cases, tier III contributes most significantly to the total CO_2-e. Only for the biggest known emitters such as thermal power plants, cement industries, and transportation tiers I and II can cover 80% of total carbon footprint. For most of other processes, only 26% of total carbon footprint could be covered up to tier II (Matthews et al. 2008b). Hence tier III estimation has been promoted to include relevant sources (relevance can be decided on the basis of size, risk exposure of GHGs, etc) and deemed critical by the stakeholders (CDP 2008). Inclusion of an additional tier IV to cover emissions exclusively related to delivery, use, and disposal of products is also proposed (Matthews et al. 2008b). As more and more organizations start reporting complete LCA, a database can be developed through which average firm specific data can be estimated to suite the purpose (Matthews et al. 2008b; Weidema et al. 2008). Inclusion of international trade in carbon footprint calculations has also been suggested (Courchene and Allan 2008). Emissions embodied in traded goods, if consumed out of the country should be shared based on appropriate assumptions (Peters 2010). But drawing boundary to estimate emissions related to trading particularly the international trade may be tough.

Regarding natural systems and land uses, the selection of boundaries and tiers are very unclear. But studies are going on to estimate and identify different mechanisms operating in nature that control GHG emissions. National GHG inventories have been accepted worldwide as a reference methodology to account for the GHGs emissions from land use, land use change, and forestry (IPCC 1996, 2006). Almost all the carbon footprint studies focus on emissions; the amount of GHG removal and sequestration appears neglected (Peters 2010). These factors must be included in calculations.

Collection of GHG data

GHG data can be collected through direct onsite real-time measurements, or through estimations based on emission factors and models. The choice of appropriate method depends on the objective (mandatory, voluntary, or for internal management), credibility, feasibility as well as on cost and capacity considerations. Emission factors and models are the most preferred and used techniques. In general, for products, organizations, and events, emissions are calculated using specific emission factors and models utilizing data on consumption of fuels, energy, and other inputs leading to emissions (particularly CO_2). Emission factors are available for a wide range of industrial processes and land uses in GHG protocol, PAS-2050, IPCC (2006), and country-wise emission factors have been developed in many countries such as national inventories under UNFCCC, US EPA, UK DEFRA, etc. (IPCC 2007; WRI/WBCSD 2004). But verification is required at different operational and geographical contexts. Hence region-specific emission factors and models have been recommended (WRI/WBCSD 2004; IPCC 2006). But for other sources and fugitive emissions, direct measurements should be applied. Direct measurements include optical, chemical, and biological sensors such as photo acoustic infrared sensors or other instruments and techniques like collecting gases of interest in specially designed chambers and analyzing through IR spectroscopy for CO_2 and gas chromatography for all GHGs (USCCTP 2005; Berg et al. 2006). These techniques have been applied for ground-based measurements whether static, mobile, or aerial. Eddy covariance or flux towers have been utilized to measure flux covering the entire landscape (Velasco et al. 2005), while cavity ring-down spectrometers have been utilized in aerial measurements (Kelly et al. 2009). Besides onsite measurement, secondary data sources and databases are now available at global level also. A database of CO_2 emissions from different countries has been developed under global trade analysis project (GTAP; Dimaranan 2006). Other reliable data sources can be national GHG inventories and other government offices keeping the data of fuel and energy consumption, International Energy Agency, UNDP etc. (Brown et al. 2009). Low-cost real-time measurement systems are under development.

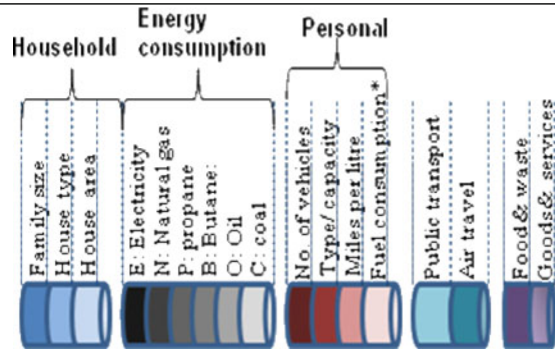
While direct measurements are more accurate and are clearly prescribed in globally accepted protocols, their cost and application may be prohibitive (WRI/WBCSD 2004). In such cases, indirect estimations may yield fairly accurate results if developed or modified specifically for a particular region or sector. Customized tools relying on direct measurements as well as on interpolation or expansion of observations to non measurable fluxes (i.e., emission factors and models) have enhanced practicability for intended users (USCCTP 2005). The GHG protocol customized GHG calculation tools (WRI/WBCSD 2006), are worldwide accepted guidance for customizing the tools for calculating GHG flux so as to suit the respective sector or entity. Besides these, continuous GHG monitoring is going on and is being expanded to get broad spatial coverage (Sundareshwar et al. 2007). For this, advanced measurement and monitoring systems (remote sensing, geographic information system, optical measurements etc.) are now being integrated with individual GHG inventories so as to provide comprehensive and uniform coverage (USCCTP 2005). Scientific community is operating terrestrial and oceanic observation networks to collect GHG data worldwide. FLUXNET, the global terrestrial observing network monitors CO_2, water vapor, and energy at more than 300 sites (Sundareshwar et al. 2007). These systems cover a very broad spatial area, but the monitoring locations in Asia and Africa are sparse and should be increased in number in order to obtain a reliable global data (Sundareshwar et al. 2007).

To overcome the reduction in accuracy of ground-based monitoring network due to patchy distribution, satellites have been launched to monitor sources and sinks of CO_2 and other GHGs with uniform coverage (Haag 2007). Japanese satellite, "the greenhouse gas observing satellite" launched in 2009 is monitoring GHGs, while joint project of NASA and US Department of Energy called "Vulcan" is quantifying CO_2 emissions due to fossil fuel burning in North America (Gurney et al. 2009; Kelly et al. 2009). Remote sensing and geographic information system are extensively in use for large and relatively less accessible areas. Chambers et al. (2007) have used landsat imagery to quantify live and dead wood, litter, soil, and shade for estimating carbon footprint of hurricane Katrina at US coast. Such GHG data are useful in calculation of carbon footprint related to natural phenomena and events (Chambers et al. 2007). GHG emissions and avoidance embodied in use of renewable energy, recycling of waste, energy recovery from landfills, and other such good management practices, are estimated through prescribed mathematical relations (WRI/WBCSD 2005; IPCC 2006; BSI 2008).

All the flux measurements are recorded relative to a base year (may be a single year or an annual average over a period of several consecutive years). Its choice depends on the objective. In most inventories, 1990 has been set as base year in lieu of commitment of reduction of CO_2-e emissions at 1990 level under UNFCCC. Selection of base year is crucial and must be made in such a way that it clearly reflects the importance of structural and operational changes in emissions over time. According to GHG protocol, the earliest relevant point in time for which reliable data are available should be chosen as a base year. Besides this, reproducibility, verifiability, and systematic documentation are essential attributes of data collection (Carbon Trust 2007b).

Regarding voluntary personal carbon footprinting, numerous carbon calculators are available online as well as from consultancies. All of these calculators claim to be based on recommended guidelines, but rarely any two of them yield similar outputs for the same set of inputs (Padgett et al. 2008; Kenny and Gray 2008). This questions the accuracy and credibility of such calculators. Among hundreds of online calculators, some calculate domestic carbon footprint, while others calculate carbon footprint related to specifically travel, food, or other such activities (Murray and Day 2009). Very few calculators indicate the use of indirect emissions under tier III. There is no coherence among the input data required for different carbon calculators. Table 2

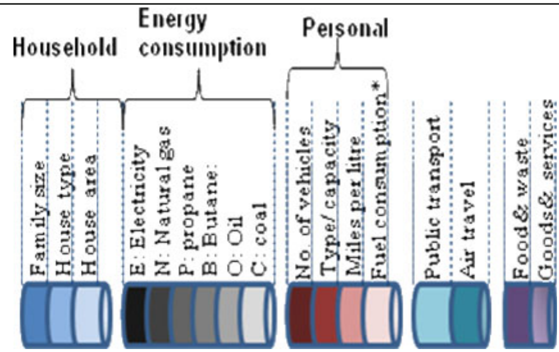
Table 2 Description of parameters included in different online personal calculators

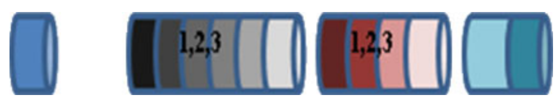
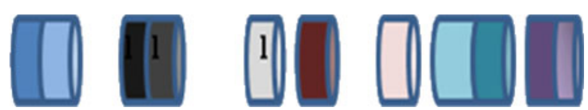


Calculator	Region	Parameters	Units	Comments	Sources	Reference
Conservation international carbon calculator	USA and outside USA		Tons CO_2/yr	Emission factors* are mentioned but sources are not mentioned. suggests donation to offset CF		Conservation international carbon calculator. http://www.conservation.org/act/live_green/carboncalc/pages/default.aspx
Climate change	USA		Tons CO_2	Disposables, recycling included in calculation	1: http://www.greenmountain.com 2: USEPA 3: Federal Aviation Administration	Climate change carbon calculator. http://www.americanforests.org
Greenhouse gas calculator	Australia			Doesn't demands actual values as inputs. Difficult to understand as any range of values have also not been mentioned. Compares		Greenhouse gas calculator. http://www.abc.net.au

				calculated carbon footprint with national average		
An inconvenient truth carbon Calculator	USA		Tons CO_2 per year	Renewables included in calculation, offsetting CF is proposed with Native energy, compares calculated CF with national average	1. Energy information administration, official energy statistics from US Government: voluntary reporting of Greenhouse gases program fuel and energy source codes and emission coefficients; http://www.eia.doe.gov/oiaf/1605/coefficients.html; 2. GHG protocol mobile combustion tool; 3. UKDEFRA, www.defra.uk.gov	An inconvenient truth carbon calculator. http://www.climatecrisis.net
Act on CO_2	UK		Tons CO_2 per year	Renewable sources of energy, house construction and maintanence, and conservation behavior also included in calculation. Compares calculated CF with similar people.	1. UKDEFRA	DEFRA Act on CO_2 carbon calculator. http://actonco2.direct.gov.uk

Table 2 (continued)



Calculator	Region		Units	Comments	Sources	Reference
				Green tariffs and renewable included in calculation. Provides tips on low carbon lifestyle. Compares calculated CF with national average.		
Resurgence quick carbon calculator					1. UK DEFRA 2. The National Energy Foundation (www.natenergy.org) 3. The National Office of Statistics (www.statistics.gov.uk)	Resurgence quick carbon calculator. http://www.resurgence.org
Carbon neutral for homes	UK, USA		Tons CO_2 per year		UKDEFRA	Carbon neutral carbon calculator. http://www.carbonneutral.com
WWF carbon calculator			Tons CO_2 per year	Conservation habits, lifestyle and behavior included in calculation.	1. Stockholm Environmental Institute	WWF carbon calculator. http://footprint.wwf.org.uk

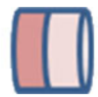
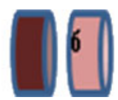
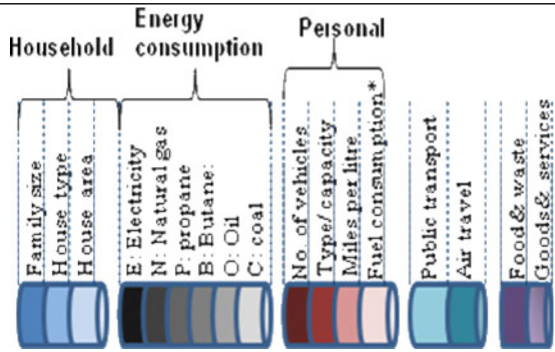
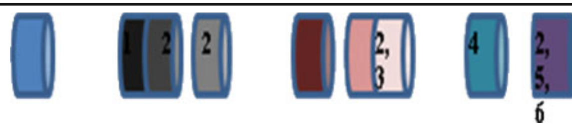
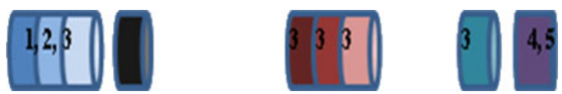
									Suggests conservation measures. Estimates number of planets required to sustain life with the calculated footprint		
Liveclimate	USA						Tons CO_2		Emission factors* specifically not mentioned but sources are given. Basically an offset seller	USEPA and USDoE	Liveclimate carbon calculator http://www.liveclimate.org
Carbon calculator							Tons CO_2 per year		Offsets offered. Compares calculated CF with national and world average.	1. US EPA 2. Stockholm Environmental Institute 3. United States Department of Energy (USDoE) 4. The Ontario Ministry of Energy of Canada 5. UK Environment Watch 6. State Government Environment Department of Australia 7. Sightline Institute 8. Eshel and Martin 2005	Carbonify carbon calculator http://www.carbonify.com

Table 2 (continued)

Calculator	Region		Units	Comments	Sources	Reference
						
Livegreen carbon offset programme	USA		Tons CO_2 per year	Indirect emissions are also included in calculation. Compares calculated CF with national and world average	1. California Climate Action Registry 2005 2. USEPA 3. www.fuel Economydata 4. WRI/WBCSD (2004) 5. Eshel and Martin 2005 6. Pimental et al. (2005)	Sacramento municipal Utility district, Livegreen carbon calculator http://calc.positiveenergyusa.com
Carbon footprint calculator	USA		Tons CO_2 per year	Calculations based on conservation behaviour, Indirect emissions are also included in calculation. Compares calculated CF with national average.	1. USEPA; 2. UK DEFRA; 3. US DoE; 4. Eshel and Martin 2005; 5. Pimental et al. (2005)	The nature conservancy carbon footprint calculator. http://www.nature.org/initiatives/climatechange/calculator

Solid cylinders corresponding to the parameters not included in the calculation have been omitted. Cells corresponding to the parameters not included in the calculator have been left blank. *Based on distance travelled, fuel consumption, or time for which the vehicle runs describes some of the online carbon calculators. Incorporation of information technology to design a personal environmental tracker has been proposed to increase accuracy of such calculators, while household and device level monitoring using specific sensors is gaining popularity in developed world (Brewer 2008a, b).

Footprint calculation

The GHG data are translated into CO_2-e using conversion factors provided by IPCC (WRI/ WBCSD 2004; BSI 2008). Some organizations report carbon footprint as carbon equivalent (Wiedmann and Minx 2007), but based on widespread acceptance, CO_2-e is more popular. The unit of carbon footprint varies according to entity under consideration. Carbon footprint for individuals and dynamic processes is calculated periodically, usually annually. Events such as conferences, fairs, sports events, etc. have one-time emissions. Some entities have a combination of both, like carbon footprint of a building is a one-time figure during construction phase, while periodic calculations are needed during the operation phase. Therefore, the time dimension must be mentioned so as to indicate clearly the time period over which the emissions have been estimated, or if it is a one-time emission. PAS 2050 gives provision of sharing one-time emissions over operation phase. Regarding services such as travel, post, search engines, etc. emissions are reported over an appropriate service unit like CO_2-e per flight, CO_2-e per hour of surfing, CO_2-e per post per mile, CO_2-e etc. Natural processes are highly complex and hence they may be said to have a temporally as well as spatially "dynamic carbon footprint". Uncertainties in calculations must also be mentioned while reporting carbon footprint (Carbon Trust 2007b).

Following examples demonstrate different approaches for carbon footprint calculations

1. Carbon footprinting of nations: Edgar and Peters (2009) used multiregional input--output, analysis coupled with the database GTAP including all the Kyoto gases to calculate per capita carbon footprints of 73 nations for the year 2001. The boundary covered construction activities, shelter, food, clothing, mobility, manufactured products, services, and trade in their analysis. Minimum carbon footprint was observed for Bangladesh, Mozambique, and Uganda (1.1 ton CO_2-e) and was maximum for Luxembourg (33.8 ton CO_2-e) as measured over 100-year time horizon.
   UNDP (2007) also reported per capita carbon footprint for nations for the year 1990 and 2004, but they include only CO_2 emissions arising from fuel combustion and cement production. The estimate showed United Arab Emirates leaving the biggest footprint with 34.1 ton CO_2 and smallest by India (1.2 ton CO_2). Carbon footprint of India as reported in Edgar and Peters (2009) is 1.8 ton CO_2. This clearly shows the difference due to variations in boundaries and GHG selections. Some studies take into account the regional details for producing a better picture of footprinting, but important issues of concern in such comparisons are international trade related to exporting or importing countries, the emissions embodied in manufacture, transport etc. (Peters 2010). Other economic situations, including parity in purchasing power of the consumers, is also suggested to be counted (Herrmann and Hauschild 2009).
2. Carbon footprint of large areas: studies have been conducted to indicate the energy intensiveness and lifestyle of metropolitan cities with the help of carbon footprinting. Brown et al. (2008) estimated carbon footprint of 100 metropolitan areas in the USA based on CO_2 arising only due to fossil fuel combustion in transport and electricity consumption in homes. Lebel et al. (2007) included CH_4 and black carbon along with CO_2 in comparative carbon footprinting for five metropolitan cities of southeast Asia from 1980 to 2000 and found that per capita emissions were comparable in all the selected cities. Their selection of gases and particulate carbon tends to include all carbon-based emissions that have warming effect. Sovacool and Brown (2010) extend the boundary to include emissions from agriculture and waste, wherever applicable in addition to tiers I and II that include

direct and indirect emissions in transport, industries, and buildings. They also include the emissions associated with goods manufactured within the city boundary, irrespective of their point of use. In lack of single GHG database, different data sources have to be utilized thus making the studies difficult to compare. As the secondary data sources may have large uncertainties associated, or they cannot be used in certain conditions, actual measurements have to be carried out. Kelly et al. (2009) collected data on CO_2 and CH_4 in planetary boundary layer over the region of Indianapolis through aircraft-based measurements. Such measurements can measure the overall net release of GHGs over a larger area when interpolated through Kriging technique. Fluxes were calculated through mass balance approach. The uncertainties in their study were due to wind speed. If still larger spatial scale is to be covered, satellite data can be utilized. Utilizing LANDSAT and MODIS imageries, Chambers et al. (2007) projected the amount of CO_2 released during the decomposition of litter generated and change in sink capacity due to the devastation caused by the hurricane Katrina and calculated the carbon footprint by utilizing the Monte Carlo model. As a legal requirement, Good Company (2008) carried out the GHG inventory for the city of Vancouver deriving methodologies from The Climate Registry and a software program of International Council for Local Environmental Initiatives under Cities for Climate Protection campaign. The issues which were not covered in these protocols were analyzed independently. Choosing 2006 as the baseline year, inventory was designed to cover three tiers. Tiers I and II covered direct emissions resulting from equipments and other operations under control of the city, and GHG embodied in electricity, heat, and steam, respectively. All the other indirect emissions from institutional activities, business air travel, landfills, solid waste generation, and commutation of public were covered under the tier III. Emissions covered under tier III left the biggest footprint, but the precision of the data was also lowest.

It is clear that sink capacity has been considered in scientific studies, and carbon footprint is being used as an environmental indicator rather then a pressure indicating term. Incoherence in selection of gases is also clear from these studies. It is important to give a careful consideration to the socioeconomic status, cultures, consumer behavior, and lifestyle, while comparing such studies because such reports form the basis of climate agreements.

3. Carbon footprints of academia: carbon footprinting for universities, schools, and similar institutions are going on. University of Pennsylvania got its carbon footprint calculated by T C Chan Center for Building Simulation & Energy Studies/Penn Praxis (2007). All the three tiers were defined to cover almost all possible emissions inside the university (energy use in buildings and equipments, GHG releases from agricultural farm and waste, employees and student's commutation, and business flights etc.). The calculation tool, derived from an organization called 'Clean Air Cool Planet' was based on IPCC (2006) and covered all the Kyoto gases. The calculations were based on emission factors from secondary data sources (records of the university). The carbon footprint as calculated for the year 1993 was approximately 3.5×10^5 ton CO_2-e. As a result of partial GHG offsetting through wind-generated power, the carbon footprint reduced to 2.5×10^5 ton CO_2-e in 2006.
4. The University of British Columbia and the Simon Fraser University adopted the methodology outlined by 'American College & University Presidents' Climate Commitment' involving all the three tiers and all the GHGs for footprint calculations (Ferris et al. 2007). The calculated carbon footprint for University of British Columbia was 8.275×10^4 ton CO_2-e. In Universities, tier II emissions were found to be the highest. All of these studies calculate carbon footprints based on emission factors utilizing secondary data. Other type of analysis that has been used in such cases is EIO-LCA as carried out by Garg and Dornfeld (2008) for carbon footprinting of Kresege Engineering Library at University of

California, Berkeley. Estimations of energy consumption in electronic equipments, GHGs embodied in infrastructure and publication and transport of books, CDs, periodicals, and other documents to the library and employee's commutation, were based on those estimated by the researchers at University of California, which yielded an annual carbon footprint of 1.172×10^4 ton CO_2-e. (Garg and Dornfeld 2008). PA and EIO LCA were integrated in a model called Resource and Energy Analysis Program developed by Stockholm Environment Institute, York, to estimate CO_2 emissions from schools of UK, covering the three well-defined tiers (Global Action Plan 2006).

5. Events: for London Olympic games 2012, expected carbon footprint is under calculation (London 2012, Sustainability Plan 2007). In lack of any proper guideline for GHG accounting for large public events, the study selected the GHG protocol. The tiers are not classified according to the order of emissions (direct and indirect), but according to the responsibility of the London 2012 Organizing Committee of the Olympic and Paralympics Games (LOCOG) over the emissions. In direct emissions, the activities funded fully by LOCOG (construction of venue, office, and utilities and the share of emissions for which the games are responsible in jointly owned facilities) have been covered. Other joint activities that include transportation, infrastructure, and upbringing of Olympic village have been dealt separately. The third tier covers for all the other associated activities, not funded by LOCOG, but is attributable to the games. This includes activities of media, sponsors, and visitors. Beyond this, the control of LOCOG will be negligible; however, the associated emissions can be important. However, accounting for those will make the study too complex and uncertainties will also be high.
6. Carbon footprinting for individuals and households: individual and household carbon footprint calculators have surged the internet. Despite of their claim to be based on globally accepted protocols and emission factors, they yield different results (Kenny and Gray 2008; Padgett et al. 2008; Murray and Day 2009). The disparity among them has been illustrated in Table 2. Besides these commercial calculators, certain scientific studies have also been conducted. Druckman and Jackson (2009) classified the selected households in UK according to their socioeconomic status through Local Area Resource Analysis model, based on the input data of expenditure, fuel use, and census. The authors focused to analyze the change in carbon footprint as the status of living is modernized. Using the MRIO model, it was observed that in high level of functional needs, highest share in carbon footprint was of recreation, leisure, and personal air travels. It is important to note that this study counted only CO_2, covering up to tier II.
7. Carbon footprinting of corporations: any national or international climate agreement will put direct pressure on businesses to cut their carbon, owing to their biggest share and capability. Predicting the stricter carbon norms, fine returns in the form of incentives for emission reductions, and consumers preferences for products with low GHG contents, businesses have started to count and then cut their emissions. Around 475 world's largest companies revealed their carbon footprints in CDP (2009). About 83% of the participating companies disclosed carbon footprint for tiers I and II only. Total tier III emissions of 5.8×10^9 ton CO_2-e were much higher than combined emissions of tiers I and II (0.6 and 3.6×10^9 ton CO_2-e, respectively). The total direct GHG emissions under CDP together contributed 11.5% of total global emissions. Companies are therefore taking actions to reduce their carbon footprints. Ford and Chrysler joined the US Climate Action Partnership to cut emissions, whereas Google and Dell decided to take steps to go carbon neutral (Kleiner 2007).

   Carbon footprints of food: like commodities, separate carbon calculators have appeared online to calculate the footprints related to the dietary habits. As food habits are directly related to the culture, geography, etc., food carbon footprint is very crucial. Pathak et al. (2010) selected common Indian food items and considered the relevant GHGs (CO_2, CH_4, and N_2O) associated with production of raw materials, processing, transportation, and final preparations for calculating carbon footprint. Their calculations utilized the emission factors and data from NATCOM (2004), MoA (2006), Pathak and Wassmann (2007), and Pathak et al. (2009a, b). It was found that the biggest footprint taking all the food items was at production stage (87%), and maximum contribution was made by CH_4 (71%). An average non-vegetarian diet had high carbon footprint (1.031×10^{-3} for adult male and 8.918×10^{-4} ton CO_2-e for adult female) over the vegetarian (7.23×10^{-4} for adult male and 5.838×10^{-4} ton CO_2-e for adult female). A comparison between the online food carbon footprint calculators by Kim and Neff (2009) revealed that the inputs as well as scopes for different calculators varied. The calculations were based on different sources, some of whom were also misapplied by calculators. Emissions avoided by shifting to organic or locally grown foods add a challenge quantifying diet-related emissions accurately. Most of these calculators calculate carbon footprint of food based on Eshel and Martin (2006). They used FAOSTAT (2005) to estimate the food exports and emission factors were derived from different studies. GHG emissions associated with agriculture, and transportation of variety of vegetarian and animal-derived food items were estimated, covering CO_2, CH_4, and N_2O. With objective of achieving GHG emissions associated with individual diets, different combination of food items were made to prepare hypothetical average diets and the carbon footprints were calculated. Their study illustrated that counting only CO_2 cannot produce a realistic carbon footprint as inclusion of other GHGs made many food items distinct, which otherwise were of similar energy intensity.

A wide range of carbon footprinting studies, involving corporate, governments, institutions, and households are available, although there is prevailing differences in boundaries, gases, and methodologies selected for these calculations. Increasing carbon footprinting at all the areas of life indicated that we have started recognizing our responsibilities towards environment. Many of them are a part of legal or voluntary emission reduction targets, which is an appreciable act.

Conclusions

Carbon footprint has emerged as a strong mode of GHG expression. While earlier studies focused only on CO_2 emissions as the guidelines and suggested inclusion of all the important GHGs in calculation, carbon footprint started becoming synonymous to a comprehensive GHG account, over the life cycle stages of any product or activity. No definition, however, has yet been accepted coherently as is clear from the fact that there are different selection of gases and tiers among studies. However, as carbon footprint reports are increasing in response to legal or business requirements, most of the calculations are following the GHG protocol worldwide. Since it has been extended to cover natural system as well, it becomes essential to deal with the unavoidable emissions. Carbon footprint has been commercialized and is being utilized by organizations to count their carbon and adopt measures to cut down emissions. This business sense has taken carbon consciousness to the households through numerous online calculators and has helped in making the civil society aware of how much their activities are contributing to global warming. Ironically, there is no check on such carbon calculating facilities and they lack coherence and transparency. Since carbon footprinting is associated with money transactions and has been found to influence businesses, legal guidelines are necessary to monitor these calculations. Carbon footprinting must be harnessed as a strong tool to promote GHG emission reductions among businesses, events, and civil society and should be included as indicator of sustainable development.

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