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Current Opinion in Environmental Sustainability

Carbon footprints and embodied carbon at multiple scales

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Carbon footprints and embodied carbon have a strong methodological foundation and provide valuable input into policy formation. The widespread use of carbon footprints using existing knowledge needs to be encouraged and even regulated. At the product level, carbon footprints can empower consumers to shape their own climate friendly behaviour and help governments design policies that do not give the wrong incentives. Companies can use carbon footprints to reduce exposure to carbon prices or highlight the positive actions they have taken. Cities and regions can use carbon footprints to implement local policies that help meet overarching national objectives. National carbon footprints can help design equitable and efficient climate agreements that avoid shifting problems to other administrative territories. Further advances can provide strong interdisciplinary links between the physical carbon-cycle, emission drivers, and policy at a variety of scales.

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Current Opinion in Environmental Sustainability 2010, **2**:245–250

This review comes from a themed issue on Carbon and nitrogen cycles
Edited by Josep G Canadell

Received 24 January 2010; Accepted 10 May 2010
Available online 8th June 2010

1877-3435/$ – see front matter

DOI 10.1016/j.cosust.2010.05.004

Introduction

Greenhouse gas mitigation has historically focussed on emission sources and given relatively little attention to emission drivers. A coal power plant, for example, would not operate if it was not for the downstream demand for electricity from industry, buildings, households, and so on. Tracing the pathway from emission sources back through the production system ultimately leads to individual emission drivers [1•]. In many cases the emission driver could be considered as individual consumers, but in a broader perspective an individual consumer may have little control over, for example, existing infrastructure, production systems, or government policies. Emission drivers, therefore, need to be considered at several scales and in different contexts, covering for example, individuals, households, companies, different levels of government, and even entire nations (Figure 1). A re-orientation of mitigation policy to start at the emission driver, and not the emission source, may afford a more holistic approach to mitigation and policy design [1•].

In recent years there has been a growing interest in understanding emission drivers via carbon footprints and embodied flows of carbon at a variety of scales [2••,3,4•,5•]. While the term 'carbon footprint' is new [6], the underlying tools and methods are well established having been previously developed for a variety of environmental issues [7•]. The aim of this article is to give an overview of the recent literature of carbon footprints and embodied carbon. The article will start with some remarks on definitions and methods before providing an overview of applications at different scales and highlighting areas of future research.

Definition and methods

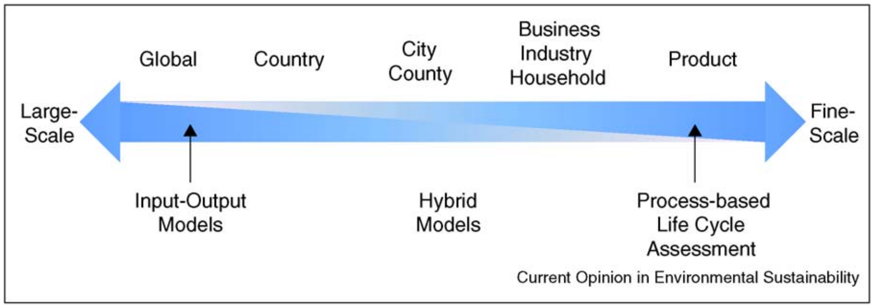
A 'carbon footprint' is difficult to define, as it requires a clear statement of underlying assumptions and often, the methodological approach [6]. Conceptually, a carbon footprint should consider all emissions of a product both backward in time from the point of consumption to emission sources and forward in time to include the use and disposal phase of products. The definition must span several scales, allowing the analysis of everyday consumer products through to countries (Figure 1). In its most general form, the system boundary is global but this is often hard to achieve in practice. Emission sources, sinks, and storage should be considered, but this may introduce further uncertainties and methodological issues. A carbon footprint is constructed in the context of anthropogenic climate change, suggesting that the term 'carbon footprint' may be too restrictive as climate is affected by more than carbon (e.g. N_2O, SO_2, black carbon, land-use change, albedo, and so on).

A widely accepted and concrete definition of a carbon footprint does not exist [6], but the notion of what a footprint is does exist. An open definition that attempts to allow for all possible applications (functional units) across scales could be:

The 'carbon footprint' of a functional unit is the climate impact under a specified metric that considers all relevant emission sources, sinks, and storage in both consumption and production within the specified spatial and temporal system boundary.

Following the definition of a carbon footprint is the notion of 'embodied carbon', 'carbon flows', 'embedded carbon',

Figure 1



A schematic of carbon footprint applications and corresponding methods across scales.

'virtual carbon', and similar terms. Historically, the emissions that occur along the supply chain of a functional unit have been said to be 'emissions embodied' in the functional unit. The emissions are not a physical part of the functional unit, but are *associated* with the functional unit via the production network. A carbon footprint and embodied emissions are synonyms under consistent definitions.

The methods used to determine the carbon footprint should not be specified in the definition. It is only necessary that the method satisfactorily meet the requirements of the definition. In practice, the method depends on functional unit via scale (Figure 1). Consumer products would generally use bottom-up Life-Cycle Assessment [3], while studies at the national level would apply top-down input–output analysis [2••]. Hybrid methods which combine the strength of both LCA and IOA are an active area of research and are increasingly being used in practice [8,9•,10].

Scales of analysis

A carbon footprint can be analysed for many different functional units at different scales and using different methods (Figure 1).

Products

A carbon footprint is a subset of all Life-Cycle Assessments and is generally based on long-lived greenhouse gases using a 100-year global warming potential as specified in the Kyoto Protocol [11]. A core problem with LCA is the comparability of studies owing to different methods and assumptions [9•]. The LCA community is currently in the process of developing and improving specific standards for calculating the carbon footprint of products [12–14]. While a standardization process may help alleviate some consistency issues, compromises may mean standards do not use the ideal methodology [15,16].

Given the widespread acceptance of LCA and incorporation into policy documents [17], it has had relatively little direct impact on climate policy with the, arguably belated, exception of biofuel debates [18•]. LCA traditionally focuses on a variety of environmental impacts [3,11] and this allows a more comprehensive environmental analysis, particularly in the context of co-benefits [19•]. The LCA community should be encouraged to have a more active role in climate policy through, for example, greater inclusion in IPCC reports, as guidance in early stages of policy formation [18•,19•], and in the broader development of alternate metrics [20•].

Households

The energy shocks in the 1970s instigated many studies on the carbon footprint of households [7•]. These studies are not limited to direct energy use by the household, but rather include the much larger footprint of goods and services purchased by the household [21]. Many studies focus on how the household carbon footprint varies with socio-economic characteristics [21]. The dominant factor increasing the carbon footprint is household expenditure [22]. The elasticity between the footprint and expenditure is generally between 0.6 and 1.0, reflecting that as households get wealthier their consumption shifts to higher value-added or more service-based goods and services [23•]. More detailed studies consider socio-economic characteristics such as household size, spatial location, lifestyles, eating habits, and so on [21,24••,25•,26,27•].

A recent global study considered the carbon footprint of nations, of which a core component is the carbon footprint of household consumption [28••]. Across broad consumption categories the elasticity of the footprint with expenditure was found to vary considerably. The elasticity for food and shelter was quite low confirming that as households earn more they spend marginally less on necessities. The elasticity for manufactured products and mobility was high, suggesting that households spend their excess income on luxury items. There is little understanding in what causes the differences between countries, and cross-country comparisons comparing energy mixes, consumption and production technologies, consumer behaviour, climatic differences, and even cultural differences are needed. Inequality may play an important role [29] which may have important implications for future climate agreements [30].

Companies

As a consequence of potential exposure to carbon pricing, companies are increasingly interested in understanding their carbon footprint. The Greenhouse Gas Protocol [14], currently being updated, was developed to focus at the company level and has three levels of detail: Scope 1 are the emissions from sources under the jurisdiction of the company, Scope 2 are offsite emissions from the purchase of electricity, and Scope 3 are offsite emissions from the company's supply chain or from products sold by the company. In the GHG protocol, Scope 3 emissions are not mandatory but a robust carbon footprint requires all three components.

Scope 3 emissions are the most difficult for a company to estimate, but as for household consumption, they are often the most important [31•,32••]. The failure to include Scope 3 emissions can also lead to perverse incentives such as outsourcing activities to different companies (shifting emissions from Scope 1 to Scope 3). While Scope 3 emissions are perceived as overly difficult for an average company to calculate, the tools and methods are available [5•,33]. As for LCA, various hybrid methods can be used to improve the initial estimate [8,9•,10]. Despite the extra effort of Scope 3 emissions, a company has a much better understanding of the potential risk of carbon price fluctuations on their business activities both upstream through supply chain purchases and potential loss in downstream sales.

An issue that has been highlighted in the case of company carbon footprints in particular is double counting of suppliers in the middle of the supply chain [33]. If a company includes its entire supply chain in a carbon footprint, and additionally, companies in its supply chain do the same there will be a double counting of emissions. From one perspective, this double counting can be ignored particularly if reporting is not combined with other companies. From another perspective, suppliers might at some point be held responsible for the emissions their products cause. For example, a coal mine could be considered to be partially responsible for the emissions caused by the use of the coal. Methods have been developed to share responsibility upstream and downstream along the supply chain while avoiding double counting [34,35] and applied in different applications [33,36].

Cities and regions

There is increasing interest in the carbon footprint of cities and geo-political regions [37•,38••,39,40]. In regions with a small physical territory, such as a city, the emissions that occur outside of the administered territory can dominate. In many respects, cities or regions can be considered as large companies and use the same principles as in company carbon footprints. Studies on cities often attempt to include electricity production (Scope 2) which often lies outside city limits [37•,39]. Less widespread, owing to data availability and more detailed methods, is the inclusion of the Scope 3 emissions due to goods and services consumed within the city or region, but produced elsewhere [38••,40]. As at the product and company levels, there are various initiatives to develop standard methodologies [41–43]. The sink and storage capacity of urban areas may be significant relative to forests [44], in which case there is a strong argument to report sinks and storage within the system boundary [1•]. Additional definition issues arise as cities not only serve residents, but also support activities outside the city and even in other continents [45]. This difficultly is highlighted in city-states where the carbon footprint is often significantly larger than domestic emission [28••,46••].

Countries

There is a growing number of studies on the carbon footprint of nations, but very few include the regional detail necessary for a correct calculation of the emissions associated with imported goods and services [2••]. Recent applications have filled this gap in the literature using large and globally harmonized data sets [28••,46••,47•]. These studies generally find that rich countries have a larger carbon footprint than their territorial emissions, while the opposite holds for poor countries. Using a slightly different method, related studies have focused on bilateral trade flows [48••] owing to a closer connection to trade policy than carbon footprints which involve processing trade in multiple countries [49•]. Policy relevant issues such as carbon leakage, competitiveness concerns, border-tax adjustments, and the distribution of emissions between countries are a natural part of carbon footprint analysis [46••,50•,51•,52]

Of particular interest at the country level is how the carbon footprint changes over time with respect to territorial emissions. In the case of both the UK and the USA, the national carbon footprints have grown faster than territorial emissions signifying that these countries have allowed their economies to shift towards the provision of services while increasingly importing manufactured products [53•,54••,55•]. Parallel studies on China confirm this [56•,57•] and assuming consistent results across more countries as indicated in static studies [48••] as much as one-half of the emissions growth in poor countries could be the result of consumption in rich counties [58]. More detailed studies across a wider range of countries and time spans will allow a more holistic assessment of the effectiveness of climate policy.

Conclusions

Parallel to applying existing knowledge, there is considerable scope for strengthening the foundations and applicability of carbon footprint analysis. Existing studies are weak on the inclusion of emission sinks, storage, and land-use change though studies exist [47,59•,60••]. Carbon footprints have focused on long-lived greenhouse gases, but there is scope to include short-lived components [20•] and biophysical factors [61] using a variety of metrics [20•]. A strong collection of analysis tools exists largely based on input–output analysis [7•], but there is scope for method development particularly to identify environmentally important linkages in production networks [62]. Databases exist for product-based studies and global studies, but there is scope to streamline data collection and harmonization to allow up-to-date studies. Databases and methods for hybrid studies are more difficult, owing primarily to data availability and lack of consistency between data sources. Accurate data in time series is needed for regular reporting as it is not necessarily the size of the carbon footprint that matters, but rather how and why it changes over time [1•,53•,54••,55•]. Uncertainty analysis has been poorly treated in many studies, but recent progress has been made [9•,63•].

The use of carbon footprints gives a stronger linkage of the physical carbon-cycle with emission drivers and policy. The concept of a 'footprint' has been useful for communicating relevant issues to a wide audience providing consumers with additional information to adjust behaviour and naturally links to the growing field of sustainable consumption [21,64]. Direct applications of carbon footprints and related fields into policy have generally been rare [25•], though exceptions exist. In the European Union, for example, life-cycle thinking often enters into policy documents [17]. The process of standardization at the product, company, and city level [12–14,43] indicates that companies and governments are starting to include carbon footprint analysis in their decision making. At the international level the ability of carbon footprint and embodied carbon to address issues such as carbon leakage, competitiveness concerns, border-tax adjustments, and the distribution of emissions between countries [46,50–52] are receiving increased interest from media and policy makers. There is a large potential for carbon footprint analysis to be broadly used in policy at a variety of scales, but interdisciplinary research on policy design and implementation needs to be prioritized.

Acknowledgements

I would like to thank Tommy Wiedmann, Steve Davis, Jan Minx, and reviewers for helpful comments.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. • Peters GP, Marland G, Hertwich EG, Saikku L, Rautiainen A, Kauppi PE: **Trade, transport, and sinks extend the carbon dioxide responsibility of countries**. *Climatic Change* 2009, **97**:379-388.

An overview and comparison of three important responsibility issues.

2. •• Wiedmann T: **A review of recent multi-region input-output models used for consumption-based emissions and resource accounting**. *Ecological Economics* 2009, **69**:211-222.

A review of recent studies on national carbon footprints.

3. Finkbeiner M: **Carbon footprinting – opportunities and threats**. *International Journal of Life Cycle Assessment* 2009, **14**:91-94.

4. • Minx J, Wiedmann T, Wood R, Peters GP, Lenzen M, Owen A, Scott K, Barrett J, Hubacek K, Baiocchi G *et al.*: **Input-output anslysis and carbon footprinting: an overview of regional and corporate applications**. *Economic Systems Research* 2009, **21**:187-216.

A broad catalogue of UK carbon footprint applications at different scales.

5. • Wiedmann TO, Lenzen M, Barrett JR: **Companies on the scale: comparing and benchmarking the sustainability performance of business**. *Journal of Industrial Ecology* 2009, **13**:361-382.

Discusses carbon footprints at the company level.

6. Wiedmann TO, Minx J: **A definition of "carbon footprint"**. In *Ecological Economics Research Trends.* Edited by Pertsova CC. Hauppauge, NY: Nova Science; 2008.

7. • Wiedmann T: **Carbon footprint and input-output analysis – an introduction**. *Economic Systems Research* 2009, **21**:175-186.

An introduction to a special issue with a historic background of methods and applications.

8. Suh S, Nakamura S: **Five years in the area of input-output and hybrid LCA**. *international Journal of Life Cycle Assessment* 2007, **12**:351-352.

9. • Williams ED, Weber CL, Hawkins TR: **Hybrid framework for managing uncertainty in life cycle inventories**. *Journal of Industrial Ecology* 2009, **13**:928-944.

Discusses strengths and weaknesses of different methods and how they can be overcome.

10. Lenzen M: **The path exchange method for hybrid LCA**. *Environmental Science and Technology* 2009, **43**:8251-8256.

11. Finnveden G, Hauschild MZ, Ekvall T, Guinee J, Heijungs R, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S: **Recent developments in life cycle assessment**. *Journal of Environmental Management* 2009, **91**:1-21.

12. ISO, **Carbon footprint of products**. International Organization for Standardization, ISO/CD 14067-1 (under development), http://www.iso.org/iso/catalogue_detail.htm?csnumber=43278

13. BSI, **PAS 2050 – Assessing the life cycle greenhouse gas emissions of goods and services**. The British Standard Institute; 2008.

14. WRI and WBCSD, **The Greenhouse Gas Protocol – A Corporate Accounting and Reporting Standard**. World Resources Institute (WRI) and World Business Council on Sustainable Development (WBCSD); 2004.

15. Minx J, Wiedmann T, Barrett J, Suh S: **Methods review to support the PAS process for the calculation of the greenhouse gas emissions embodied in goods and services, Report to the UK Department for Environment, Food and Rural Affairs (DEFRA, London)**. Stockholm Environment Institute at the University of York and Department for Bio-based Products at the University of Minnesota; 2008.

16. Sinden G: **The contribution of PAS 2050 to the evolution of the international greenhouse gas emission standards**. *International Journal of Life Cycle Assessment* 2009, **14**:195-203.

17. European Commission, **Communication [...]** on the Sustainable Consumption and Production and Sustainable Industrial Policy Action Plan. COM (2008) 397 final; 2008.

18. • Campbell JE, Lobell DB, Field CB: **Greater transportation energy and GHG offsets from bioelectricity than ethanol**. *Science* 2009, **324**:1055-1057.

Highlights the strength of life-cycle assessment for technology comparisons.

19. • Hill J, Polasky S, Nelson E, Tilman D, Huo H, Ludwig L, Neumann J, Zheng H, Bonta D: **Climate change and health costs of air**

emissions from biofuels and gasoline. *Proceedings of the National Academy of Sciences* 2009, 106:2077–2082.
Shows how life-cycle assessment can compare different environmental problems.

20. • Fuglestvedt JS, Shine KP, Berntsen T, Cook J, Lee DS, Stenke A, Skeie RB, Velders GJM, Waitz IA: **Transport impacts on atmosphere and climate: Metrics**. *Atmospheric Environment* 2010, In Press, http://dx.doi.org/10.1016/j.atmosenv.2009.04.044.
A comprehensive review of different metrics to compare greenhouse gas emissions.

21. Hertwich EG: **Lifecycle approaches to sustainable consumption: a critical review**. *Environmental Science and Technology* 2005, **39**:4673-4684.

22. Lenzen M, Wier M, Cohen C, Hayami H, Pachauri S, Schaeffer R: **A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan**. *Energy* 2006, **31**:181-207.

23. • Girod G, de Haan P: **More or better? A model for changes in household greenhouse gas emissions due to higher income**. *Journal of Industrial Ecology* 2010, **14**:31-49.
Shows how the quality of consumption changes with income.

24. •• Baiocchi G, Minx J, Hubacek K: **The impact of social factors and consumer behavior on carbon dioxide emission in the United Kingdom: a regression based on input-output and geodemographic consumer segmentation data**. *Journal of Industrial Ecology* 2010, **14**:50-72.
A combination of different datasets to give a high degree of policy relevant information.

25. • Tukker A, Cohen MJ, Hubacek K, Mont O: **The impacts of household consumption and options for change**. *Journal of Industrial Ecology* 2010, **14**:13-30.
Overviews some of the key gaps in the sustainable consumption literature, namely implementation issues.

26. Druckman A, Jackson T: **The carbon footprint of UK households 1990-2004: a socio-economically disaggregated, quasi-multi-regional input-output model**. *Ecological Economics* 2009, **68**:2066-2077.

27. • Weber CL, Matthews HS: **Food-miles and the relative climate impacts of food choices in the United States**. *Environmental Science and Technology* 2008, **42**:3508-3513.
A provocative analysis which puts the food-miles debate into context.

28. •• Hertwich EG, Peters GP: **Carbon footprint of nations: a global, trade-linked analysis**. *Environmental Science and Technology* 2009, **43**:6414-6420.
A cross-country comparison of carbon footprints with a focus on how consumption patterns vary with income.

29. Groot L: **Carbon Lorenz curves**. *Resource and Energy Economics* 2010, **32**:45-64.

30. Chakravarty S, Chikkatur A, Coninck Hd, Pacala S, Socolow R, Tavoni M: **Sharing global CO_2 emission reductions among one billion high emitters**. *Proceedings of the National Academy of Sciences* 2009, 106:11884–11888.

31. • Huang YA, Lenzen M, Weber CL, Murray J, Matthews HS: **The role of input-output analysis for the screening of carbon footprints**. *Economic Systems Research* 2009, **21**:217-242.
Develops a screening method to help estimate the contribution of the supply chain to a carbon footprint.

32. •• Matthews HS, Hendrickson CT, Weber CL: **The importance of carbon footprint estimation boundaries**. *Environmental Science and Technology* 2008, **42**:5839-5842.
Shows that the supply-chain makes a substantial contribution to carbon footprints.

33. Lenzen M, Murray J, Sack F, Wiedmann T: **Shared producer and consumer responsibility – theory and practice**. *Ecological Economics* 2007, **61**:27-42.

34. Rodrigues J, Domingos T: **Consumer and producer environmental responsibility: comparing two approaches**. *Ecological Economics* 2008, **66**:533-546.

35. Lenzen M: **Consumer and producer environmental responsibility: a reply**. *Ecological Economics* 2008, **66**:547-550.

36. Andrew R, Forgie V: **A three-perspective view of greenhouse gas emission responsibilities in New Zealand**. *Ecological Economics* 2008, **68**:194-204.

37. • Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havranek M, Paraki D, Phdungsilp A, Ramaswami A, Mendez GV: **Greenhouse gas emissions from global cities**. *Environmental Science and Technology* 2009, **43**:7297-7302.
An overview the carbon footprint of selected cities.

38. •• Lenzen M, Peters GM: **How city dwellers affect their resource hinterland: a spatial impact study of australian households**. *Journal of Industrial Ecology* 2010, **14**:73-90.
A detailed assessment which demonstrates that a large share of the carbon footprint of a city occurs well outside the geographic area of the city.

39. Hillman T, Ramaswami A: **Greenhouse gas emission footprints and energy use benchmarks for eight U.S. cities**. *Environmental Science and Technology* 2010, **44**:1902-1910.

40. Larsen HN, Hertwich EG: **The case for consumption-based accounting of greenhouse gas emissions to promote local climate action**. *Environmental Science and Policy* 2009, **12**:791-798.

41. Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havranek M, Pataki D, Phdungsilp A, Ramaswami A, Mendez GV: **Methodology for inventorying greenhouse gas emissions from global cities**. *Energy Policy* 2010, In Press, http://dx.doi.org/10.1016/j.enpol.2009.08.050.

42. Ramaswami A, Hillman T, Janson B, Reiner M, Thomas G: **A demand-centered, hybrid life-cycle methodology for city-scale greenhouse gas inventories**. *Environmental Science and Technology* 2008, **42**:6455-6461.

43. ICLEI, **International Local Government GHG Emissions Analysis Protocol**. ICLEI – Local Governments for Sustainability; 2009.

44. Churkina G, Brown DG, Keoleian G: **Carbon storage in human settlements: the conterminous United States**. *Global Change Biology* 2009, **16**:135-143.

45. Streets DG, Yu C, Bergin MH, Wang X, Carmichael GR: **Modeling study of air pollution due to the manufacture of export goods in China's Pearl River Delta**. *Environmental Science and Technology* 2006, **40**:2099-2107.

46. •• Davis SJ, Caldeira K: **Consumption-based accounting of CO_2 emissions**. In *Proceedings of the National Academy of Sciences* 2010, **107**:5687-5692.
A comprehensive global study of the carbon footprint of nations from a variety of perspectives.

47. • Wilting H, Vringer K: **Carbon and land use accounting from a produer's and a consumer's perspective: an empirical investigation covering the world**. *Economic Systems Research* 2009, **21**:291-310.
One of the few studies that includes land-use change in carbon footprint analysis.

48. •• Peters GP, Hertwich EG: **CO_2 embodied in international trade with implications for global climate policy**. *Environmental Science and Technology* 2008, **42**:1401-1407.
A comprehensive global study of the CO_2 emissions from the production of internationally traded goods and services.

49. • Peters GP: **From production-based to consumption-based national emission inventories**. *Ecological Economics* 2008, **65**:13-23.
A methodological article discussing different approaches to estimating the carbon footprint of nations.

50. • Weber CL, Peters GP: **Climate change policy and international trade: policy considerations in the United States**. *Energy Policy* 2009, **37**:432-440.
An analysis which shows the importance of considering emissions along the supply chain when discussing carbon leakage and competitiveness concerns.

51. • Peters GP, Hertwich EG: **Trading Kyoto**. *Nature Reports Climate Change* 2008, **2**:40-41.
A short article highlighting the difference between policy-induced (strong) and demand-induced (weak) carbon leakage.

52. Peters GP, Hertwich EG: **Post-Kyoto greenhouse gas inventories: production versus consumption**. *Climatic Change* 2008, **86**:51-66.

53. Wiedmann T, Wood R, Minx J, Lenzen M, Guan D, Harris R: **A carbon footprint time-series of the UK – results from a multi-region input-output model**. *Economic Systems Research* 2010, **22**:19-42.
• The first detailed time-series analysis of a carbon footprint of a country highlighting that the UK's carbon footprint is growing faster than territorial emissions.

54. Baiocchi G, Minx JC: **Understanding changes in the UK's CO_2 emissions – a global perspective**. *Environmental Science and Technology* 2010, **44**:1177-1184.
•• An analysis of the drivers for the rapid growth in the UK's carbon footprint despite a drop in territorial emissions.

55. Weber C, Matthews HS: **Embodied environmental emissions in U.S. international trade, 1997–2004**. *Environmental Science and Technology* 2007, **41(14)**:4875-4881.
• A comprehensive analysis of the USA carbon footprint highlighting that it is growing faster than territorial emissions.

56. Guan D, Peters GP, Weber CL, Hubacek K: **Journey to the world top emitter: an analysis of the driving forces of China's recent CO_2 emissions surge**. *Geophysical Research Letters* 2009, **36**:L04709.
• Demonstrates that Chinese exports are a key emission driver in China.

57. Weber CL, Peters GP, Guan D, Hubacek K: **The Contribution of Chinese exports to climate change**. *Energy Policy* 2008, **36**:3572-3577.
• Demonstrates that Chinese exports are a key emission driver in China.

58. Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely R, Foster P *et al.*: **Trends in the sourecs and sinks of carbon dioxide**. *Nature Geoscience* 2009, **2**:831-836.

59. Erb K-H, Krausmann F, Lucht W, Haberl H: **Embodied HANPP: mapping the spatial disconnect between global biomass production and consumption**. *Ecological Economics* 2009, **63**:328-334.
• Demonstrates the spatial separation between consumption and production of human appropriation of net primary production (HANPP).

60. Zaks DPM, Barford CC, Ramankutty N, Foley JA: **Producer and consumer responsibility for greenhouse gas emissions from agricultural production – a perspective from the Brazilian Amazon**. *Environmental Research Letters* 2009, **4**:044010.
•• A combination of models used to estimate the carbon footprint of agricultural production and land-use change in Brazil.

61. Jackson RB, Randerson JT, Canadell JG, Anderson RG, Avissar R, Baldocchi DB, Bonan GB, Caldiera K, Diffenbaugh NS, Field CB *et al.*: **Protecting climate with forests**. *Environmental Research Letters* 2008, **3**:044006.

62. Lenzen M: **Environmentally important paths, linkages and key sectors in the Australian economy**. *Structural Change and Economic Dynamics* 2003, **10(6)**:545-572.

63. Lenzen M, Wood R, Wiedmann T: **Uncertainty analysis for multi-region input-output models – a case study of the UK's carbon footprint**. *Economic Systems Research* 2010, **22**:43-63.
• The first detailed uncertainty analysis of a national carbon footprint showing that the uncertainty is smaller than many would expect.

64. Jackson T: *Prosperity without Growth: Economics for a Finite Planet* London: Earthscan; 2009.