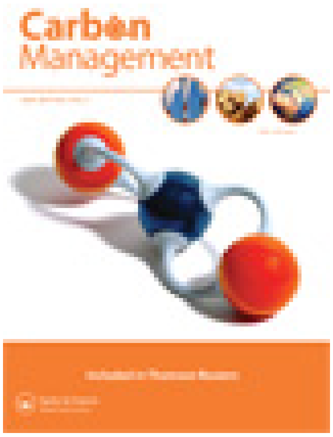

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A beginner's guide to carbon footprinting

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Carbon footprinting is one of the foremost methods available for quantifying anthropogenic environmental impacts and for helping tackle the threat of climate change. However, for any person undertaking a carbon footprinting analysis for the first time, they will almost certainly be struck by the broad array of definitions, approaches and terminology surrounding the field. This paper provides an introductory guide to some basic concepts in carbon footprinting for researchers and lay people interested in the area. Each stage of calculating a carbon footprint is considered and an introduction to the main methodologies is provided. The advantages and disadvantages of the various approaches are discussed and a rough framework of procedures is provided for the calculation of carbon footprints over a variety of subjects. Some general data sources are included and a glossary of key carbon footprinting terminology is available in supplementary data online.

In recent years the need to tackle anthropogenic GHG emissions has become increasingly urgent as our understanding of the risks of climate change has advanced [1]. For this reason, mechanisms to bring about a reduction in the quantities of anthropogenic GHG emissions must be devised and perfected, in order that responsibility for anthropogenic climate forcing may be equitably assigned and specific, pragmatic emission-reduction targets can be set and progress measured [2].

The **carbon footprint** has, since its inception sometime around the millennium, become a commonly recognized phrase for relating a given human activity with a certain amount of GHG emissions [3–5]. The origin of the term stems from the concept of 'ecological footprinting', which was introduced in the mid-1990s as a methodology for estimating the area of the Earth's surface needed to provide all necessary resources to, and process waste and pollution from, a given population, organization or activity [6].

The term 'carbon footprint' has been criticized in the past as a misnomer, given that it does not have a unit of area while the word 'footprint' suggests a form of land take [7]. However, there is already wide acceptance of the term 'footprint' as a measure of human environmental impact and, thus, the fact that the carbon footprint does not apply literally to an amount of land area is not a conceptual problem with the use of the term. Furthermore, the additional uncertainties introduced by converting to a unit of land take makes such a calculation step undesirable [4].

A multitude of definitions for the carbon footprint have been forwarded in both the academic press [3,4,8] and grey literature [101,102]. Some definitions include only CO_2 emissions [4], others include all GHGs [8], some involve all direct and indirect GHG emissions [3], while others stipulate that only direct fuel and energy use should be included [101]. To reduce confusion surrounding the definition of a carbon footprint, Wright *et al.* recently proposed a definition aimed at being practicable, requiring only relatively easily obtainable data, whilst still capturing the bulk of anthropogenic climate forcing [3]. For the purposes of this article, we adopt the definition for a carbon footprint as proposed by Wright *et al.* [3], as we believe it to be the most clear, pragmatic and accurate definition available.

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Key terms

Carbon footprint: Measure of the total amount of CO_2 and 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 CO_2 equivalent using the relevant 100-year global warming potential [3].

Kyoto Protocol: International agreement linked to the UNFCCC. The Protocol sets legally binding targets for industrialized (Annex I) party nations for the reduction of their GHG emissions.

Climate footprint: A measure of the total amount of CO_2, CH_4, nitrous oxide, hydrofluorocarbons, perfuorocarbons and sulfur hexafuoride 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 CO_2 equivalent using the relevant 100-year global warming potential [3].

Whist in most cases it will only be necessary to calculate the carbon footprint of a given activity, system or population, there may be some situations where there is a need to evaluate climate risk more accurately. In these cases, Wright *et al.* suggest that a wider measure of the emissions of all GHGs controlled under the **Kyoto Protocol** be quantified. Wright *et al.* suggest that this measure be called a **climate footprint** [3].

Finally, for those situations that require the quantification of a yet broader suite of GHGs, reaching beyond the extent of the climate footprint, a 'GHG inventory' should be calculated. This will entail the full completion of a climate footprint with the addition of a further measure of the total amount of emissions of a set of clearly defined and stated GHGs. Such GHGs may include (but are not limited to) aerosols, contrails, particulate matter, ozone, water vapor and black carbon.

A visualization of the relationship between the three terms, the carbon footprint, the climate footprint and the GHG inventory, is presented in Figure 1. The outer edge of the GHG inventory circle takes the form of a dashed line to signify the absence of an exact definition for what may be included in a GHG inventory.

A number of standards exist that concern the quantification of emissions of various collections of GHGs across different scales: at the national level, guidance for compiling national GHG inventories is provided by the IPCC [9]; at the local level, guidance is provided by the Local Government GHG Emissions Analysis Protocol [10]; for organizations, guidance is provided by the internationally recognized World Resources Institute/World Business Council for Sustainable Development GHG Protocol Corporate Accounting and Reporting Standard (henceforth, the GHG Protocol) [11], which has been adopted by the UK's Department for Environment, Food and Rural Affairs in its 'Guidance on How to Measure and Report your GHG Emissions' [12] and has formed the basis of the International Organization for Standardization 14064 series [13–15] and the Carbon Trust Standard [16]; finally, guidance on how to quantify GHG emissions from products and services is provided by the Publicly Available Standard 2050 for the Assessment of Life Cycle GHG Emissions of Goods and Services [17]. These standards do not adopt a common terminological approach and, therefore, the outputs of the processes described do not conform strictly to the definitions used in this paper. Nevertheless, these standards provide useful information and outline a variety of techniques that can be used in the compilation of carbon footprints as defined by Wright *et al.* [3].

Calculating a carbon footprint is, in essence, a relatively simple process that follows five general steps:

- All conceivable emissions sources for the subject of interest should be identified and categorized;
- A decision-making process must then determine which emissions sources are relevant to the subject of the carbon footprint, and which should therefore be included in a carbon footprint calculation;
- An appropriate method for translating the measurable activities of each emissions source to a weight of CO_2e emissions must be selected;
- The necessary data should be gathered and the method applied to calculate a total weight of CO_2 and CH_4 emissions, expressed as CO_2e;
- The method must be thoroughly documented in order that future iterations of the carbon footprint can be undertaken with the same methods and, therefore, be comparable.

This paper aims to provide an introductory guide to the methods, approaches, terminology and applications of carbon footprinting for the interested lay person or researcher. A guide to the data needed for carbon footprint calculation and the sources of that data is also offered. Finally, a glossary of terms is presented in the Supplementary Data; the definitions contained within here are proposed by these authors to become the international standard definitions for the field. Many of the methodologies of carbon footprinting are common to various applications, such as carbon footprinting for an individual or household, a corporate entity, product or event, or a nation or other geographic region. As such, the term 'subject' of the carbon footprint will be used as a generic term for factors such as the individual, company or region for which a carbon footprint is being calculated.

Guiding principles

The central reason for undertaking a carbon footprint project at any level, be it national, organizational or local, is to reduce the risk of climate change through enabling targeted and effective reductions of GHG emissions [18]. It is this reasoning that underpins a host of regulatory GHG emissions monitoring and reduction programs, such as the Carbon Reduction Commitment Energy Efficiency Scheme in the UK [103] and the EU Emissions Trading Scheme [104], or international agreements such as the Kyoto Protocol [105]. The implications of this are that the carbon footprint should enable identification and evaluation of emissions reduction opportunities. It should therefore be inclusive of as broad a spectrum of relevant emissions sources to the subject of the carbon footprint as is practicable, in order that cost-effective reduction strategies can be devised.

Results should be delivered in a timely fashion, so as to be current at such a time as they can be acted upon. For example, if budgets for emissions reduction projects are set at a certain time of year, current and accurate data should be available at that point in time to enable effective strategy creation and budget allocation. Similarly, if progress is monitored at predetermined time intervals then an objective of any carbon footprinting program should be to prepare data for those intervals.

The data should be presented in a way that enables effective analysis. For example, if a corporate carbon footprinting initiative resulted in a single aggregated figure, it would not be particularly useful when attempting to develop targeted carbon management strategies. However, if the carbon footprint was presented as sufficiently granular data it would be easy to present figures for the whole company or any business area within it, yet also possible to break the data down to identify specific areas where improvements can be made.

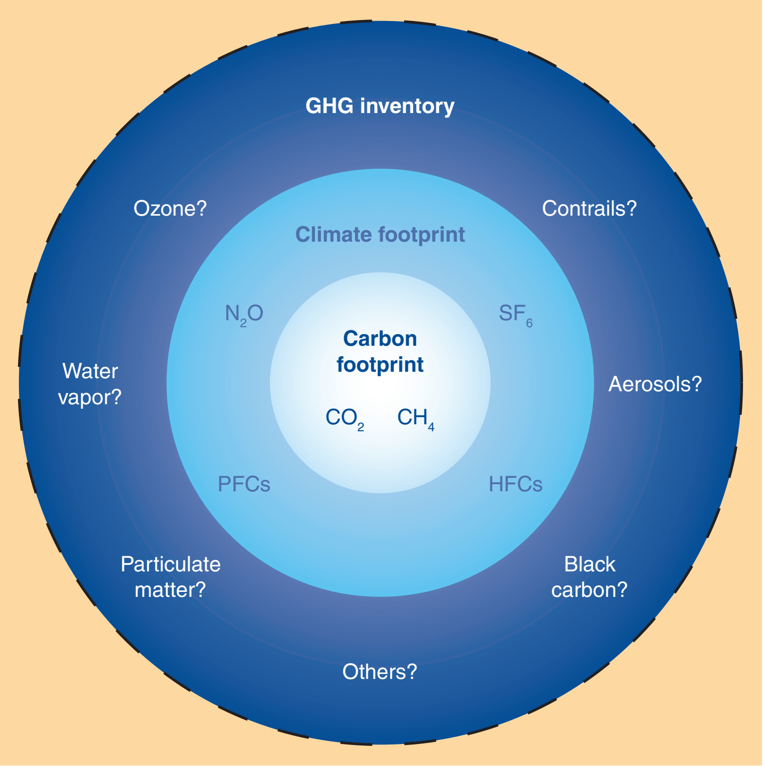

Figure 1. The relationship between the three approaches, the carbon footprint, the climate footprint and the GHG inventory, which may be applied to quantify GHG emissions from a given population, system or activity. The outer edge of the GHG inventory is dashed to signify how there is no clearly defined limit of what GHGs may be included in a GHG inventory.

HFC: Hydrofluorocarbon; N_2O: Nitrous oxide; PFC: Perfluorocarbon; SF_6: Sulphur hexafluoride.

Emissions source identification

The first stage of calculating a carbon footprint is to identify all possible emissions sources. In doing this, it is useful to think in terms of direct and indirect emissions. Direct emissions are associated with the combustion of a fossil fuel [11], but may also be associated with other processes that lead to GHG emissions; for example, anaerobic decomposition of organic matter causing CH_4 emissions [11,19]. Some direct emissions might also fall into the category of 'fugitive emissions', which are those that might occur due to leaking machinery or piping. For example, natural gas (CH_4) may leak from a damaged or corroded pipe [20]. Direct emissions sources can be regarded as those over which the subject of a carbon footprint has the highest level of control [2,21,22].

Indirect emissions are those that are caused by the demands that the subject of the carbon footprint exerts upon the wider economy in which it operates [2,23]. For example, when a product is purchased this generates demand for its manufacture. Responsibility for the CO_2e emissions associated with raw material extraction and processing, product manufacturing, retailing and distribution, could reasonably be attributed to the consumer for generating the demand [5,24].

To identify both direct and indirect emissions it is worth considering the full range of possible sources. The IPCC guidance provided for the compilation of national GHG inventories outlines the major activities that cause GHG emissions (Table 1). These sources can apply directly or indirectly depending on the subject of the carbon footprint. For details of processes forming all GHGs, refer to the IPCC good practice guidelines [9].

Categorizing emissions by Scope

One of the key issues that must be considered in carbon footprinting is that of double counting, which occurs when a quantity of GHG emissions are reported to be caused by multiple carbon footprint subjects [25]. This could be problematic if emissions trading schemes or carbon pricing are to be implemented [11], or if data from various carbon footprinting initiatives are to be combined in an effort to determine aggregated emissions levels [10].

A method to avoid double counting, whilst allowing multiple subjects to recognize a source of emissions within their carbon footprints, is to categorize emissions into Scopes. The GHG Protocol defines Scopes 1–3:

Table 1. Categorization of possible GHG emissions sources according to the major activities that cause GHG emissions, with descriptions and examples.

Source category	Source	Description or examples
Stationary combustion (gas, liquid or solid fuel)	To generate electricity, heat or steam	Fossil fuel power stations and combined heat and power stations
	To generate mechanical work	Onsite stationary engines
Mobile combustion (gas, liquid or solid fuel)	Road transport	Domestic and commercial cars, vans, trucks and motorcycles
	Railway transport	Freight and passenger trains
	Water-born navigation	Passenger ferries, freighters and oil tankers
	Aviation	Commercial and private aircraft
	Off-road vehicles	Off-road vehicles such as those operating in harbors, airports and other off-road environments
	Pipeline transport	Piped goods moved through the operation of powered pumps
GHG emissions from chemical processes	Cement production	CO_2 formation during the production of clinker
	Lime production (calcium oxide/quicklime)	Limestone is heated, producing quicklime and CO_2
	Glass production (window, fiber and specialty glass)	CO_2 released from the use of limestone, dolomite and soda ash in glass production
	Ammonia production	CH_4 used in ammonia production, resulting in CO_2 as byproduct
	Carbide production	Production can result in formation of CO_2 and CH_4
	Titanium dioxide (a white pigment used in paint and other products)	Production causes significant formation of CO_2
	Soda ash	Production causes formation of CO_2
	Petrochemical production	Various petrochemical production processes produce CO_2 as a byproduct
	Carbon black production	Creates byproducts of CO_2 and CH_4
	Iron, steel and metallurgical coke production	Formation of CO_2 and CH_4
	Ferroalloy production	Formation of CO_2 and, in some processes, CH_4
	Aluminum production	Process consumes carbon anodes resulting in formation of CO_2
	Magnesium production	Processing of magnesium and dolomite in the manufacture of magnesium metal produces CO_2
	Lead production	Reduction of lead oxide during smelting produces CO_2
	Zinc production	Some zinc production processes involve the reaction of non-energy CO_2 emissions
Agriculture	CH_4 production by livestock and livestock manure	The result of enteric digestion and fecal excretion
Land use, land use change and forestry	Biomass carbon stock change	Related emissions to or removals from the atmosphere of CO_2 inferred from change in carbon stock
	Soil carbon stock change	Related emissions to or removals from the atmosphere of CO_2 inferred from change in carbon stock
Waste	Organic waste decay in solid waste disposal facilities	CH_4 generated under anaerobic conditions and not captured for use or flaring may be emitted to the atmosphere
	Biological treatments of organic waste: anaerobic digestion, composting and mechanical–biological treatment	Potential for emissions of CH_4 that should be accounted except where CH_4 is used for energy production
	Waste incineration	CO_2 emissions that are not from organic materials and any CH_4 emissions
	Wastewater treatment	Anaerobic decomposition of wastewater leads to CH_4 emissions

Adapted with permission from [9].

Scope 1 – all emissions as a direct result of the population, system or activity; Scope 2 – expands the boundary to encompass upstream emissions from energy generation (e.g., electricity production and steam); Scope 3 – further expands the boundary to consider indirect life cycle emissions (Table 2) [11]. This final Scope is often cited as 'optional' with little guidance given as to the cut-off procedure for external upstream process emissions. This system of definition makes it possible for multiple subjects to account for a given emissions

Table 2. Emissions scopes.

Scope	Definition	Examples
1	Emissions that occur as a direct result of, or within, the organizational or geographical boundaries and the defined system processes or activities (e.g., the emissions from a company owned vehicle) [9,11]	Emissions from fuel combusted in vehicles, machinery and appliances directly operated by the subject of a carbon footprint
2	Emissions from energy generation that occur upstream of the defined system processes or activities that are purchased for own consumption [9,11]	The emissions from fuel combusted in a power station generating electricity used by the subject of the carbon footprint
3	Emissions that occur as a consequence of the defined system processes or activities but occur outside the organizational or geographic boundaries [9,11]	Emissions in a factory manufacturing a product purchased by the subject of the carbon footprint or emissions caused by transport operated by a third party, such as an airline or shipping operator

Adapted with permission from [9].

source; that is, the same emissions source may be accounted for by one company in their Scope 1 emissions inventory and by another company in their Scope 3 emissions inventory, whilst clearly indicating whether a specific subject of the carbon footprint is directly or indirectly responsible for the emissions source. Indirect emissions are divided into two Scopes in recognition of the different levels of responsibility and the influence the subject of a carbon footprint has for emissions related to the consumption of energy products and other types of goods and services [11].

There may be instances where Scope 3 emissions are shared by various carbon footprint subjects. This may occur if, for example, two companies operating in the same sector share a largely similar upstream supply chain and subsequently share many of the same Scope 3 emissions sources. Thus, Scope 1 emissions and, to some extent, Scope 2 emissions, can be regarded as belonging solely to the subject of the carbon footprint, but Scope 3 emissions cannot; that is, they are inherently shared with other populations, systems or activities. In order to avoid double counting entirely, it would be necessary to only include Scope 1 (direct) emissions in a subject's carbon footprint, with this being the approach taken in UNFCCC national GHG inventory reporting [9,26]. It would then be possible to add various subjects' carbon footprints together to create a high-level aggregate. Whilst this may be desirable in some cases, ultimately this does not allow for allocation of any responsibility for indirect emissions caused by the activities of the subject of a carbon footprint [25] and would not provide the carbon footprint with as detailed an inventory of its GHG emissions.

Boundary setting

Carbon footprinting involves gathering and processing data and, as such, involves a cost in terms of time and resources. For this reason, it is often not practical for all conceivable emissions sources to be considered when calculating a carbon footprint. Therefore, boundaries must be set that determine which processes are included in the footprint. Boundaries must be considered in a number of ways. 'System boundaries' are a set of criteria that indicate and fix a limit or extent to the population, system or activity under consideration. For example, it is essential for a carbon footprint analysis of a company to first define which of the company's operations are to be included. 'Geographical boundaries' define the geographic extent for which GHG emissions sources will be included in the carbon footprint. Geographical boundaries are particularly important to carbon footprinting studies of infrastructural subjects, such as academic institutions, regional energy production or households, and for carbon footprint analysis of geographically confided subjects, such as municipalities, nations or national parks. 'Temporal boundaries' exist due to the number of temporal elements that must be considered in the undertaking of a carbon footprinting analysis. It is therefore essential that boundaries be set not only in space, but also in time. Examples of time-dependent variables that must be taken into consideration include the reporting time period, global warming potential (GWP) time horizon, GHG residence time and treatment of time-lagged GHG emissions (e.g., emissions from landfill continue long after the closure of the landfill site and possibly beyond the 100-year time horizon that is commonly set).

In the case of carbon footprints for subjects that are ongoing in nature, for example a household, product, organization or country, the temporal boundary could be set in-line with existing temporal units, such as a month, quarter, calendar year or financial year. For example, the UK Department of Energy and Climate Change's Act on CO_2 Carbon Calculator allows users to calculate their personal or household carbon footprint for a given calendar year [106]. Calculating a carbon footprint for each year will allow inter-annual comparison to determine changes in emissions levels and to track progress against predefined targets. The calculation of carbon footprints over temporal boundaries of less than one year may be useful for analysis of intra-annual variability.

For subjects that are temporally limited (e.g., products or events), rather than setting strict temporal boundaries, it is more appropriate to apply event-based boundaries. For example, the boundary for a carbon footprint of a sports event or festival may be set at the start and end point of the event, or extended to include the goods and service provision to the event and visitor transport [27]. For a life cycle carbon footprint of a product, boundaries may be set as the entire cradle-to-grave product life cycle, such as suggested in the Publicly Available Standard 2050 [17].

Boundary selection is about striking the balance between completeness of the carbon footprint and the cost of calculating the carbon footprint [2]. Exclusion of entire Scopes of emissions can have a profound effect upon the results of a carbon footprint. For example, approximately 40% of an average country's carbon emissions are embodied in imports (Scopes 2 and 3) [28], and on average approximately 80% of a company's carbon footprint is made up of Scope 3 emissions [29].

The objective of boundary setting should be to provide as complete a picture as possible of emissions caused by the subject in question, whilst operating within existing time and resource constraints. If the boundary is set too wide and the costs involved in completing the carbon footprint are too high, then it is unlikely that the carbon footprint will be calculated frequently enough to be an effective measure of performance. However, if the boundary is set too small, it may not serve to highlight significant emissions reduction opportunities [22].

Boundaries are frequently set either in keeping with convention or based on subjective judgment [30]. However, a more objective approach is suggested by Hondo and Sakai, which involves sensitivity analysis to determine which inputs have a significant impact upon the calculated carbon footprint [31]. Carbon footprints are used for reporting and tracking progress against targets; once a boundary has been set, changing it gives rise to issues of comparability between iterative carbon footprints [11]. The boundaries associated with a variety of carbon footprinting standards are outlined briefly in Table 3.

Emissions calculation methods (tiers)

Once the emissions sources to be included have been selected, the quantity of emissions from each source must be calculated and apportioned to the subject of the carbon footprint. There are a range of methods that can be applied to calculating carbon footprints.

At its most simple, a carbon footprint is calculated by determining the quantity of emissions of a particular GHG per unit of an activity (an emissions factor), and multiplying that by the number of units of that activity that have occurred within the boundaries of the carbon footprint [2]. For example, the unit of activity could be liters of liquid fuel consumed, which is then multiplied by emissions factors (mass/l), giving quantities of CO_2 and CH_4 emitted. Emissions factors can either apply directly to the use of fuels, energy products (e.g., electricity) or to other activities, such as traveling a distance using a certain mode of transport, consuming a quantity of fresh water [107] or generating a quantity of waste [108].

The IPCC categorize methods for calculating emission into three tiers [9]. Tier One methods are the least accurate and specific but tend to be the easiest to apply, while Tier Three methods are the most accurate but also more time consuming and costly to apply (Table 4) [17].

The highest practicable tier of method should be used with the objective of calculating an accurate carbon footprint based on specific information. It is usually possible to apply at least Tier Two methods to the calculation of direct emissions, such as the fuel or electricity consumed by the subject of a carbon footprint, as most developed countries publish national emissions factors based on national average carbon contents of fuels [107,109,110].

The IPCC emissions factors database provides internationally applicable emissions factors [108]. However, the units used are primarily intended for national GHG inventory calculation and, therefore, are inappropriate for carbon footprinting activities on a smaller scale. For this reason, Tier Two methods using national GHG emissions factors are often easier to apply than Tier One methods.

Activity data & tiers

The tier of method used in calculating carbon emissions will largely be determined by the specificity of data available (Figure 2); for example, the calculation of carbon emissions from a motor vehicle over the duration of a year. The quantity of fuel used depends on many factors including the vehicle, age, condition, distance traveled, types of journey that the vehicle is used for, vehicle loading and how economically the vehicle is driven [32].

A Tier Three method may use measured fuel consumption (inferred from fuel inputs) and directly calculate emissions based on published national emissions factors for the fuel type. Fuel inputs can be measured with a high degree of accuracy and, therefore, there is little uncertainty in the result. The various factors mentioned above that affect fuel consumption would all be indirectly taken into account as they will have resulted in the observed fuel consumption.

A Tier Two method may use odometer readings (measured activity data) from the vehicle in conjunction with the manufacturer's published emissions factor per unit of

Table 3. Boundaries, expressed in terms of emissions Scopes, associated with different carbon footprinting standards.

Standard	Scope 1	Scope 2	Scope 3
Publicly Available Specification 2050 – Specification for the Assessment of the Life Cycle GHG Emissions of Goods and Services [17]	All	All	Most, excluding capital goods used in production of goods purchased
World Resources Institute/World Business Council for Sustainable Development GHG Protocol Corporate Accounting and Reporting Standard [11]	All operationally responsible for	All operationally responsible for	Optional, suggested inclusion of employee travel
International Local Government GHG Emissions Analysis Protocol [10]	All within geopolitical boundaries	All within geopolitical boundaries	Some, for example waste processing outside of geopolitical boundaries
IPCC Guidelines for National GHG Inventories [9]	All	None	None

distance traveled. This method would be specific to the type of vehicle and would use relatively accurate data to determine the specific distance traveled. However, the mechanical condition of the vehicle and factors relating to vehicle use may cause actual emissions levels to be significantly different from those predicted using the manufacturer's published emissions factor.

A Tier One method may use a national estimate of annual distance traveled (generalized activity data) and an emissions factor per unit of distance traveled for the class of motor vehicle. This method would have a high level of inherent uncertainty as it is specific to neither the vehicle nor the nature of its use.

It is important to note that the uncertainty associated with a given tier of methodology varies depending on the scale of the carbon footprint. For example, using the Tier Two method outlined above would have relatively high uncertainty for calculating the CO_2e emissions from a specific vehicle because the usage profile of the vehicle is unlikely to align with the manufacturer's definition of 'average'. However, if the manufacturer was quantifying the CO_2e emissions associated with the 'in-use' stage of the vehicle life cycle it would not be unreasonable to assume 'average' use of the vehicle across all units sold, provided that the methods used to define 'average' use were robust.

CO_2e & GWP

When calculating a carbon footprint, emissions of both CO_2 and CH_4 are accounted. However, it is desirable to express a carbon footprint using a single meaningful unit rather than separate emissions quantities for each GHG [33]. The unit used for this purpose is CO_2e, which is based on a calculation of the GWP of 1 kg of a GHG over a certain number of years and expressed as the amount of CO_2 that would cause the same effect if emitted to the atmosphere. GWP values are released by the IPCC for three time horizons, 20 years (GWP_{20}), 100 years (GWP_{100}) and 500 years (GWP_{500}), although GWP_{100} is used almost universally in accounting methodologies and protocols. The IPCC published its first series of GWP values in its Second Assessment Report [34], and have subsequently updated these values twice as a result of improvements in the calculation and increases in atmospheric concentrations of anthropogenic GHGs. Concerning the carbon footprint, it is important to note the evolution of the GWP value of CH_4, which has increased from GWP CH_4 = 21 CO_2e in the IPCC Second Assessment Report [34] to GWP CH_4 = 23 CO_2e

Table 4. Three tiers of emissions estimation approaches.

Tier	Description	Examples
One	Use of nonspecific data to estimate emissions	National average fuel or electricity use per capita IPCC default emissions factors Assumption that technology meets minimum regulatory requirements
Two	Use of country-specific data to calculate emissions	Country-specific emissions factors Engineering estimates of system use and design Technology modeled based on design specifications Annual fuel use calculated from money spent multiplied by average fuel price for a year Total distance traveled within a community, based on traffic counts and road segment distances
Three	Use of technology-specific data to calculate emissions	Metered and submetered energy and fuel use GHG emissions directly monitored using specialist equipment Equipment modeled based on design specification, age of equipment and quality of maintenance

Adapted with permission from [9].

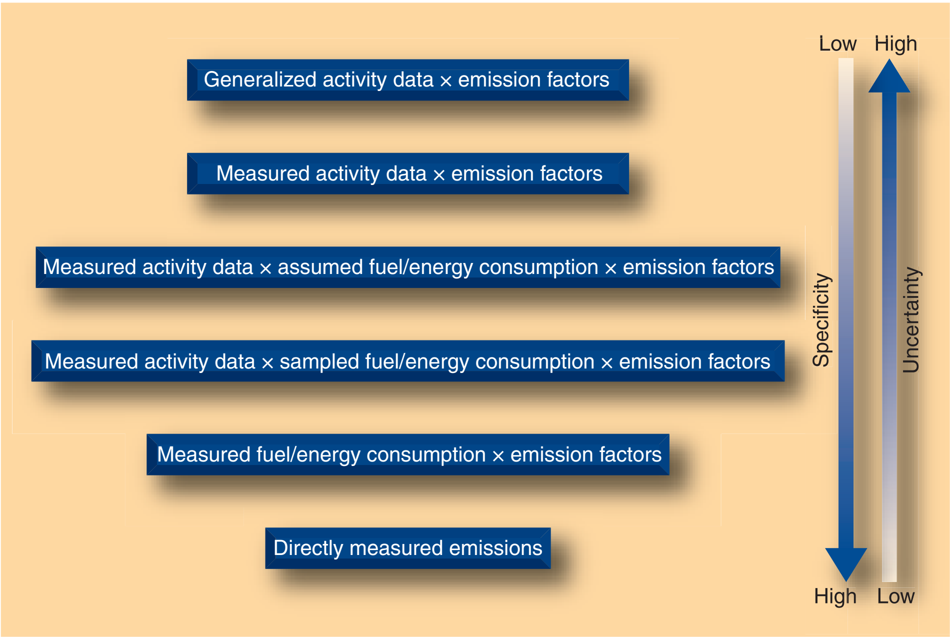

Figure 2. Examples of the various methods for quantifying emissions.

sulfur hexafluoride emissions, using the GWP_{100}. Many national emissions factors represent all GHG emissions factors in CO_2e, meaning no conversion has to be made. Internationally applicable GWPs are published by the IPCC [33].

Calculating Scope 1 & 2 emissions

Calculation of Scope 1 and 2 CO_2e emissions using a Tier Two or Three method should be possible for the majority of subjects, yielding results with a high degree of specificity and certainty. Liquid and solid fuel use can be very accurately measured simply by keeping a record of volume or weight purchased and used; information that should be freely available on sales receipts. Gas and electricity use data should be available through utility bills. These figures can then be multiplied by national emissions

in the IPCC Third Assessment Report [35] and finally to GWP CH_4 = 25 CO_2e in the IPCC Fourth Assessment Report [33]; an overall increase of 19%.

To ensure accuracy, it is important that any individual undertaking a carbon footprint analysis uses the most up-to-date GWP values available, which are currently those published in the IPCC Fourth Assessment Report [33]. However, the majority of mandatory GHG reporting initiatives, such as the EU Emissions Trading Scheme or the Kyoto Protocol, require users to adopt the GWP values of the IPCC Second Assessment Report [34] as convention. The benefit of this is that it ensures consistency and comparability between involved parties. This does, however, come at the cost of accuracy, as out-of-date GWP values are being used. It is important that, come the end of the Kyoto Protocol reporting period in 2012, the updated GWP values of the IPCC Fourth Assessment Report are adopted as a convention, as this will ensure that GHG emissions are being measured accurately as well as being reported consistently between involved parties.

In the case of the carbon footprint as defined by Wright *et al.*, CO_2e emissions are calculated as an aggregation of CO_2 and CH_4 emissions using the relevant GWP_{100} [3]. In the case of a climate footprint, CO_2e are calculated as the aggregate of CO_2, CH_4, nitrous oxide, hydrofluorocarbons and perfluorocarbons, and

Key term

Life cycle assessment: Provides a methodology for the measurement of the full range of environmental and social impacts associated with a process, product or activity from 'cradle-to-grave' (i.e., from raw materials through processing, distribution, use and disposal).

factors if available, or IPCC default emissions factors, to determine CO_2e emissions. This approach to emissions calculation using specific fuel and energy use data, multiplied by emission factors, or direct monitoring of emissions, is referred to as 'process analysis' – a term derived from the discipline of life cycle assessment [36].

When the subject of a carbon footprint is small, such as a household or small business, these data may be sufficiently granular for the purposes of the carbon footprint. However, in carbon footprinting of larger organizations it may be preferable to perform more detailed energy auditing to determine emissions levels associated with equipment and processes at a submetered level [37].

Quantifying Scope 1 and 2 emissions to a high degree of certainty should be seen as a top priority when calculating a carbon footprint. First, gathering the data necessary to apply at least Tier Two methods should be possible without incurring unreasonable costs [11]. Second, as with the emissions sources themselves, the subject of the carbon footprint has a higher degree of responsibility for Scope 1 and 2 emissions calculation methods than for Scope 3. The Scope 1 and 2 emissions calculated by the subject of a carbon footprint may be passed on to form the Scope 3 emissions of parallel carbon footprints, significantly increasing the impact of uncertainties and inaccuracies.

Capturing Scope 3 emissions

The definition of a carbon footprint stipulates that 'all relevant sources' be considered [3]. Standards based on the discipline of life cycle assessment include upstream (supply chain) and downstream (use and end-of-life) emissions associated with any product or service [17,22,36], and therefore extend beyond Scope 1 and 2 emissions to include as complete a picture of Scope 3 emissions as possible. The justification for inclusion of all Scope 3 emissions in a given subject's carbon footprint is that consumers create a demand for upstream emissions and suppliers enable downstream emissions [38]. Including as full a range of these emissions sources as practicable greatly increases the diversity of possible emissions reduction initiatives.

Capturing these Scope 3 emissions is one of the most sizeable challenges in carbon footprinting. This is because, by their definition, Scope 3 emissions take place outside of the normal geographical, financial and operational boundaries of the subject of a carbon footprint. In addition, Scope 3 emissions sources may be owned by organizations that may not be forthcoming with data. There are two main methods for inclusion of these emissions in a carbon footprint. The first is to calculate Scope 3 emissions using process analysis, in a similar way as when calculating Scope 1 and 2 emissions [39]. This necessitates the cooperation of the subjects responsible for the Scope 1 and 2 emissions, both in calculating the carbon footprint and sharing the data. For example, a manufacturer may calculate the CO_2e emissions associated with a unit of production [40,41]. This data may then be shared with customers for calculation of their Scope 3 emissions based on the number of units of the product that they purchase.

As the complexity of a supply chain increases, the more massive a task this approach becomes. At its simplest, a company may own the entirety of a supply chain from the extractive operations involved in obtaining the raw materials to the distribution network that delivers directly to customers. In reality, supply chains are more likely to involve many geographically dispersed organizations [30]. This should, however, become less of an issue as a greater number of organizations calculate their carbon footprints and publication of environmental performance metrics becomes the norm [22].

Where this data is not available other methods must be employed. One may be to jointly undertake a carbon footprinting project with main suppliers in order to accurately determine their Scope 1 and 2 emissions [29]. If this is not practicable, the alternative method for including Scope 3 emissions is to use economic and environmental data to allocate responsibility for a portion of an upstream industry's CO_2e emissions to the subject of a carbon footprint. This method is called environmental input–output analysis (EIOA) [4,23,30,39]. Input–output analysis is an approach to modeling interdependence within an economy to better understand the total demand for products and services caused by a unit of final consumption [30,42]. The data are presented in input–output tables showing the fiscal flows between industrial sectors within an economy in matrix form. These tables, in conjunction with industry standard data on the GHG emissions associated with a unit of financial output from that industry, can be used to estimate the Scope 3 emissions throughout an entire economy associated with the subject of a carbon footprint [39].

EIOA is relatively inexpensive to apply provided that the necessary national input–output tables and environmental accounts for each industry are available [30]. However, the additional calculation steps and assumptions involved in estimating embodied CO_2e emissions based on economic flows means that this approach has a high level of inherent uncertainty [43]. This becomes even more problematic when companies of significantly different natures are categorized into the same industry in economic input–output tables. For example, in the USA's input–output tables, publishing companies are categorized into the same industrial sector as paper producers; two types of business with vastly different emissions profiles [44]. In addition to the inherent uncertainty of this approach, it also fails to account for any variation within an industry [4,39]. For example, a company or individual may decide to purchase products from a supplier with a lower carbon footprint than its competitors. Using EIOA, this would have no impact upon the calculated carbon footprint due to the lack of specificity in the EIOA approach. This lack of specificity puts EIOA methods into the category of Tier One emissions calculation methods, which should only be applied when other more specific methods are not practicable.

Both process analysis and EIOA have associated advantages and disadvantages and are not necessarily mutually exclusive. Process-analysis methods use specific activity data and therefore yield results with a substantially lower level of uncertainty than EIOA [4,39]. However, it is rarely feasible to use process-analysis methods for all Scope 3 emissions sources, leading to substantial truncation errors due to omitted emissions sources [30]. EIOA lacks specificity, but does not suffer from truncation errors, and so offers full inclusion of Scope 3 emissions sources [4,30,39].

Hybridization of these two broad approaches is possible and takes advantage of the strengths of each category of method [4]. An approach suggested by Hondo and Sakai uses EIOA methods to calculate a preliminary carbon footprint. Sensitivity analysis can then be used to mathematically quantify the significance of emissions sources based on this preliminary carbon footprint.

Emissions sources that have above a predetermined level of impact upon the total carbon footprint can then be included within the boundary set for more specific and detailed process analysis [31].

Carbon neutrality of biogenic carbon

The decomposition of biomass in anaerobic conductions (such as in landfill) produces emissions of CH_4. When this CH_4 is combusted – for example, through gas flaring at a landfill site – the CH_4 is converted into heat, water and, most significantly, CO_2. It is common practice in the majority of GHG emissions quantification methodologies to disregard emissions of this biomass-derived CO_2 [9–11,17]. This is due to the concept of 'carbon neutrality', where the assumption is that, over a short time period (i.e., under 100 years), emissions of biomass-derived CO_2 will be negated by photosynthetic CO_2 absorption during the growth of new organic matter [45]. It must also be noted that some of GHG emissions quantification methodologies do not assume that CO_2 reabsorption is instant and therefore factor a lag time into assumptions about the rate of carbon reabsorption [46,47].

It has been suggested that permitting the concept of carbon neutrality in carbon footprinting creates risks; for example, that large scale deforestation for fuel could be wrongly regarded as preferable to the use of fossil fuels [46]. However, by considering changes in stocks of stored carbon as suggested by Wright *et al.* [3], this would be captured as land use change leading to reduction in carbon stocks in a similar way, as is standard in national GHG inventory reporting [9]. It should also be noted that combustion and decomposition of organic matter produces CH_4 emissions, which must be accounted given that no CH_4 is absorbed in photosynthesis [9].

Carbon sinks & stores

A carbon sink is a natural or artificial reservoir that accumulates and stores CO_2 or other GHGs for an indefinite period of time [2]. Usually the term carbon sink will refer to a natural stock of biogenic carbon, such as a forest, but may also refer to an anthropogenic stock, such as a waste disposal site [2,9]. Changes in the size of natural and anthropogenic carbon stores cause net emissions or removals (sequestration) of atmospheric CO_2 [48]. Biogenic carbon can be seen as belonging to three broad categories: carbon in soils and decomposing organic matter (soil organic carbon), carbon in biomass (biomass carbon) and carbon stored in man-made products (including harvested wood products) [9]. The quantity of soil organic carbon and biomass carbon for a given land use type are largely determined by climate [49–52].

There are a range of methods for estimating carbon stock size and changes over time. The resultant estimated CO_2 removals and CO_2 and CH_4 emissions should be recorded as part of a carbon footprinting exercise. A Tier One method is provided within IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry [9]. Standard carbon stock figures per unit of area are provided for a range of land uses within broad climatic zones and standard emission and sequestration rates for various land use changes. This method is fairly simple to apply, but lacks specificity to local conditions and management approach.

Tier Two methods could involve computer modeling to simulate plant growth and organic matter decomposition to estimate biomass and soil carbon stocks for specific climatic conditions and land-management regimes [51,53,54,111]. Not only would this offer a greater level of accuracy, it would also offer the opportunity for explicit simulation of the effect of land use changes. However, the lack of a standard modeling approach and the level of expertise required to implement such an approach may render this impracticable for carbon footprinting projects, for which land use change is not a major factor.

Tier Three methods would use soil samples to directly measure the quantity of carbon per unit mass of soil [52,55] and vegetation samples to estimate the biomass stored in trees and other vegetation [56]. This level of approach yields the most accurate results [55] but can be costly and time consuming, especially in large areas of varying land use [57]. Soil and vegetation carbon stocks approach a static state under steady climate, management and land use regimes [50,51]. Therefore, estimating biomass and soil carbon stocks is of primary concern at times of change, where significant emissions or removals of atmospheric CO_2 can occur.

Future perspective

The discipline of carbon footprinting is still relatively young and, as such, there is likely to be significant evolution of approaches as universal standards emerge. Because of this, carbon footprinting programs initiated may now be subject to significant methodological and conceptual revisions in the future. In order to allow for comparability over time it is of principal importance that methods are thoroughly documented and justified so that the implications of changing approaches can be quantified and taken into account when comparing past and present carbon footprints. Methods should also be designed in such a way that CO_2e emissions and removals can be directly associated with activities with as fine a level of granularity as is practicable. This will facilitate any necessary retrospective reformulation of results.

Supplementary data

To view the supplementary data that accompany this paper please visit the journal website at: www.future-science.com/doi/suppl/10.4155/CMT.11.80.

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Executive summary

- Carbon footprinting is an emerging set of techniques to enable the calculation of emissions of the GHGs CO_2 and CH_4, and encourage GHG emissions reductions.
- A carbon footprinting project should always be undertaken in such a way as to yield results that enable targeted reductions of GHG emissions.
- The process of calculating a carbon footprint involves a series of steps: identification and categorization of emissions sources, boundary setting, data gathering, emissions quantification and documentation.
- All sources of GHG emissions should be identified including both direct emissions sources, such as fuel combustion, and indirect emissions sources, such as emissions embodied in (released during the creation of) electricity or goods used.
- Emissions sources should be categories into Scope 1 (all direct emissions), Scope 2 (emissions embodied in electricity, heat and steam) and Scope 3 (all other indirect emissions).
- The spatial and temporal boundaries should be set and documented in order to define the emissions sources that will be included in the carbon footprint analysis. Justification should be given for the exclusion of any emissions sources.
- For each emissions source an emissions calculation methodology must be chosen with the aim of attaining results that are specific to the subject of the carbon footprint and with the lowest levels of uncertainty practicable.
- Emissions are usually calculated by multiplying the quantity of an activity measured or estimated by published or sampled fuel use rates and GHG emissions factors (the quantity of GHGs emitted per unit of activity or fuel use).
- Methods of emissions quantification include multiplication of average activity data with noncountry specific emissions factors, computer simulation to model GHG emissions and direct monitoring of emissions.
- Emissions from Scope 1 and 2 emissions sources should be measured with a high level of certainty and specificity using high-quality data on quantities of fuel and energy use or directly monitored emissions where possible. This form of calculation approach is called process analysis.
- Scope 3 emissions can be included using process analysis techniques, where data is available. Where data is unavailable, a technique using financial flows and standard emissions intensities per unit of monetary output from an industry can be employed to avoid truncation. This is called environmental input–output analysis (EIOA).
- Process analysis offers considerably more specificity and lower uncertainty than EIOA, but lacks the level of inclusiveness of emissions sources offered by EIOA approaches.
- Process analysis and EIOA are not exclusive and can be hybridized to eliminate truncation whilst maintaining specificity where data and resources permit the application of a process analysis emissions quantification method.
- Changes to carbon sinks and stores, such as land use changes causing an increase or reduction of carbon stored in biomass and soils, should be included in a carbon footprint. The IPCC provides guidance on the quantification of carbon stock changes. Measurement and simulation approaches are also available that offer a higher degree of specificity and reduced uncertainty if practicable.

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