An Ecological Footprint Study of New South Wales and Sydney

Report for DEC by Manfred Lenzen,
The University of Sydney

Department of **Environment & Climate Change** NSW

An ecological footprint study of New South Wales and Sydney is the result of consultancy work undertaken for the Department of Environment and Conservation NSW [predecessor of the Department of Environment and Climate Change] by Dr Manfred Lenzen, Integrated Sustainability Analysis (ISA), The University of Sydney.

Date of consultancy report: 25 February 2006

The University of Sydney
Integrated Sustainability Analysis ™

For further inquiries please contact:

Dr Manfred Lenzen
School of Physics
The University of Sydney NSW 2006
Phone: (02) 9351 5985
Fax: (02) 9351 7725
Email: m.lenzen@physics.usyd.edu.au
Website: www.isa.org.usyd.edu.au

Published by:

Department of Environment and Climate Change NSW
59–61 Goulburn Street, Sydney
PO Box A290
Sydney South 1232
Phone: (02) 9995 5000 (switchboard)
Phone: 131 555 (environment information and publications requests)
Phone: 1300 361 967 (national parks information and publications requests)
Fax: (02) 9995 5999
TTY: (02) 9211 4723
Email: info@environment.nsw.gov.au
Website: www.environment.nsw.gov.au

ISBN 978 1 74122 415 3
DECC 2008/215
June 2008

Contents

Executive summary

This work covers the calculation of ecological footprints for the populations of Statistical Divisions (SDs) in Sydney and NSW. These were calculated by applying input-output analysis to population and expenditure data from the 1993–94 and 1998–99 ABS Household Expenditure Survey and the 1996 and 2001 Australian Censuses.

The input-output approach has been applied dozens of times throughout the past 30 years and is the most robust approach for assessing the environmental impacts of populations. Since its first application in New Zealand in 1988, the use of input-output analysis for estimating ecological footprints has grown to include research organisations all over the world. Recently, a pilot study for Victoria compared the original method of estimation with an input-output analysis for the first time (www.epa.vic.gov.au/eco-footprint/docs/vic_ecofootprint_demand.pdf).

Input-output-based ecological footprints have many advantages: they are complete without artificial boundaries; they draw on detailed data sets which are regularly collected by government statistical agencies; and they can be calculated for industry sectors and product groups, for states, local areas and cities, and for companies and households. Finally, input-output-based ecological footprints allow valid trade-offs with other sustainability indicators, thus placing the ecological footprint within the broader context of the 'triple bottom line' approach to environmental reporting.

All calculations have been carried out using a prototype software based on the Integrated Sustainability Analysis group's Triple Bottom Line (TBL) framework (www.bottomline3.com). This software is based on an input-output model of the domestic Australian economy as of 1998–99, coupled with an extensive data base on TBL indicators. The methodology underpinning the software has been successfully piloted in a range of Australian company and government applications, a pilot program on TBL reporting (www.isa.org.usyd.edu.au/research/TBLEPA.shtml) and in a widely publicised nationwide whole-economy TBL study *Balancing Act* (www.isa.org.usyd.edu.au/publications/balance.shtml).

Table 1 summarises the main results for the per-capita ecological footprint of the two regions and all years examined in this work, based on both shared responsibility and full consumer responsibility. The quantities shown are 'total impact' (total ecological footprint per capita) and 'total intensity' (ecological footprint per capita per dollar of expenditure). The categories 'government administration' and 'capital infrastructure' cover expenditures that are not made by final consumers themselves, but by the government and producers in order to provide the 'commons', i.e. government administration and infrastructure such as buildings, roads, ports, etc. Note that results for 1996 and 2001 are based on *estimated* not surveyed expenditure figures. Results are therefore partly an effect of the regression estimation procedure and the explanatory variables used. Finally, the benchmark is the average Australian consumer, as defined by the average Australian sample of the 1998–99 ABS Household Expenditure Survey.

The following main results were found:

1 The per-capita ecological footprint of Sydney is above that of NSW, and in turn the latter is above that of the average Australian, no matter which calculation method is employed. This is most likely due to the greater affluence of households in Sydney, compared with NSW, and NSW compared in turn with the average Australian.

Table 1: Summary of results

	Total impact		**Total intensity**	
	Shared responsibility	**Full consumer responsibility**	**Shared responsibility**	**Full consumer responsibility**
Sydney HES* 1993–94	2.40 ha	4.23 ha	3.27 m^2/$	2.12 m^2/$
Sydney HES 1998–99	2.79 ha	5.02 ha	2.94 m^2/$	1.98 m^2/$
Sydney SD** 1996	2.40 ha	4.22 ha	3.23 m^2/$	2.20 m^2/$
Sydney SD 2001	2.52 ha	4.53 ha	3.06 m^2/$	2.04 m^2/$
NSW HES 1993–94	2.32 ha	4.04 ha	3.42 m^2/$	2.27 m^2/$
NSW HES 1998–99	2.65 ha	4.70 ha	3.07 m^2/$	2.08 m^2/$
NSW 1996	2.29 ha	3.98 ha	3.39 m^2/$	2.30 m^2/$
NSW 2001	2.41 ha	4.27 ha	3.20 m^2/$	2.13 m^2/$
Government administration	0.11 ha	0.34 ha	0.70 m^2/$	0.59 m^2/$
Capital infrastructure	0.57 ha	1.31 ha	1.80 m^2/$	1.89 m^2/$
Benchmark: Average Australian consumer	2.04 ha	3.57 ha	3.53 m^2/$	2.23 m^2/$
Including government and infrastructure				
Sydney HES 1993–94	3.08 ha	5.88 ha	4.31 m^2/$	3.16 m^2/$
Sydney HES 1998–99	3.47 ha	6.67 ha	3.98 m^2/$	3.02 m^2/$
Sydney SD 1996	3.08 ha	5.87 ha	4.27 m^2/$	3.24 m^2/$
Sydney SD 2001	3.20 ha	6.18 ha	4.10 m^2/$	3.08 m^2/$
NSW HES 1993–94	3.00 ha	5.69 ha	4.46 m^2/$	3.31 m^2/$
NSW HES 1998–99	3.33 ha	6.35 ha	4.11 m^2/$	3.12 m^2/$
NSW 1996	2.97 ha	5.63 ha	4.43 m^2/$	3.34 m^2/$
NSW 2001	3.09 ha	5.92 ha	4.24 m^2/$	3.17 m^2/$
Benchmark: Average Australian consumer	2.72 ha	5.22 ha	4.57 m^2/$	3.27 m^2/$

* HES: Household expenditure survey

** SD: Statistical Division

2 The per-capita ecological footprint based on shared responsibility is smaller than the footprint based on full consumer responsibility. This is because with shared responsibility, ecological footprints are shared between producers and consumers, and only a part of the responsibility is passed on to consumers. Shared responsibility recognises that Australian companies have started to calculate their own ecological footprints: the sum of all producer and consumer footprints equals the total national ecological footprint. With full consumer responsibility, the ecological footprint of any producer (company, industry sector, etc.) must be zero, or else it will be double-counted.

3 The ecological footprint intensity (ecological footprint per dollar of expenditure) is low in areas with a high ecological footprint and high in areas with a low ecological footprint. This is because wealthy households spend more of their income on services than less wealthy households. Since services are associated with a smaller ecological footprint intensity, the overall ecological footprint intensity of wealthier households is lower.

4 The per-capita ecological footprint of Sydney increased between 1994 and 1999 and between 1996 and 2001. This result is independent of inflation, which has been taken out of the figures. It is most likely due to an increasing living standard. The percentage increases of the ecological footprint with full consumer responsibility and including government and infrastructure by main area are tabulated below.

Sydney 1994 to 1999	13.4%
Sydney 1996 to 2001	5.3%
NSW 1994 to 1999	11.6%
NSW 1996 to 2001	5.2%

5 Most of the total ecological footprint is due to land disturbance, and not to greenhouse gas emissions. Indirect upstream ecological footprint contributions make a larger contribution than on-site ecological footprints.

1. Introduction and objective of study

In order to provide input into the preparation of the NSW State of the Environment Report by the Department of Environment and Conservation NSW, the ecological footprints for the populations of Sydney and NSW have been calculated. Two aspects are identified as of key concern:

1. The calculation should employ updated data sources, using the population census and household expenditure surveys over a number of years

2. The calculation should reflect landcover disturbance as a proxy for biodiversity impacts.

This report is structured as follows: Section 2 outlines the general approach taken in this work; Section 3 provides an introduction into the main aspects of the methodology applied; the highlights of results are presented in Section 4; the Appendix provides details on the mathematics of the methodology; and a list of references completes the work.

2. General approach – the ISA ecological footprint framework

The Integrated Sustainability Analysis (ISA) group at the University of Sydney has assembled a framework for calculating ecological footprints tailored to Australian conditions. This framework employs the most detailed and comprehensive information on land disturbance and greenhouse gas emissions available in Australia today, using the Australian Bureau of Statistics' (ABS) comprehensive input-output tables, and the CSIRO's satellite-image-based assessment of land disturbance over the Australian continent. The assessment offered by the University of Sydney guarantees 100% coverage of all upstream impacts on land and emissions, and is therefore the only complete ecological footprint assessment to date. Significant truncation errors (often 25–50%) of upstream requirements that are common in conventional ecological footprints do not occur in the proposed methodology.

Using the ISA framework, the ecological footprint for Sydney and NSW can be calculated from household expenditure data. This approach has been applied in dozens of applications over the past 30 years, and is therefore the most robust approach for assessing the environmental impacts of populations. See Lenzen *et al.* (2004) for an example of such a study on Sydney. In this work, we also use multiple regression in order to estimate ecological footprints for local areas, based on both household expenditure and census data.

Final ecological footprints were calculated using software based on ISA's Triple Bottom Line (TBL) framework (www.bottomline3.com). This software is based on a static, single-region, open, basic-price, industry-by-industry input-output model of the domestic Australian economy as of 1998–99, coupled with an extensive database on TBL indicators.[1] The methodology underpinning the software has been successfully piloted in a range of Australian company and government applications (see www.isa.org.usyd.edu.au), a pilot program on TBL reporting (www.isa.org.usyd.edu.au/research/TBLEPA.shtml), and in a widely publicised nationwide whole-economy TBL study *Balancing Act* (www.isa.org.usyd.edu.au/publications/balance.shtml).

The software adds an entity as a hypothetical sector to the economy[2] and performs a Leontief-type, final-demand-driven, upstream, indirect-impact calculation, complemented by a Taylor expansion and a Structural Path Analysis.[3] The results are presented as the sum of on-site impacts, taken directly from user data, and indirect impacts, calculated by input-output analysis (hybrid analysis).[4]

Results can then be interpreted *ex-post*, that is as answers to the questions: 'What ecological footprint would have been assigned to the user's entity, given base year economic and resource use structure, and assuming proportionality between monetary and resource flows?' Results however can not readily be interpreted in an *ex-ante*, predictive way, such as: 'How would the ecological footprint change as a consequence of changes in the entity's financial and resource flows?'[5]

2.1 Input-output-based ecological footprinting – an approach growing worldwide

Since its first application in New Zealand in 1998, the use of input-output analysis for estimating ecological footprints has grown to include research organisations all over the

---

[1] Foran *et al.* (2005a), with a summary in Foran *et al.* (2005b). See also United Nations Department for Economic and Social Affairs (1999) and Lenzen (2001b).
[2] Joshi (2001)
[3] Lenzen (2002)
[4] Suh *et al.* (2004)
[5] For interpretation of static input-output models, see Miller and Blair (1985).

world.[6] Recently, a pilot study for Victoria compared the original method with an input-output-based methodology for the first time (www.epa.vic.gov.au/eco-footprint/docs/vic_ecofootprint_demand.pdf). At present, the ecological footprint methodology is being standardised (www.footprintstandards.org), with a strong focus on input-output analysis.

Input-output-based ecological footprints have many advantages: they are complete without artificial boundaries; they draw on detailed data sets which are regularly collected by government statistical agencies; and they can be calculated for industry sectors and product groups, for states, local areas and cities, and for companies and households. Finally, input-output-based ecological footprints allow valid trade-offs with other sustainability indicators, thus placing the ecological footprint within the broader context of the 'triple bottom line' approach to environmental reporting.

[6] Ferng (2001); Albino and Kühtz (2002); Bagliani *et al.* (2002); Hubacek and Giljum (2003); Lenzen *et al.* (2003); Lenzen and Murray (2003); McDonald and Patterson (2003); Nichols (2003); Wood and Lenzen (2003); Wiedmann *et al.* (2005)

3. Project methodology

This section provides an overview of the methodology applied in this work. It is aimed at readers who are unfamiliar with the concept of the ecological footprint, and who wish to read up on most recent developments. The following provides a background to the ecological footprint concept and the shared responsibility accounting principles of calculations applied in this work. A more technical exposition of the methodology appears in Appendix I.

3.1 Background to ecological footprints

The ecological footprint was originally conceived as a simple and elegant method for comparing the sustainability of resource use among different populations (Rees 1992). The consumption of these populations is converted into a single index: the land area that would be needed to sustain that population indefinitely. This area is then compared to the actual area of productive land that the given population inhabits, and the degree of unsustainability is calculated as the difference between available and required land. Unsustainable populations are simply populations with a higher ecological footprint than available land. Ecological footprints calculated according to this original method became important educational tools in highlighting the unsustainability of global consumption (Costanza 2000). It was also proposed that ecological footprints could be used for policy design and planning (Wackernagel *et al.* 1997; Wackernagel and Silverstein 2000).

Since the formulation of the ecological footprint, however, a number of researchers have improved the method as originally proposed (Levett 1998; van den Bergh and Verbruggen 1999; Ayres 2000; Moffatt 2000; Opschoor 2000; Rapport 2000; van Kooten and Bulte 2000). The improvements largely refer to the oversimplification in ecological footprint calculations of the complex task of measuring the sustainability of consumption, leading to comparisons among populations becoming meaningless[7] or the result for a single population being significantly underestimated. In addition, the aggregated form of the final ecological footprint makes it difficult to understand the specific reasons for the unsustainability of consumption by a given population (Rapport 2000) and to formulate appropriate policy responses (Ayres 2000; Moffatt 2000; Opschoor 2000; van Kooten and Bulte 2000). In response to the problems highlighted, the concept has undergone significant modification and improvement (Bicknell *et al.* 1998; Simpson *et al.* 2000; Lenzen and Murray 2001).

Recently, a standardisation process was initiated by the Global Footprint Network. One particular area of work within this process is aimed at unifying the divergent approaches in order to communicate clearer the numbers generated in ecological footprint calculations. The University of Sydney's Integrated Sustainability Analysis (ISA) group is at the forefront of integrating the many issues described below with the existing method.

3.1.1 Original concept

The original ecological footprint is defined as the land area needed to meet the consumption of a population and to absorb all its waste (Wackernagel and Rees 1995). Consumption is divided into five categories: food, housing, transportation, consumer goods, and services. Land is divided into seven categories: energy land; degraded or built land; gardens; crop land; pastures; managed forests; and 'land of limited availability', considered to be untouched forests and 'non-productive areas', which the authors defined as deserts and icecaps. These non-productive areas are not included further in the analysis. Data is collected from disparate

[7] For example, as a result of calculations by Wackernagel (1997), some countries with extremely high land clearing rates (Australia, Brazil, Indonesia, Malaysia) exhibit a positive balance between available and required land, thus suggesting that these populations are using their land sustainably.

sources such as production and trade accounts, state of the environment reports, and agricultural, fuel use and emissions statistics. The ecological footprint is calculated by compiling a matrix in which a land area is allocated to each consumption category. In order to calculate the per-capita ecological footprint, all land areas are added up, and then divided by the population, giving a result in hectares per capita. For example, the land that was needed in 1991 to support the lifestyle of an average Canadian was calculated by Wackernagel and Rees (1995, p. 83) to be 2.34 ha of energy land, 0.2 ha degraded land, 0.02 ha garden, 0.66 ha crop land, 0.46 ha pasture, and 0.59 ha forest, giving a total ecological footprint of 4.27 ha per capita.

The total ecological footprint for a population can also be subtracted from the 'productive' area the population inhabits. If this gives a positive number, it is taken to indicate an ecological 'remainder', or remaining ecological capacity for that population. A negative figure indicates that the population has an ecological 'deficit'. According to Wackernagel and Rees (1995, p. 97), Canadians in 1991 had an ecological remainder of 10.94 ha per capita.

3.1.2 Including all areas of land

In the original ecological footprint, areas which were 'unproductive for human purposes', such as deserts and icecaps, were excluded from the calculation (Wackernagel and Rees 1995). A problem with this approach is that deciding which land is unproductive for human purposes is subjective. There are many examples of indigenous peoples who have lived in deserts, in some cases, for thousands of years, such as the Walpiri people of Central Australia. In addition, large tracts of arid and semi-arid land in Australia support cattle grazing and mining. The ecosystems present in these areas have been, and continue to be, disturbed by these activities. Finally, many ecosystems that are not used directly may have indirect benefits for humans through providing biodiversity or other ecosystem functions. Therefore, in a recent calculation of the ecological footprint of Australia all areas of land were included, irrespective of their productivity (Simpson *et al.* 2000).

3.1.3 Including indirect requirements by using input-output analysis

In the calculation of ecological footprints of populations by Wackernagel and Rees (1995) and Simpson *et al.* (2000), the land areas included were mainly those directly required by households, and those required by the producers of consumer items. These producers, however, draw on numerous input items themselves, and the producers of these inputs also require land. Generally speaking, in modern economies all industry sectors are dependent on all other sectors, and this process of industrial interdependence proceeds infinitely in an upstream direction, through the whole life cycle of all products, like the branches of an infinite tree.

Such a production 'tree' is shown schematically in Figure 1: the population to be examined represents the lowest level, or production layer zero (0). The land required directly by the population (for example land occupied by the house, land required to absorb emissions caused in the household, or by driving a private car) is called the direct land requirement. All other, indirect land requirements originate from this layer. The providers of goods and services purchased by the population form the production layer 1 and their land requirements are called first-order requirements. The suppliers of these providers are production layer 2, and so on. The sum of direct and all indirect requirements is called total requirements.

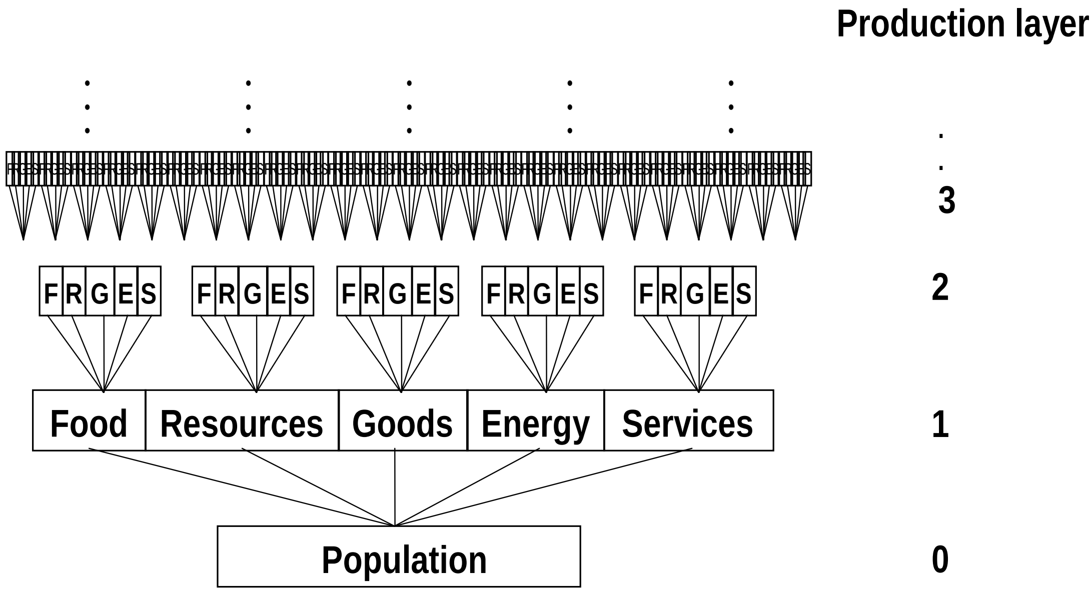


Figure 1: Industrial interdependence in a modern economy – a 'tree' of upstream production layers

A specific example for direct and indirect requirements in the ecological footprint of a Sydney household is shown in Figure 2. Direct requirements in production layer zero are represented by the land required for the household's home and for absorbing the emissions caused by the burning of petrol, natural gas and other fuels in the household and the car. One item contributing to the household's ecological footprint could be a train journey. The household does not directly require land by using this train. However, the train uses diesel fuel, which causes the emission of greenhouse gases. The rail transport operator providing this service is part of production layer 1, and the land required to absorb these emissions is an example for a first-order indirect requirement. Furthermore, the train itself needed to be built, and the land occupied by the train manufacturer (part of production layer 2) is a second-order requirement. Land and emissions associated with the steel plant producing the steel sheet (production layer 3) for the train are third-order requirements, the land mined to extract the iron ore (production layer 4) for making the steel sheet is a fourth-order requirement, and so on. Each stage in this infinite supply process involves land use and emissions. Figures 1 and 2 demonstrate that calculations that consider only layers 0 and 1 underestimate the true ecological footprint.

Even though indirect requirements, production layers and structural paths can be very complex, there exists a method for their calculation: input-output analysis. This is a macroeconomic technique that relies on data on inter-industrial monetary transactions, such as the Australian input-output tables compiled by the Australian Bureau of Statistics (2001a). It was first applied by Bicknell *et al.* (1998) to calculate an ecological footprint for New Zealand. Since then, the users of input-output analysis for ecological footprint analysis has grown continuously to include research organisations all over the world (Lenzen and Murray 2003; Wiedmann *et al.* 2006). Recently, a pilot study for Victoria compared the original method of estimation with an input-output-based method for the first time (www.epa.vic.gov.au/eco-footprint/docs/vic_ecofootprint_demand.pdf).

In addition, input-output analysis draws on detailed data sets which are regularly collected by government statistical agencies, such as the input-output tables (Australian Bureau of Statistics 2001a) and the household expenditure survey (Australian Bureau of Statistics 2000a). Using Australian data, input-output-based ecological footprints can be calculated for more than 300 industry sectors and product groups, for states, local areas and cities, and for companies and households.

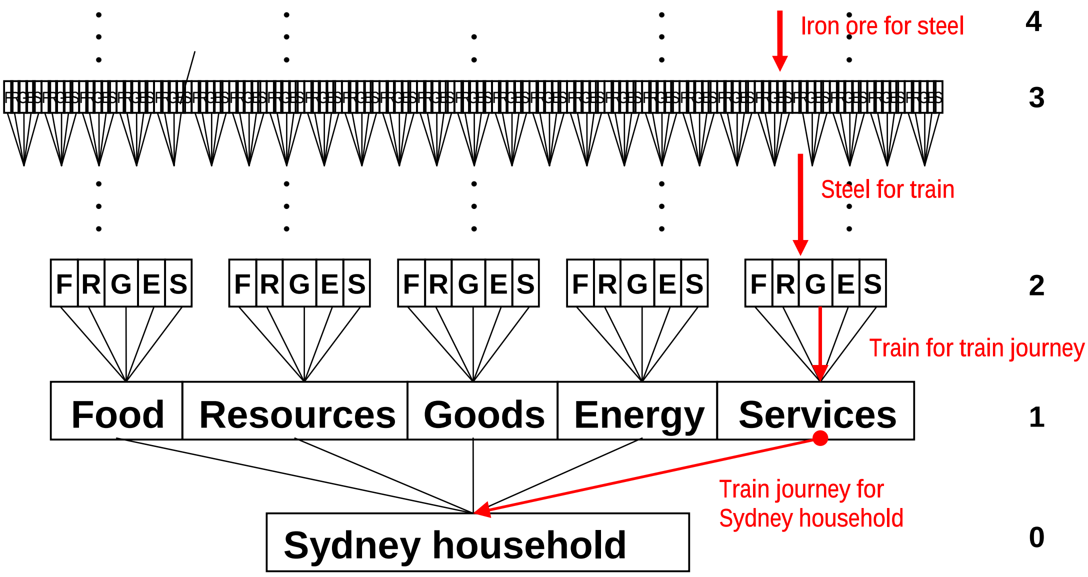


Figure 5: Production layers and input paths in the ecological footprint of a Sydney household

3.1.4 Using actual land areas and assessing land disturbance

In the original ecological footprint method, the areas of forest, pasture and crop land did not represent real land, but hypothetical areas that would be needed to support the consumption of the population, if local farming and forestry was conducted at 'world average productivity'. Proceeding as such made it easy to compare ecological footprints of different countries or populations (Wackernagel *et al.* 1999). However, the loss in detail through the conversion to world-average productivity made it impossible to use an ecological footprint for formulating regional policies, because these always involve region-specific economic, political, technological, environmental and climatic aspects (Lenzen and Murray 2001). The Australian ecological footprint used in this work expresses footprints in hectares of actual Australian land that people can see and touch. Because it expresses actual Australian land, decision-makers can see what issues there are for land management.

In addition, areas belonging to different land types as identified in the original ecological footprint are added according to their productivity for human purposes to obtain the final ecological footprint. In other words, each land type is weighted by its productive output of crops, livestock, timber, etc. However, intuitively it seems clear that the actual impact exerted and damage done by different types of land use does not depend on its productivity (van den Bergh and Verbruggen 1999). Land converted to roads and buildings, used for mining or for intensive cropping – whether productive or not – is drastically altered from its natural state, whereas land used for non-intensive grazing or native forestry may be only slightly altered.

This land condition was, however, not captured in the productivity-based approach of the original concept, because – even though called 'ecological' footprint – the original method examines a resource question (i.e. how much productivity we have and how much we use), and not an ecological question (i.e. what is the impact of humans on our ecological systems). It has been shown that pursuing the original, productivity-based ecological footprint can even lead to outcomes that *deteriorate* ecosystems (Lenzen *et al.* 2007a).[8] This is because, for example, expanding high-yield croplands and monocultures at the expense of natural forest improved the original footprint score.

[8] www.isa.org.usyd.edu.au/publications/documents/ISA&WWF_Bioproductivity&LandDisturbance.pdf

For this reason, Lenzen and Murray (2001) have argued that a better approach is to base the ecological footprint on land condition, using actual areas of land used by the respective population. The measurement of land condition forms a field of investigation in itself, and a number of approaches have been made in studies incorporating land use into life-cycle assessment (Lindeijer 2000a; Lindeijer 2000b). Ecosystem biodiversity and bioproductivity measures (Swan and Pettersson 1998) as well as species diversity of a particular group of plants (Köllner 2000; van Dobben *et al.* 1998) have also been proposed as suitable indicators. For Australia, the degree of landcover disturbance may be a useful proxy for land condition at a very broad scale, as it indicates processes such as biotic erosion that lead to land degradation. A comprehensive survey of landcover disturbance over the Australian continent has been conducted by Graetz *et al.* (1995) using satellite imagery to compare the current coverage of vegetation with the 'natural' state, taken to be that of 1788. Based on these authors' disturbance categories, Lenzen and Murray (2001) derived a list of weightings for different types of land use ranging from 0 (undisturbed or slightly disturbed) to 1 (completely disturbed).

Table 2: Basic weighting factors for land use, reflecting land condition in Australia

Land use type	Land condition
Consumed: Built	1.0
Degraded: Degraded pasture or crop land; mined land	0.8
Replaced: Cleared pasture and crop land; non-native plantations	0.6
Significantly disturbed: Thinned pasture; urban parks and gardens; native plantations	0.4
Partially disturbed: Partially disturbed grazing land	0.2
Undisturbed or slightly disturbed: Reserves and unused Crown land; slightly disturbed grazing land	0

To obtain a disturbance-based ecological footprint, each area of land is multiplied by its land condition factor. An example of this procedure is provided in Figure 3: the 100-hectare area shown in the photo includes a road (5 ha), a quarry (5 ha), cleared land (75 ha), and some less intensively cleared (thinned) land (15 ha). In the original ecological footprint calculation, these areas would all be treated as equivalent, and simply be added to reach the 100 ha total. In a disturbance-based approach, however, each area would be weighted with the land condition factors in Table 2, yielding 5 ha × 1.0 = 5 ha disturbance on built land, 5 ha × 0.8 = 4 ha on mined land, 75 ha × 0.6 = 45 ha on cleared land and 15 ha × 0.4 = 6 ha on thinned land to a weighted total of 60 ha. These figures demonstrate the effect of weighting: each part of the land receives a value that reflects both its area and its condition.

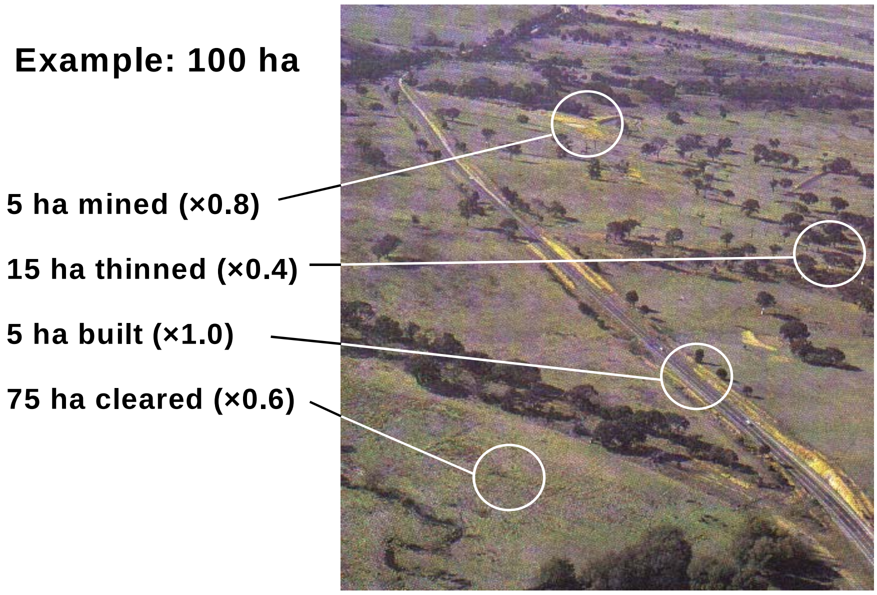


Figure 3: Assessment of land disturbance

3.1.5 Emissions land – incorporating the effects of climate change

In the original ecological footprint method, only emissions of CO_2 from energy use were considered, and not the emissions of other greenhouse gases, nor emissions from other sources, which are particularly important in Australia, such as land clearing, enteric fermentation in livestock, industrial processes, waste, coal seams, venting and leakage of natural gas. Therefore, an improvement was made to include other greenhouse gases (compare Ayres 2000) as well as all non-energy emission sources (see Lenzen and Murray 2001).

Another problem is the method of conversion of energy consumption into an equivalent land area. In the original ecological footprint, the amount of land that would need to be forested in order to sequester CO_2 emissions at a world-average rate of 6.6 tonnes of CO_2 per hectare was taken as 'energy land' (Wackernagel and Rees 1995). However, the choice of forest type (native or introduced species) and planting location (disturbed or degraded land, arid or temperate climate) significantly influence both the amount of land required and the sequestration rate. Moreover, subject to geographic, climatic and technological circumstances, there may be better options for a population to reduce or compensate its emissions. Substituting renewable energy for fossil energy sources, improving energy efficiency, fuel mix changes or structural economic shifts are already alternatives (Ayres 2000; Moffatt 2000). Therefore, some authors have argued that current methods are too inaccurate to include land for sequestering greenhouse gas emissions in the ecological footprint (van den Bergh and Verbruggen 1999).

The disturbance-based approach taken in this work is most suitable for measuring 'emissions land' (Lenzen and Murray 2001). Climate change is predicted to cause temperature and sea level rises, and thus widespread disturbance to natural ecosystems (Intergovernmental Panel on Climate Change 1995; Darwin *et al.* 1996). A population's climate change impact can therefore be characterised as the projected land disturbance due to climate change caused by the greenhouse gas emissions of that population.

3.1.6 Remaining issues

In the original method, the use of our water catchments did not show up in the ecological footprint. Using the new method, footprints have been calculated for many water service providers.[9]

The original method did not deal with the extraction of minerals. Since mining is such an important aspect of Australia's economy, the Australian method appropriately describes the impact of mining on our land.

Previously, built-up land was counted as displaced crop land, even if in reality it displaced desert or forest. The Australian method used here measures the change in land condition that is caused by building roads and cities.

Finally, when measured using the original method, the ecological footprint of a farm does not change at all, even if the local land efficiencies (yields) on that farm increase or decrease. This is because farm efficiencies were always converted to global averages. However, the original method did not convert any other efficiencies (for example electricity generation or manufacturing) into global averages. This has been found to advantage some industries over others, and distort comparisons (Wiedmann and Lenzen 2007). The Australian method applied here does not suffer from this drawback since it uses actual Australian land.

3.2 Shared producer and consumer responsibility

In 2004, three committees were set up by the Global Footprint Network, with the task of drafting a set of standards for ecological footprint practitioners, dealing with National Accounts, application standards and communication standards.[10] Various parts of the application standards draft reflect the following requirements:

A: producers (businesses, industry sectors) can be assessed, in addition to consumers (populations in cities, regions, nations, etc.)

B: there should be no double-counting of ecological footprints of sub-national entities; the ecological footprint summed over cities, regions, companies and industries of a nation must match the national ecological footprint as listed in the Global Footprint Network's National Footprint Accounts

C: ecological footprints should encompass the full life cycle of products.

In a recent issue of the journal *Ecological Economics* (Lenzen *et al.* 2007b), researchers from the UK and Australia showed that:

- strictly speaking, only two of the three requirements can be fulfilled at any one time
- this dilemma is identical to the problems previous authors had in conceptualising producer responsibility
- shared responsibility provides a way of meeting most of all three requirements.

---

[9] Lenzen *et al.* 2003
[10] www.footprintstandards.org/

3.2.1 The problem of double-counting

When traditional Life-Cycle Assessment (LCA) looks at the upstream ecological footprint embodied in consumer goods, it adds up all upstream footprints. In the supply chain example (food in a glass jar) in Figure 4, this is the footprint caused by the food manufacturer, plus the footprint caused by the manufacturer of the glass containers that the food manufacturer buys, plus the footprint caused for making the glass for the containers, plus the footprint caused by mining sand to make glass, etc.

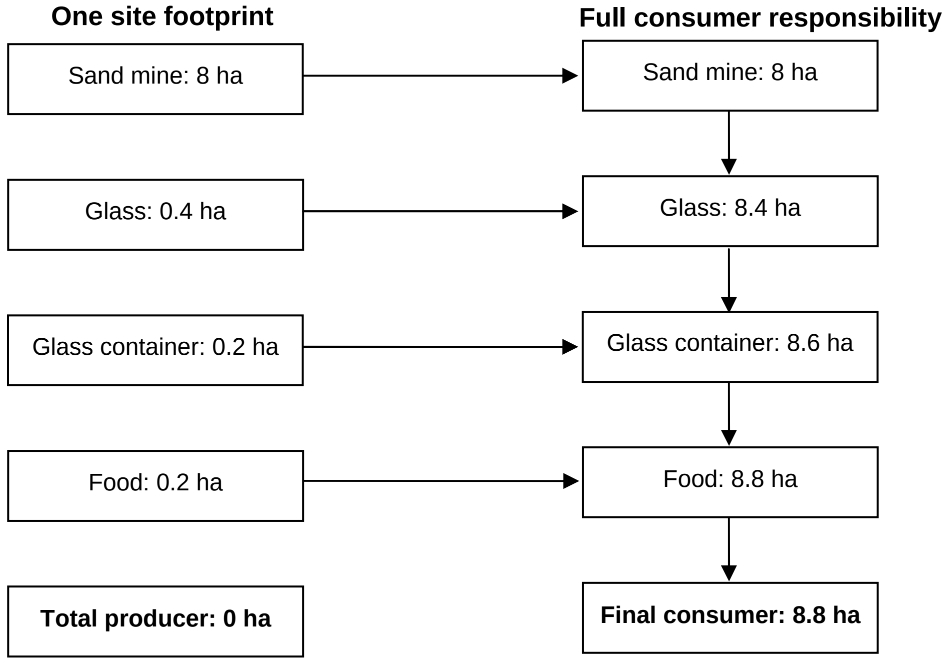


Figure 4: Full consumer responsibility in ecological footprint for one particular supply chain. The sum of all ecological footprints is 8.8 hectares.

Assume for the sake of illustration that the participants of this supply chain do not supply anyone other than their successor. Imagine that the producers of food and containers, plus the glass maker and the sand mining company all use traditional LCA to calculate and publicise their ecological footprint. The footprint caused by the food manufacturer supplying the consumer with food would appear in the population's ecological footprint, plus they would appear in the food manufacturer's ecological footprint. It is hence double-counted, as shown in Figure 5.

The footprint caused by mining sand appears in the ecological footprint of the sand mining company (as an on-site impact), in that of the glass maker, the container producer, the food company, and the final consumer (as an upstream impact). Hence, it is multiple-counted (Figure 5). If every business and consumer in the economy used traditional LCA to calculate their ecological footprint, the sum would be much greater than the total national ecological footprint. The National Footprint Accounts would not balance. Obviously this cannot be right.

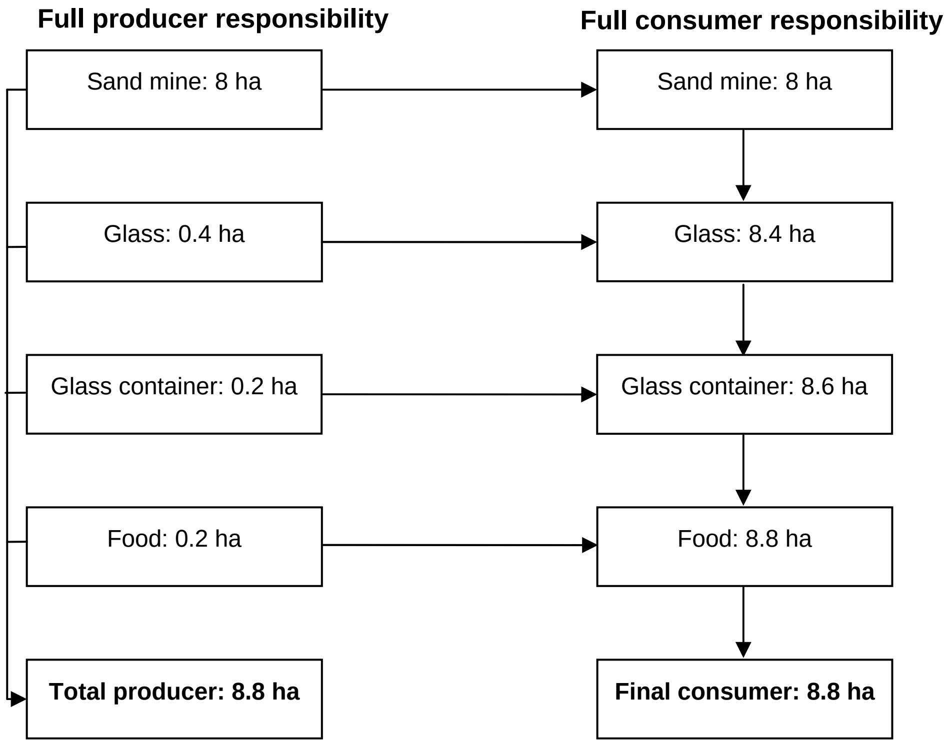


Figure 5: Double-counting of ecological footprints for one particular supply chain

3.2.2 Consumer or producer responsibility?

LCA is a method that assumes full *consumer* responsibility. In life-cycle thinking, the final consumer is placed at the very end of the supply chain. All impacts incurred during production are heaped onto the final product, making the final consumer ultimately responsible for them.[11] Therefore, if double-counting is to be avoided, LCA can only be used for the final consumers in an economy.

Other approaches assume full *producer* responsibility. For example, every country has to report their greenhouse gas emissions to the Intergovernmental Panel on Climate Change (IPCC). Some countries like Australia emit a lot during the production of goods that are exported. However the IPCC asks that these emissions appear in Australia's report, not in the report of the country that imports and consumes these goods. The literature contains some interesting debates about which approach is best.

Full consumer and producer responsibility are consistent with National Accounting principles; they do not lead to double-counting.

Returning to the requirements for ecological footprint standards, the LCA approach (Figure 4) fulfils conditions A (producer assessment) and C (full life cycle), but fails B (double-counting). Full producer responsibility (Figure 5) fulfils A and B, but fails C. Full consumer responsibility (Figure 5) fulfils B and C, but fails A. Hence, neither approach satisfies all three requirements.

A particular disadvantage of full producer or consumer responsibility is that it does not allow for *both* producers and consumers to report on their ecological footprints without double-counting. Moreover, in the commonly employed full consumer responsibility for ecological

[11] Already in 1774, Adam Smith remarked that 'consumption is the sole end and purpose of all production' (Smith 1904).

footprints, companies and industries must have an ecological footprint of zero by default. The extreme results of full producer and consumer responsibility therefore appear somewhat unrealistic. Both producers and consumers wish to report their ecological footprint, and it is intuitively clear that responsibility is somehow shared between the supplier and the recipient of a commodity, because the supplier has caused the impacts directly, but the recipient has demanded that the supplier do so.

When thinking about environmental impacts of producers and consumers, crucial questions arise such as: 'Who is responsible for what?', or: 'How is the responsibility to be shared, if at all?' For example: 'Should a firm have to improve the eco-friendliness of its products, or is it up to the consumer to buy or not to buy?' And further: 'Should the firm be held responsible for only the downstream consequences of the use of its products, or – through its procurement decisions – also for the implications of its inputs from upstream suppliers? And if so, how far should the downstream and upstream spheres of responsibility extend?' Similar questions can be phrased for the problem of deciding who takes the credits for successful abatement measures that involved producers and consumers: 'Who has the best knowledge of, or the most influence over, how to reduce adverse impacts associated with the transfer of a product from producer to consumer?'

3.2.3 Shared responsibility

As with many other allocative problems, an acceptable consensus probably lies somewhere between producer and consumer responsibility. In order to assign responsibility to agents participating in these transactions, one has to know the respective supply chains or inter-industry relations.

As a result, the problem poses itself in the form of the question: 'How can one devise an accounting method that allows apportioning ecological footprints (or any other quantity) to both producers and consumers while avoiding double-counting?' This problem has been addressed in a recent publication by Gallego and Lenzen (2005).

In reality, both the final consumers and their upstream suppliers play some role in causing ecological footprints: the suppliers use land and energy in order to produce, and make decisions on how much land and energy to use, while consumers decide to spend their money on upstream suppliers' products. And this role-sharing probably holds for many more situations in business and life. The concept of shared responsibility recognises that there are always two groups of people who play a role in commodities produced and impacts caused, and two perspectives involved in every transaction: the supplier's and the recipient's. *Hence, responsibility for impacts can be shared between them.* Naturally, this applies to both burdens and benefits.

The idea of shared responsibility is not new. In 2003 the NSW Environment Protection Authority (EPA) suggested extended producer responsibility schemes (Environment Protection Authority 2003). However shared responsibility has only recently been consistently and quantitatively conceptualised by Gallego and Lenzen (2005). Sharing each impact – for example on a 50-50 basis between the supplier and the recipient – gets rid of the double-counting problem (Figure 6).

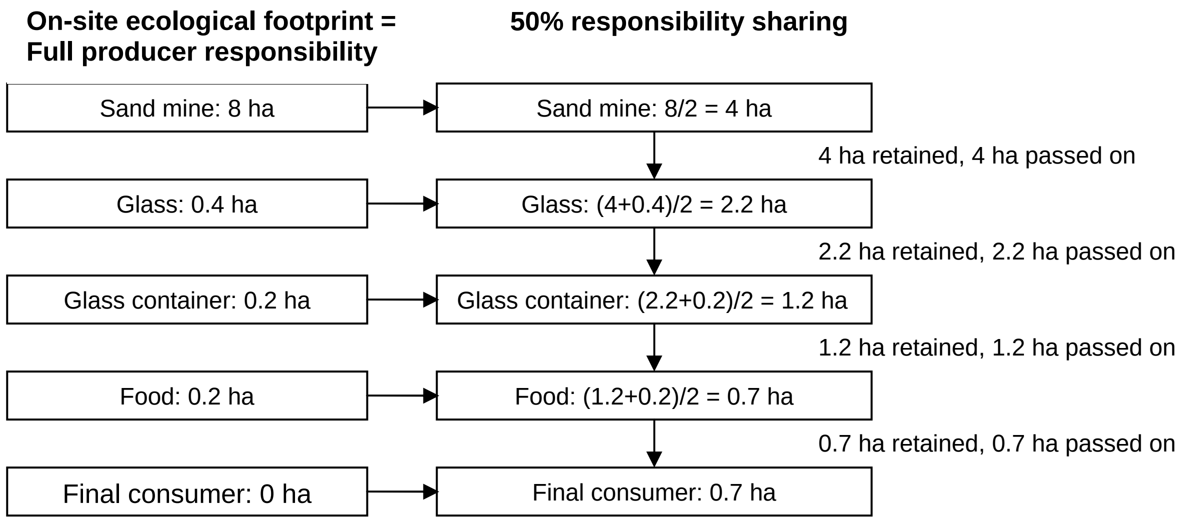


Figure 6: Shared producer and consumer responsibility in ecological footprint reports for one particular supply chain

Adding up all ecological footprints in Figure 6 gives 8.8 ha, which is required for accounting consistency. The main differences between the principle of shared responsibility and that of either full producer or full consumer responsibility are:

- in contrast to full producer responsibility, in shared responsibility every member of the supply chain is affected by their upstream supplier and affects their downstream recipient, hence it is in all agents' interest to enter into a dialogue about what to do to improve supply chain performance. There is no incentive for such a dialogue in full producer responsibility. In shared responsibility, producers are not alone in addressing the ecological footprint issue, because consumers play a role too.
- in contrast to full consumer responsibility, in shared responsibility every player in the shared supply chain plays a role in addressing the ecological footprint issue. Consumers are not alone in addressing the ecological footprint issue, because producers play a role too.

The latter point is also acknowledged by Bastianoni *et al.* (2004, p. 255) who wrote that 'assuming a consumer responsibility viewpoint, producers are not directly motivated to reduce emissions, while consumers, instead, should in theory assume responsibility for choosing the best strategies and policy by showing a preference for producers who are attentive to GHG reductions. However, without adequate incentives or policies, consumers are not likely to be sensitive with respect to their environmental responsibilities …'.

An interesting feature arising out of applying the shared responsibility principle is that the upstream responsibility for a given impact decreases with increasing distance between actors in the supply chain. In the above example: the final consumer's demand of food entails an ecological footprint at the sand mine. The sand mine is five transactions away from the final consumer, and hence its ripple impact is hardly noticeable (0.7 ha out of an initial 8 ha). However, the sand mine is only two transactions away from the glass container manufacturer, and hence the ripple impact is higher at 1.2 ha. Finally the sand mine operator has the highest control and influence over how much land is used in mining and is assigned 4 ha. Diminishing influence is an interesting feature since it seems logical to assume that the further a receiving sector is located from the producer of the impact, the less control it has over that impact.

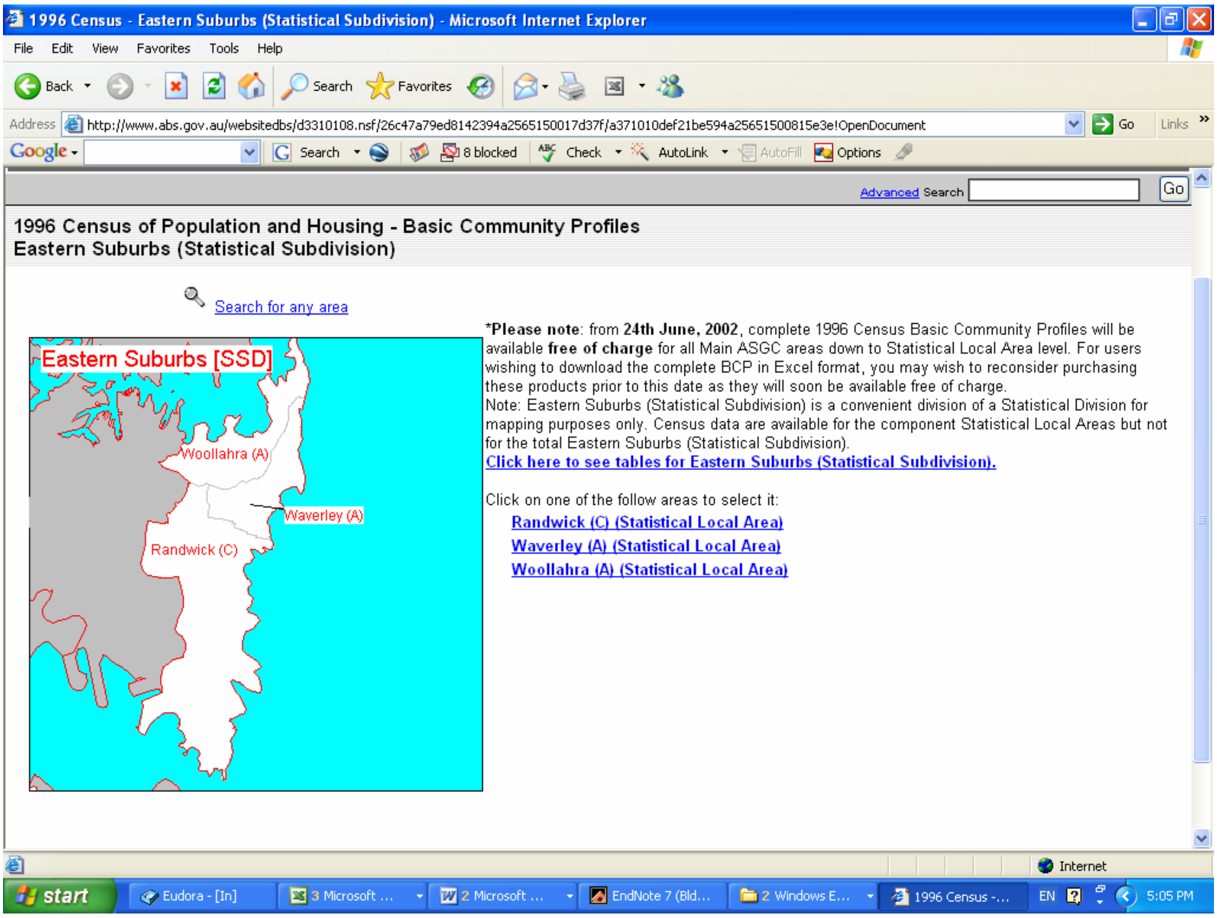
Considering the ecological footprint standards requirements, shared responsibility fulfils A (producer assessment) and B (double-counting). With respect to C (full life cycle), all stages of the supply-chain are present in the ecological footprint allocated to both producers and consumers, although each stage is shared at varying degrees with other supply chain participants.

In this work, shared and full consumer responsibility are applied and contrasted for both total ecological impact (ecological footprint in hectares per capita) and total intensity (ecological footprint per capita per dollar of expenditure).

4. Results highlights and summary

4.1 Regional detail

At present, ecological footprint calculations based on ABS Household Expenditure Surveys (HESs) are feasible for the Statistical Division of Sydney and for NSW. However, there is also ABS Household Expenditure Survey data for Statistical Sub-Divisions (SSDs) for NSW and all of Australia. This SSD data can be used to carry out a multiple regression over a large range of socio-economic and demographic characteristics of these regions (see Appendix I), yielding household expenditure for spatial entities smaller than an SSD. Thus, these regressions can be used, for example, to forecast the ecological footprint of Statistical Local Areas (SLAs), such as the SSD for Sydney's Eastern Suburbs below.



Map 1: Eastern Suburbs Statistical Local Areas (SLAs)

4.2 Main results

Table 3 summarises the main results for the per-capita ecological footprint of all regions and years examined in this work, based on both shared responsibility and full consumer responsibility. The quantities shown are 'total impact' (total ecological footprint per capita) and 'total intensity' (ecological footprint per capita per dollar of expenditure).

The categories 'government administration' and 'capital infrastructure' cover expenditures that are not made by final consumers themselves, but by the government and producers in order to provide the 'commons', i.e. government administration and infrastructure such as buildings, roads, ports, etc.

Note that non-HES results are based on *estimated* not surveyed expenditure figures. Results are therefore partly an effect of the regression estimation procedure and the explanatory variables used.

Finally, the benchmark is the average Australian consumer, as defined by the average Australian sample of the 1998–99 ABS Household Expenditure Survey.

Table 3: Summary of results

	Total impact		**Total intensity**	
	Shared responsibility	**Full consumer responsibility**	**Shared responsibility**	**Full consumer responsibility**
Sydney HES* 1993–94	2.40 ha	4.23 ha	3.27 m^2/$	2.12 m^2/$
Sydney HES 1998–99	2.79 ha	5.02 ha	2.94 m^2/$	1.98 m^2/$
Sydney SD** 1996	2.40 ha	4.22 ha	3.23 m^2/$	2.20 m^2/$
Sydney SD 2001	2.52 ha	4.53 ha	3.06 m^2/$	2.04 m^2/$
NSW HES 1993–94	2.32 ha	4.04 ha	3.42 m^2/$	2.27 m^2/$
NSW HES 1998–99	2.65 ha	4.70 ha	3.07 m^2/$	2.08 m^2/$
NSW 1996	2.29 ha	3.98 ha	3.39 m^2/$	2.30 m^2/$
NSW 2001	2.41 ha	4.27 ha	3.20 m^2/$	2.13 m^2/$
Government administration	0.11 ha	0.34 ha	0.70 m^2/$	0.59 m^2/$
Capital infrastructure	0.57 ha	1.31 ha	1.80 m^2/$	1.89 m^2/$
Benchmark: Average Australian consumer	2.04 ha	3.57 ha	3.53 m^2/$	2.23 m^2/$
Including government and infrastructure				
Sydney HES 1993–94	3.08 ha	5.88 ha	4.31 m^2/$	3.16 m^2/$
Sydney HES 1998–99	3.47 ha	6.67 ha	3.98 m^2/$	3.02 m^2/$
Sydney SD 1996	3.08 ha	5.87 ha	4.27 m^2/$	3.24 m^2/$
Sydney SD 2001	3.20 ha	6.18 ha	4.10 m^2/$	3.08 m^2/$
NSW HES 1993–94	3.00 ha	5.69 ha	4.46 m^2/$	3.31 m^2/$
NSW HES 1998–99	3.33 ha	6.35 ha	4.11 m^2/$	3.12 m^2/$
NSW 1996	2.97 ha	5.63 ha	4.43 m^2/$	3.34 m^2/$
NSW 2001	3.09 ha	5.92 ha	4.24 m^2/$	3.17 m^2/$
Benchmark: Average Australian consumer	2.72 ha	5.22 ha	4.57 m^2/$	3.27 m^2/$

* HES: Household expenditure survey

** SD: Statistical Division

The following main results were found:

1. **The per-capita ecological footprint of Sydney is above that of NSW, and in turn the latter is above that of the average Australian, no matter which calculation method is employed.** This is most likely due to the greater affluence of households in Sydney, compared with NSW, and NSW compared in turn with the average Australian.
2. **The per-capita ecological footprint based on shared responsibility is smaller than the footprint based on full consumer responsibility**. This is because with shared responsibility, ecological footprints are shared between producers and consumers, and only a part of the responsibility is passed on to consumers. Shared responsibility recognises that Australian companies have calculated their own ecological footprints: the sum of all producer and consumer footprints equals the total national ecological footprint. With full consumer responsibility, the ecological footprint of any producer (company, industry sector, etc.) is zero, or else it will be double-counted.
3. **The per-capita ecological footprint of Sydney increased between 1994 and 1999 and between 1996 and 2001.** This result is independent of inflation, which has been taken out of the figures. It is most likely due to an increasing living standard. The percentage increases of the ecological footprint with full consumer responsibility and including government and infrastructure by main area are tabulated below.

Sydney 1994 to 1999	13.4%
Sydney 1996 to 2001	5.3%
NSW 1994 to 1999	11.6%
NSW 1996 to 2001	5.2%

4. **The ecological footprint intensity (ecological footprint per dollar of expenditure) is low in areas with a high ecological footprint and high in areas with a low ecological footprint.** This is because wealthy households spend more of their income on services than less wealthy households. Since services are associated with a smaller ecological footprint intensity, the overall ecological footprint intensity of wealthier households is lower (see Figure 7).

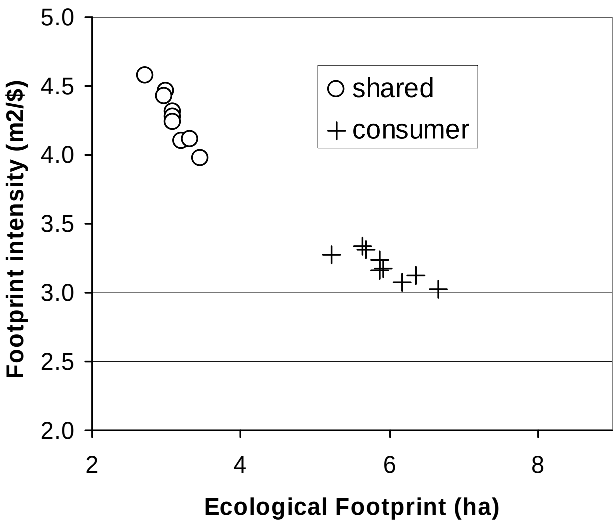


Figure 7: How the footprint intensity decreases for households with larger footprints

5. **It is not readily possible to compare the Household Expenditure Survey (HES) and Census data sets, although within one data set, comparisons are valid.** This is due to samples in HESs not representing the entire population; differences in classification between the 1993 and 1998 HES and the National Accounts' input-output tables; and possible over- or under-reporting of expenditures in the HES.
6. **The per-capita ecological footprint for our commons (government and infrastructure) constitutes about 30% of the average Australian's per-capita ecological footprint, but only about a quarter of the ecological footprint of Sydney residents**. This result is due to the fact that the common components were allocated on a per-capita basis, i.e. an equal amount to each Australian.
7. **Ecological footprint intensities based on shared responsibility are higher than ecological footprint intensities based on full consumer responsibility.** This is because within a household's consumption bundle, footprint-intensive commodities such as meat, electricity or petrol have their impacts in production stages that are relatively close to the final consumer. Considering that shared responsibility has an inherent feature of down-weighting ecological footprints that are caused in more remote production stages, and up-weighting ecological footprints in more proximate stages, this leads to an overall increase of the ecological footprint intensity compared to full consumer responsibility.[12]

8. **The ecological footprint of the average Australian consumer is lower at 5.22 ha per capita than a previously calculated value of 6.7 ha based on the 1994–95 input-output system**. This is because the previous figure included capital expenditure as intermediate and not final demand. The previous procedure calculated Australia's national ecological footprint in the long term, including the capital requirements to produce commodities, the capital to produce capital to produce commodities, and so on. This calculation required capital flow matrices, which for 1994–95 were estimated manually by the ISA team in a tedious process, and based on limited data (see Lenzen and Treloar 2005). For the study year 1998–99, these capital flow matrices were not available. It is unlikely that capital flow matrices will be estimated in the future by the ABS on a regular basis (ABS, personal communication). Therefore, the short-term ecological footprint procedure applied in this work – with leaving capital flow exogenous to the input-output table and calculating the ecological footprint for the capital requirements only for the current year – is likely to remain the standard method of input-output-based ecological footprints.

9. **Most of the total ecological footprint is due to the land component, and not to greenhouse gas emissions.** This is demonstrated in the following section.

4.3 Ecological footprint components

Tables 4 and 5 in the following sections are structured in the same way as Table 3 in Section 4.2, but instead contain the ecological footprint components *land disturbance* and *greenhouse gas emissions*.

Further details are listed in Appendix I.

[12] Note that this effect does not occur for capital infrastructure. This is because this category does not involve particularly footprint-intensive commodities, but instead a relatively homogeneous mix of capital commodities. Hence shared and full consumer responsibility produce about the same intensity.

4.3.1 Land disturbance

The land disturbance trends closely mirror those of the total ecological footprint in the previous section, so that here only the final numerical results are given. Indirect land disturbance constitutes the main component of Sydney's and NSW's ecological footprint.

Table 4: Land disturbance component of ecological footprints and footprint intensities for NSW and Sydney

	Total impact		**Total intensity**	
	Shared responsibility	**Full consumer responsibility**	**Shared responsibility**	**Full consumer responsibility**
Sydney HES* 1993–94	1.76 ha	3.06 ha	2.40 m^2/$	1.54 m^2/$
Sydney HES 1998–99	2.04 ha	3.62 ha	2.15 m^2/$	1.43 m^2/$
Sydney SD** 1996	1.76 ha	3.06 ha	2.36 m^2/$	1.59 m^2/$
Sydney SD 2001	1.86 ha	3.29 ha	2.26 m^2/$	1.48 m^2/$
NSW HES 1993–94	1.70 ha	2.93 ha	2.51 m^2/$	1.65 m^2/$
NSW HES 1998–99	1.92 ha	3.38 ha	2.23 m^2/$	1.49 m^2/$
NSW 1996	1.67 ha	2.88 ha	2.47 m^2/$	1.66 m^2/$
NSW 2001	1.77 ha	3.10 ha	2.35 m^2/$	1.55 m^2/$
Government administration	0.06 ha	0.17 ha	0.38 m^2/$	0.30 m^2/$
Capital infrastructure	0.40 ha	0.95 ha	1.27 m^2/$	1.37 m^2/$
Benchmark: Average Australian consumer	1.51 ha	2.60 ha	2.60 m^2/$	1.62 m^2/$
Including government and infrastructure				
Sydney HES 1993–94	2.22 ha	4.18 ha	3.09 m^2/$	3.21 m^2/$
Sydney HES 1998–99	2.50 ha	4.74 ha	2.84 m^2/$	3.10 m^2/$
Sydney SD 1996	2.22 ha	4.18 ha	3.05 m^2/$	3.26 m^2/$
Sydney SD 2001	2.32 ha	4.41 ha	2.95 m^2/$	3.15 m^2/$
NSW HES 1993–94	2.16 ha	4.05 ha	3.20 m^2/$	3.32 m^2/$
NSW HES 1998–99	2.38 ha	4.50 ha	2.92 m^2/$	3.16 m^2/$
NSW 1996	2.13 ha	4.00 ha	3.16 m^2/$	3.33 m^2/$
NSW 2001	2.23 ha	4.22 ha	3.04 m^2/$	3.22 m^2/$
Benchmark: Average Australian consumer	1.97 ha	3.72 ha	3.29 m^2/$	3.29 m^2/$

* HES: Household expenditure survey

** SD: Statistical Division

4.3.2 Greenhouse gas emissions

Table 5: Greenhouse gas emissions component of ecological footprints and footprint intensities for NSW and Sydney

	Total impact		**Total intensity**	
	Shared responsibility	**Full consumer responsibility**	**Shared responsibility**	**Full consumer responsibility**
Sydney HES* 1993–94	9.24 t CO_2-e**	16.9 t CO_2-e	1,259 g CO_2-e/$	851 g CO_2-e/$
Sydney HES 1998–99	11.0 t CO_2-e	20.5 t CO_2-e	1,154 g CO_2-e/$	807 g CO_2-e/$
Sydney SD*** 1996	9.36 t CO_2-e	17.0 t CO_2-e	1,257 g CO_2-e/$	883 g CO_2-e/$
Sydney SD 2001	9.69 t CO_2-e	18.0 t CO_2-e	1,175 g CO_2-e/$	814 g CO_2-e/$
NSW HES 1993–94	9.04 t CO_2-e	16.3 t CO_2-e	1,332 g CO_2-e/$	914 g CO_2-e/$
NSW HES 1998–99	10.5 t CO_2-e	19.3 t CO_2-e	1,220 g CO_2-e/$	852 g CO_2-e/$
NSW 1996	9.04 t CO_2-e	16.1 t CO_2-e	1,337 g CO_2-e/$	932 g CO_2-e/$
NSW 2001	9.33 t CO_2-e	17.1 t CO_2-e	1,238 g CO_2-e/$	853 g CO_2-e/$
Government administration	0.74 t CO_2-e	2.50 t CO_2-e	471 g CO_2-e/$	435 g CO_2-e/$
Capital infrastructure	2.45 t CO_2-e	5.27 t CO_2-e	774 g CO_2-e/$	761 g CO_2-e/$
Benchmark: Average Australian consumer	7.82 t CO_2-e	14.2 t CO_2-e	1,362 g CO_2-e/$	889 g CO_2-e/$
Including government and infrastructure				
Sydney HES 1993–94	12.4 t CO_2-e	24.7 t CO_2-e	1,764 g CO_2-e/$	2,047 g CO_2-e/$
Sydney HES 1998–99	14.2 t CO_2-e	28.3 t CO_2-e	1,659 g CO_2-e/$	2,003 g CO_2-e/$
Sydney SD 1996	12.6 t CO_2-e	24.8 t CO_2-e	1,762 g CO_2-e/$	2,079 g CO_2-e/$
Sydney SD 2001	12.9 t CO_2-e	25.8 t CO_2-e	1,680 g CO_2-e/$	2,010 g CO_2-e/$
NSW HES 1993–94	12.2 t CO_2-e	24.1 t CO_2-e	1,837 g CO_2-e/$	2,110 g CO_2-e/$
NSW HES 1998–99	13.7 t CO_2-e	27.1 t CO_2-e	1,725 g CO_2-e/$	2,048 g CO_2-e/$
NSW 1996	12.2 t CO_2-e	23.9 t CO_2-e	1,842 g CO_2-e/$	2,128 g CO_2-e/$
NSW 2001	12.5 t CO_2-e	24.9 t CO_2-e	1,743 g CO_2-e/$	2,049 g CO_2-e/$
Benchmark: Average Australian consumer	11.0 t CO_2-e	22.0 t CO_2-e	1,867 g CO_2-e/$	2,085 g CO_2-e/$

* HES: Household expenditure survey

** t CO_2-e: tonnes of carbon dioxide equivalent emissions

*** SD: Statistical Division

4.4 Selected results for Sydney 2001

The sections below provide some interesting results from the Sydney Statistical Division (SD).

4.4.1 Commodity breakdown – shared responsibility

The most important commodity in terms of the ecological footprint is 'retail trade', closely followed by 'fresh meat' and 'hotels, clubs, restaurants and cafes'. Note that 'retail trade' does not comprise everything that was purchased from a retailer, but represents only the retail *margin*, in accordance with the Australian Bureau of Statistics definition. This margin comprises all distribution services: packing, transport, storage, etc. Retail margins apply to almost all consumer goods, and they incur an ecological footprint because of electricity used in cooling and storage, diesel used in trucks used for transport, etc.

Fresh meat and meat products incur ecological footprints because of the upstream land disturbed for livestock grazing. Clothing and human-made fibres need land for wool and cotton. The combustion of petrol causes greenhouse gas emissions, mainly CO_2. Electricity impacts mainly because of CO_2 emissions from coal-fired power plants and methane (CH_4) from coal mine seams. 'Residential building construction' embodies land and greenhouse gas emissions in producing construction materials. 'Ownership of dwellings' is an ABS definition standing for rent actually paid, and imputed from owned homes. This commodity is not very footprint-intensive, but a large amount of money is spent on it, hence its relatively high rank.

Table 6: Ecological footprint disturbance – shared responsibility

Commodity rank	Impact
1. Retail trade	0.37 ha
2. Fresh meat	0.33 ha
3. Hotels, clubs, restaurants and cafes	0.32 ha
4. Meat products	0.31 ha
5. Clothing	0.15 ha
6. Petrol	0.11 ha
7. Electricity supply	0.08 ha
8. Residential building construction	0.06 ha
9. Human-made fibres	0.05 ha
10. Ownership of dwellings	0.05 ha

4.4.2 Commodity breakdown – full consumer responsibility

The commodity breakdown in terms of full consumer responsibility contains the same commodities as that for shared responsibility, but in a slightly different ranking. Petrol is more prominent under shared responsibility because of its proximity to the consumer – the shared responsibility principle reflects influence over the impact process by placing petrol ahead of other more indirectly impacting commodities.

Table 7: Ecological footprint disturbance – full consumer responsibility

Commodity rank	Impact
1. Retail trade	0.79 ha
2. Hotels, clubs, restaurants and cafes	0.62 ha
3. Fresh meat	0.46 ha
4. Meat products	0.42 ha
5. Clothing	0.29 ha
6. Electricity supply	0.20 ha
7. Ownership of dwellings	0.12 ha
8. Petrol	0.12 ha
9. Residential building construction	0.11 ha

4.4.3 Production layer decomposition – shared responsibility

A ‘production layer decomposition’ of the ecological footprint shows how much impact occurs on-site, i.e. within the household and the private car (production layer 0), and indirect, i.e. on the premises of companies and industries producing and supplying intermediate and final goods and services (layers 1 and up).

Figure 8 shows that the on-site ecological footprint (layer 0) is comparatively low (< 0.25 ha), and comprises business services (ownership of dwellings – the land the occupied dwelling stands on), fuels (greenhouse gas emissions from petrol and gas), and forestry (greenhouse gas emissions from firewood). Even direct suppliers (layer 1) contribute less than another 0.25 ha. The vast majority of ecological footprint is contained in layers 2 and 3, which are mining and agricultural establishments supplying food, and appliance and vehicle manufacturers. This diagram demonstrates the need to conduct an ecological footprint analysis that has a far reach into higher-order upstream production processes.

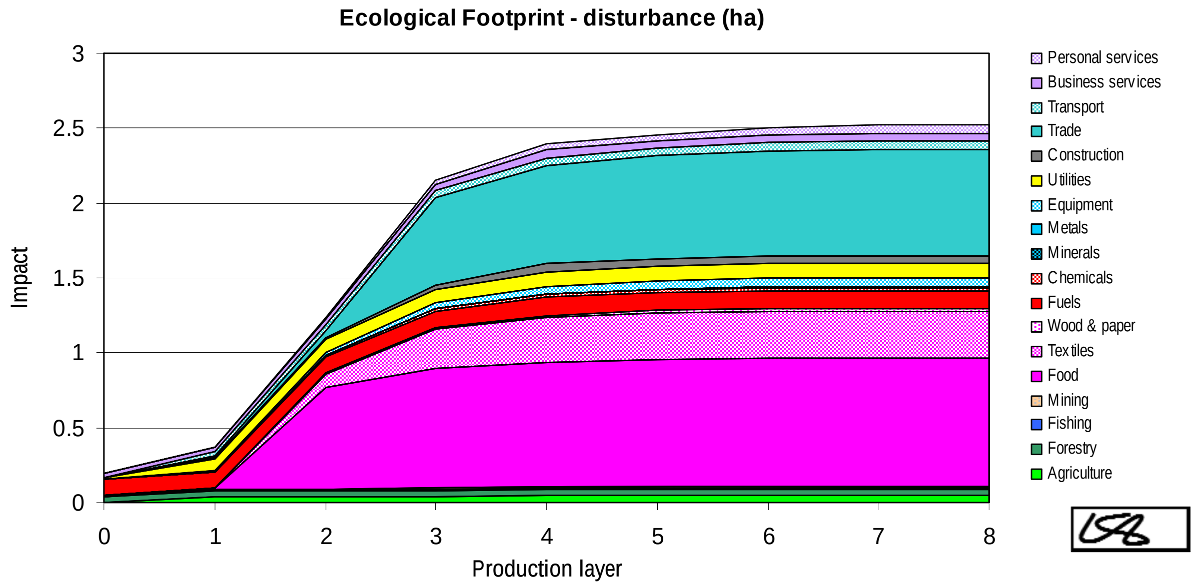


Figure 8: Production layer decomposition – disturbance with shared responsibility

Beyond layers 3 and 4, ecological footprint contributions become smaller and smaller, and eventually converge around layer 8 to the final ecological footprint value.

4.4.4 Production layer decomposition – full consumer responsibility

The production layer decomposition in terms of full consumer responsibility is not structured differently, although the curve is steeper and converges to a higher final value for the total ecological footprint (compare Section 4.2). This is shown in Figure 9.

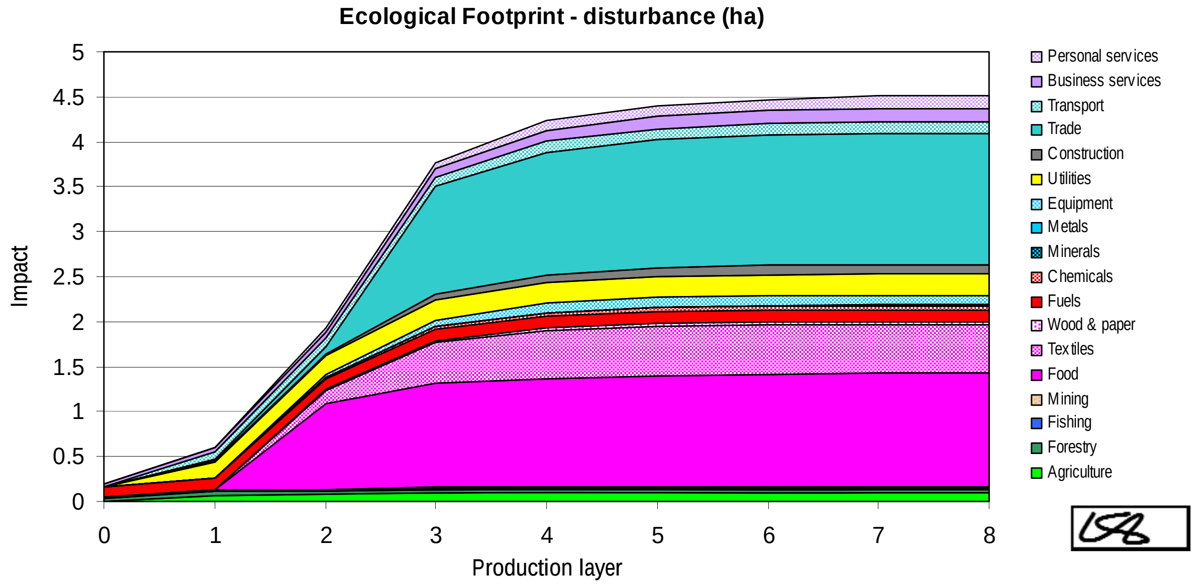


Figure 9: Production layer decomposition – disturbance with full consumer responsibility

4.4.5 Production layer decomposition – land disturbance – shared responsibility

Decomposing only the land disturbance component of the ecological footprint, the most noticeable difference from the previous production layer decompositions is that the components 'Utilities' (electricity) and 'Fuels' (petrol and gas) are not strongly represented. The main components are food and retail services (compare Section 4.4.1), because these embody mainly land, and lower greenhouse gas emissions.

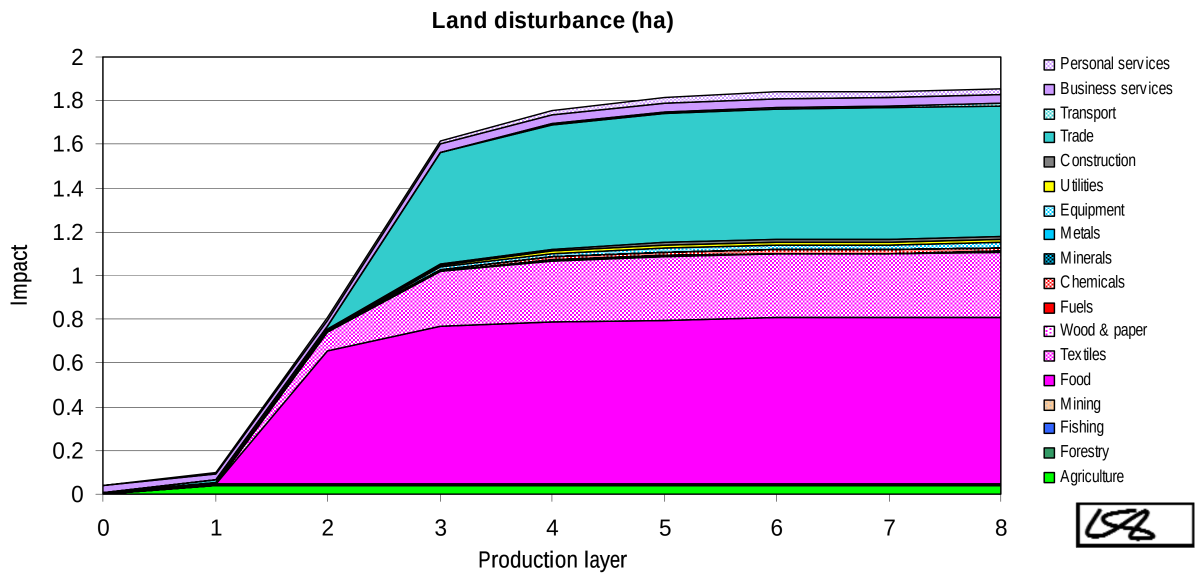


Figure 10: Production layer decomposition – land disturbance with shared responsibility

4.4.6 Production layer decomposition – greenhouse gas emissions – shared responsibility

Decomposing only the greenhouse gas emissions component of the ecological footprint, the components 'Utilities' (electricity) and 'Fuels' (petrol and gas) become more pronounced, because they are significant emission sources. Other important components are forestry (firewood), food and retail margins (electricity used for food processing, cooling, and freezing, and diesel used for transport), public transport and residential construction.

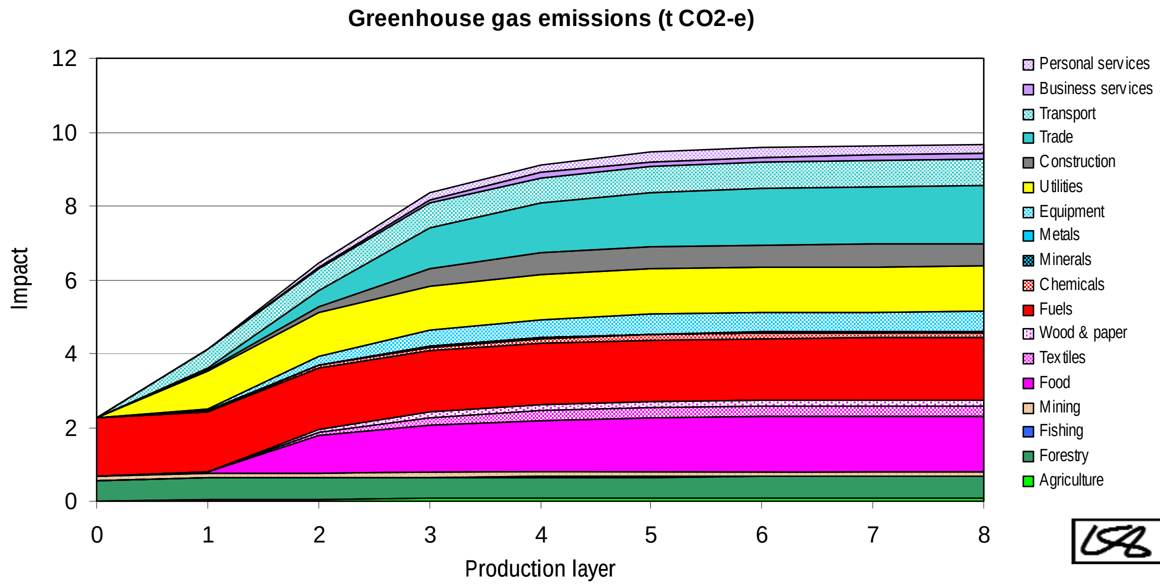


Figure 11: Production layer decomposition – greenhouse gas emissions with shared responsibility

4.4.7 Structural path analysis – shared responsibility

'Structural path analyses' are the most detailed representation of an ecological footprint. They 'unravel' the commodity breakdowns (Sections 4.4.1 and 4.4.2) and production layer decompositions (Sections 4.4.3, 4.4.4, 4.4.5 and 4.4.6).

Table 8: Structural path analysis – disturbance with shared responsibility

Rank	Path description	Path value	Path order	Percentage in total impact
1	Petrol	0.10 ha	0	4.12%
2	Beef cattle > fresh meat	0.10 ha	2	3.91%
3	Beef cattle > meat products	0.09 ha	2	3.67%
4	Electricity supply	0.07 ha	1	2.74%
5	Beef cattle > fresh meat > hotels, clubs, restaurants and cafes	0.05 ha	3	2.04%
6	Beef cattle > fresh meat > retail trade	0.05 ha	3	1.97%
7	Hardwoods	0.04 ha	0	1.54%
8	Ownership of dwellings	0.03 ha	0	1.36%
9	Sheep and lambs > fresh meat	0.027 ha	2	1.07%
10	Sheep and lambs > meat products	0.025 ha	2	1.00%

The combustion of petrol in private cars, and the associated greenhouse gas emissions, is the single most important structural path, comprising 4% of the total ecological footprint. This path is zero order, because it is an on-site impact. It is followed by two paths which originate with land disturbed for beef cattle grazing, and terminate in fresh meat and other meat products. Two other high-ranking beef paths are numbers 5 and 6, which terminate in meals in restaurants, etc. and in retail trade. The latter represents meat in take-away food sold in retail shop complexes, service stations, etc. Together, these four beef paths comprise about 11.5% of the total ecological footprint.

The area disturbed by the typical residential building – also an on-site zero-order path – is estimated to be about 0.03 ha or 300 m^2. Electricity supply constitutes a first-order path, because the ecological footprint contribution – greenhouse gas emissions – occurs at the power plant, which is a direct supplier of households. 'Hardwoods' denotes the average firewood consumption in the area. Finally, some lamb is consumed as meat. These top 10 structural paths represent about 23% of the total ecological footprint.

4.4.8 Structural path analysis – full consumer responsibility

It is very interesting to compare structural path analyses in terms of shared and full consumer responsibility. Note that the top four paths in Table 9 for full consumer responsibility appear in almost opposite order compared with the beef paths for shared responsibility. While under full consumer responsibility, third-order paths rank higher than second-order paths, the ranking under shared responsibility is reverse.

This is because under shared responsibility distant paths are shared with a higher number of producers, and therefore carry less impact when 'arriving' at the consumer's end. Under full consumer responsibility, ecological footprints are fully passed on down the supply chain, and producers share nothing of the impact. For the same reason, some wool-to-clothing paths have moved up the ranks in Table 9, compared with their ranking previously. The more proximate greenhouse gas emissions impacts due to electricity and petrol have dropped a few ranks to fifth and sixth, respectively.

Table 9: Structural path analysis – disturbance with full consumer responsibility

Rank	Path description	Path value	Path order	Percentage in total impact
1	Beef cattle > fresh meat > retail trade	0.42 ha	3	9.29%
2	Beef cattle > fresh meat > hotels, clubs, restaurants and cafes	0.40 ha	3	8.72%
3	Beef cattle > fresh meat	0.39 ha	2	8.55%
4	Beef cattle > meat products	0.36 ha	2	7.90%
5	Electricity supply	0.17 ha	1	3.66%
6	Petrol	0.10 ha	0	2.30%
7	Shorn wool > cotton fabrics > clothing	0.10 ha	3	2.11%
8	Beef cattle > meat products > retail trade	0.09 ha	3	2.03%
9	Shorn wool > human-made fibres > clothing	0.08 ha	3	1.85%
10	Shorn wool > human-made fibres	0.06 ha	2	1.27%

Appendix I: Methodology – mathematical exposition

Some of the more popular studies dealing with the sustainability of cities are ecological footprint analyses.[13] This concept adopts the idea of carrying capacity, and by inverting the standard carrying capacity ratio, seeks to characterise an area of land that is needed to sustain a given population indefinitely, wherever on earth this land is located. The obvious result of most ecological footprint calculations is that cities appropriate an area of productive land that by far exceeds their physical size, and that therefore they cannot be sustainable (Rees and Wackernagel 1996).

While ecological footprints are an instructive educational resource for raising awareness about global unsustainability, they have been criticised, for example, because the aggregated form of the final value makes it difficult to understand the specific reasons for the unsustainability of the consumption of a given population (Rapport 2000), and to formulate appropriate policy responses (Ayres 2000; Moffatt 2000; Opschoor 2000; van Kooten and Bulte 2000). Furthermore, ecological footprints on sub-national scales underestimate indirect requirements (Bicknell *et al.* 1998; Lenzen and Murray 2001). In this work, we therefore focused on providing a disaggregated description of the environmental impact of city dwellers, both in terms of impact types (fuel use, greenhouse gas emissions, land use, etc.) and consumption type (goods, services, energy, water, etc.). Furthermore, we take into account indirect requirements from all upstream production layers by using input-output analysis.

Input-output analysis

Input-output analysis is a macroeconomic technique that uses data on inter-industrial monetary transactions to account for the complex interdependencies of industries in modern economies. Since its introduction by (Leontief 1936; Leontief 1941), it has been applied to numerous economic and environmental issues, and input-output tables are now compiled on a regular basis for most industrialised and also many developing countries.

The first input-output tables to be compiled for a city were those constructed by Hirsch (1959), who surveyed large- and medium-sized companies operating in the St. Louis, USA, area and presented sectoral income, employment, fiscal and land multipliers (Hirsch 1963). Smith and Morrison (1974), and Morrison and Smith (1974) reviewed methods to compile input-output tables for cities, based on survey and non-survey techniques. They concluded that non-survey techniques are the most attractive, because of the savings of time and resources they provide to the urban planner, and because they produce reliable results. Based on a comparison of a survey-based input-output table for the city of Peterborough, UK with semi- and non-survey versions, they concluded that the RAS method 'proved to be far superior to all the other techniques which were tested' with regard to the similarity of the simulated input-output coefficients to the 'true' survey-based ones. Gordon and Ledent (1980) suggested using such local input-output coefficients for the multi-regional modelling of a system of metropolitan areas.

In this work we have used a different approach for regionalisation: we combine the national Australian input-output tables and national data on resource use and pollution (modified by regionalising some important effects) with regional household expenditure data. The assumption inherent in this approach is that products purchased by regional households are

---

[13] See, for example, studies of Vancouver (Rees and Wackernagel 1996); various cities surrounding the Baltic Sea (Folke *et al.* 1997) and in the UK (Simmons and Chambers 1998); Santiago de Chile (Wackernagel 1998); Canberra (Close and Foran 1998); Malmö (Wackernagel *et al.* 1999); Liverpool (Barrett and Scott 2001); Guernsey (Barrett 2001); and the Isle of Wight (Best Foot Forward and Imperial College 2001).

produced regionally and nationally using a similar production recipe.[14] The technique of combining input-output and household expenditure data has been used previously by a number of authors,[15] with only one study (Moll and Norman 2002) applying this approach to cities.

The ecological footprint of households in the Statistical Local Areas (SLAs) and Statistical Sub-Divisions (SSDs) examined in this work is determined via

$$\mathbf{F} = \left(\mathbf{Q}^{\mathrm{emb}} + \mathbf{Q}^{\mathrm{hh}}\right) \times \mathbf{Y} \qquad (1)$$

The variables in Equation 1 are:

F Matrix of *household factor requirements*. Its elements $\{F_{ij}\}_{i=1,\ldots,f\,;\,j=1,\ldots,g}$ describe the total amount of factor *i* required by household group *j*. The term *factor* represents resource and ecological footprint components (land disturbance; fuel consumption; greenhouse gas emissions). **F** comprises (1) factors $\mathbf{Q}^{\mathrm{hh}}\times\mathbf{Y}$ used directly by the household (in the house or by using private vehicles), and (2) factors $\mathbf{Q}^{\mathrm{emb}}\times\mathbf{Y}$ used by Australian and foreign industries, that are required indirectly to provide goods and services purchased by the household. The latter are also called *embodied factor requirements*. **F** has dimensions $f\times g$, where f is the number of factors ($f = 47$), and h is the number of household groups. For the city of Sydney for example, the Australian Household Expenditure Survey conducted by the Australian Bureau of Statistics (ABS) distinguishes $h = 240$ household groups, categorised according to 18 household characteristics (mainly family type) and the 14 SSDs.

$\mathbf{Q}^{\mathrm{hh}}$ Matrix of *household factor multipliers*. Its elements $\{Q^{\mathrm{hh}}_{ij}\}_{i=1,\ldots,f\,;\,j=1,\ldots,s}$ describe the usage by private households of factor *i* per A$ value of final consumption of commodity *j*. $\mathbf{Q}^{\mathrm{hh}}$ has dimensions $f\times s$, where s is the number of classified commodities. This number is also equal to the number of classified industry sectors. The version of the Australian *input-output tables* compiled by the ABS used in this work distinguishes $s = 344$ commodities[16] and industry sectors. These range from primary industries such as agriculture and mining, via secondary industries such as manufacturing and electricity, gas and water utilities, to tertiary industries such as commercial services, health, education, defence and government administration.

$\mathbf{Q}^{\mathrm{emb}}$ Matrix of *embodied factor multipliers*. Its elements $\{Q^{\mathrm{emb}}_{ij}\}_{i=1,\ldots,f\,;\,j=1,\ldots,s}$ describe the usage of factor *i* per A$ value of final consumption of commodity *j*, (1) by the industry sectors producing commodity *j*, (2) by all upstream industry sectors supplying industry sectors producing commodity *j*, (3) by all upstream industry sectors supplying industry sectors that supply industry sectors producing commodity *j*, and (4)

[14] Note that this study is not an analysis of regional but of national impacts. As such, the limitations in the use of national input-output tables for regional studies (Czamanski and Malizia 1969) do not apply here. In contrast, the analysis of local impacts or interregional flows requires the estimation of a set of regional input-output tables (Tiebout 1960).

[15] See Herendeen and Tanaka (1976); Herendeen (1978a); Herendeen *et al.* (1981); Peet *et al.* (1985); Aoyagi *et al.* (1992); Breuil (1992); Weber and Fahl (1993); Aoyagi *et al.* (1995); Vringer and Blok (1995); Weber *et al.* (1995); Kondo *et al.* (1996); Lenzen (1998); Biesiot and Noorman (1999); Munksgaard *et al.* (2000); Weber and Perrels (2000); Munksgaard *et al.* (2001); Wier *et al.* (2001); Carlsson-Kanyama *et al.* (2002); Cohen *et al.* (2005); Lenzen *et al.* (2006).

[16] The so-called ISAPC sector classification is a non–confidential subset of the Australian Bureau of Statistics' 8-digit Input-Output Product Classification (IOPC8; Australian Bureau of Statistics 2001b).

so on, infinitely. $\mathbf{Q}^{emb}$ thus captures the *total factor requirements* of industries in the entire economy that are needed to produce commodities consumed by households. $\mathbf{Q}^{emb}$ has dimensions $f \times s$.

Y Matrix of *household expenditure*. Its elements $\{Y_{ij}\}_{i=1,\ldots,s;\, j=1,\ldots,h}$ describe the amount of A$ spent on commodity *i* by household group *h* during the reference year. **Y** has dimensions $s \times h$.

$\mathbf{Q}^{emb}$ can be calculated according to the *basic input-output relationship*

$$\mathbf{Q}^{emb} = \mathbf{Q}^{ind}(\mathbf{I} - \mathbf{A})^{-1} \qquad (2)$$

The variables in equation 2 are:

$\mathbf{Q}^{ind}$ Matrix of *industrial factor multipliers*. Its elements $\{Q_{ij}^{ind}\}_{i=1,\ldots,f;\, j=1,\ldots,s}$ describe the usage of factor *i* by industry sector *j* per A$ value of total output by industry sector *j*. In contrast to $\mathbf{Q}^{emb}$, $\mathbf{Q}^{ind}$ represents only factors used directly in each industry, but not in upstream supplying industries. $\mathbf{Q}^{ind}$ has dimensions $f \times s$.

I The *unity matrix*. Its elements $\{I_{ij}\}_{i=1,\ldots,s;\, j=1,\ldots,s}$ are $I_{ij}=1$ if $i=j$, and $I_{ij}=0$ if $i \neq j$. **I** has dimensions $s \times s$.

A Matrix of *direct requirements*. Its elements $\{A_{ij}\}_{i=1,\ldots,s;\, j=1,\ldots,s}$ describe the amount of input in Australian Dollars (A$) of industry sector *i* into industry sector *j*, per A$ value of total output of industry sector *j*. **A** has dimensions $s \times s$. It comprises imports from foreign industries and transactions for capital replacement and growth. **A** captures the interdependence of industries in the Australian economy and their dependence on foreign industries, and – assuming that imports are produced using Australian technology[17] – thus enables the translation of industrial factor multipliers $\mathbf{Q}^{ind}$ into embodied factor multipliers $\mathbf{Q}^{emb}$.

For an introduction into input-output theory, see articles by Leontief and Ford (1970); Duchin (1992); and Dixon (1996). For a history of the development of input-output analysis, see Carter and Petri (1989); and Forssell and Polenske (1998). For examples and reviews of input-output studies applied to environmental issues, see Leontief and Ford (1971); Isard *et al.* (1972); Herendeen (1978b); Miller and Blair (1985); Proops (1988); Miller *et al.* (1989); Hawdon and Pearson (1995); and Forssell (1998). For a description of the assembly of an Australian input-output framework, see Lenzen (2001b).

Data sources

The main difficulties encountered during data collection and preparation were due to differences in industry sector classification and differences in data reference year. It was necessary to confront and reconcile data sets documented according to the Australian and New Zealand Standard Industrial Classification (ANZSIC), the Input-Output Product Classification (IOPC), the Australian land use (ALUMC) classification, the Household Expenditure Survey commodity classification, and the reporting format prescribed by the Intergovernmental Panel on Climate Change (IPCC).

---

[17] For example, in this study, Australian energy intensities were also applied to imported items (about 10% of total Australian output), which is equivalent to assuming that they are produced using Australian technology. This assumption carries an uncertainty into energy multipliers.

Surveys of industries, households and farms are not conducted in identical intervals. Hence, the input-output, household expenditure, resource use and pollution data refer to different years between 1998 and 2003. In order to minimise discrepancies, input-output and factor data was assembled for years closely around 1998–99, where data availability was best. Data were reconciled using RAS matrix balancing[18] and optimisation techniques.[19] As a consequence, small flows (monetary and physical) are associated with large uncertainties, as indicated in some of the results sheets.

The household expenditure matrix Y was derived from the 1998–99 Household Expenditure Survey (Australian Bureau of Statistics 2000b), while the direct requirements matrix A was constructed from the Australian input-output tables (Australian Bureau of Statistics 1999a; Australian Bureau of Statistics 1999b; see also Lenzen 2001b).

The industrial ecological footprint multipliers $\mathbf{Q}_{\text{ef}}^{\text{ind}}$ as well as household ecological footprint multipliers $\mathbf{Q}_{\text{ef}}^{\text{hh}}$ were obtained by consulting a range of sources such as fuel statistics (Australian Bureau of Agricultural and Resource Economics 1999; Australian Bureau of Agricultural and Resource Economics 2000), the Australian National Greenhouse Gas Inventory (Australian Greenhouse Office 1999; George Wilkenfeld & Associates Pty Ltd and Energy Strategies 2002), the ABS's Integrated Regional Database (Australian Bureau of Statistics 2001c), and a CSIRO report on landcover disturbance across the Australian continent (Graetz *et al.* 1995; Lenzen and Murray 2001).

Uncertainties

Input-output analysis suffers from uncertainties arising from the following sources:

- uncertainties of basic source data due to sampling and reporting errors
- the assumption made in single-region input-output models that foreign industries producing competing imports exhibit the same factor multipliers as domestic industries
- the assumption that foreign industries are perfectly homogeneous
- the assumption of proportionality between monetary and physical flow
- the aggregation of input-output data over different producers
- the aggregation of input-output data over different products supplied by one industry
- the truncation of the 'gate-to-grave' component of the full life cycle (see Bullard *et al.* 1978 and Lenzen 2001a).

Standard errors $\Delta Q_{ij}^{\text{emb}}$ of elements in the embodied factor multiplier matrix $\mathbf{Q}^{\text{emb}}$ due to the above sources defy analytical treatment, and can therefore only be determined using stochastic analysis. The $\Delta Q_{ij}^{\text{emb}}$ as used in this article were calculated by Monte-Carlo simulations of the propagation of normally distributed perturbations from $\mathbf{Q}^{\text{ind}}$ and $\mathbf{A}$ through to $\mathbf{Q}^{\text{emb}}$ (see Lenzen 2001a). Given the standard errors $\Delta\left(Q^{\text{emb}}+Q^{\text{hh}}\right)_{ik}$ of $\mathbf{Q}^{\text{emb}}+\mathbf{Q}^{\text{hh}}$, and ΔY_{kj} of $\mathbf{Y}$, the total standard error ΔF_{ij} of an element F_{ij} in the household factor requirement $\mathbf{F}$ in Equation 1 is

$$\Delta F_{ij}=\sqrt{\sum_{k=1}^{s}\Delta\left(Q^{\text{emb}}+Q^{\text{hh}}\right)_{ik}^{2}\,Y_{kj}^{2}+\sum_{k=1}^{s}\left(Q^{\text{emb}}+Q^{\text{hh}}\right)_{ik}^{2}\,\Delta Y_{kj}^{2}}\ . \qquad (3)$$

[18] Gretton and Cotterell (1979); Junius and Oosterhaven (2003)
[19] Tarancon and Del Rio (2005)

The uncertainty ranges of $\mathbf{Q}^{\text{emb}} + \mathbf{Q}^{\text{hh}}$ given in ISA's software output cover raw data uncertainty and allocation uncertainty only, as described in Lenzen (2001a).

Multiple regression

Multiple regression seeks to establish the relationship between an explained variable *y*, and a number of explanatory variables x_i. The explained variable is, of course, household expenditure (on 344 commodities). The explanatory variables appraised in this work are household characteristics:

–	*inc*	annual per-capita before-tax household income
–	*size*	number of household members
–	*edu*	index of highest qualification of household members aged 15 and over with a qualification (1 basic vocational; 2 skilled vocational; 3 Associate Diploma; 4 Undergraduate Diploma; 5 Bachelor degree; 6 Postgraduate Diploma; 7 Higher than 1-6)
–	*htype*	index of house type (1 caravan, cabin, houseboat or other; 2 flat, unit or apartment; 3 semi-detached, row or terrace house; 4 separate house)
–	*urb*	population density in people per km^2
–	*age*	average age
–	*kid*	percentage of household members aged 18 and below
–	*empl*	percentage of household members aged 18-64 working
–	*prov*	provenance: percentage of people in region born overseas
–	*ten*	tenure type (1 rent-free, 2 renting, 3 purchasing with mortgage, 4 owning)
–	*car*	car ownership (cars per person)
–	*wktrv*	percentage of people travelling to work by car
–	*State*	dummy variable indicating location of SD by State (8 dummies)

We have omitted one of pair-wise correlated variables (such as house type and population density, or number of children and age) in our multiple regression, because the respective variables are mutually surrogate drivers of the explained variable. The decision of which variable to exclude can be based on an exogenously stated, sequential causal structure (see, for example, Poulsen and Forrest 1988), or based on a series of regression models in order to establish the combination of variables with the strongest explanatory power. The latter approach was taken in this work.

A particular feature of the ABS Household Expenditure Survey is that the observations of expenditure apply to groups of households rather than single households. Expenditure and socio-demographic-economic characteristics of an observation *h* are therefore really group means $\overline{x_i^h}$, derived from sums $\overline{x_i^h} = \sum_{j=1}^{n_h} x_{ij}^h$ taken over n_h single-household observation x_{ij}.

Unfortunately, in general, the number of observations n_h is not the same in each group *h*. This fact has to be taken into account in the multiple regression as follows: Assume that the observations x_{ij}^h and y_j^h satisfy the regression equation

$$y_j^h = \beta_0 + \sum_i \beta_i x_{ij}^h + \varepsilon_j^h \quad \forall h, j = 1,\ldots,n_h$$

with ε_j^h being the error term with zero mean and constant variance $\text{var}\left(\varepsilon_j^h\right) = \sigma^2$ (homoskedasticity). Summation over *j* shows in a straightforward manner that the same regression equation $\overline{y^h} = \beta_0 + \sum_i \beta_i \overline{x_i^h} + \overline{\varepsilon^h}$ also holds for the group means $\overline{y^h} = \frac{1}{n_h}\sum_j y_j^h$, $\overline{x_i^h} = \frac{1}{n_h}\sum_j x_{ij}^h$, and $\overline{\varepsilon^h} = \frac{1}{n_h}\sum_j \varepsilon_j^h$. The disturbance $\overline{\varepsilon^h}$ has zero mean, but its variance is not constant anymore over group observations *h*, because each group contains a different number n_h of single-household observations: the regression becomes *heteroskedastic*. This means that the estimation of the regression coefficients β_i requires the group means to be *weighted* inversely proportional to the disturbance variances. Since the latter are $\mathrm{var}\left(\overline{\varepsilon^h}\right) = \frac{\sigma^2}{n_h}$, all group means must be weighted with the number of single-household observations n_h in each group (Cramer 1969, p. 144).

Using multiple regression, and taking into account the varying sample sizes of the Household Expenditure Survey sample groups (and resulting heteroskedasticity), the expenditure on the 344 ISAPC expenditure items was estimated from explanatory variables sourced from the census data pertaining to the regions examined. A stepwise multiple regression was followed, consisting of

- establishing correlation coefficients between the expenditure of samples on each of the 344 commodities, and all explanatory variables, starting with commodity 1
- selecting the variable with the highest correlation coefficient as the first regression variable
- selecting the variable with the next highest correlation coefficient as the second regression variable, and so on
- calculating an adjusted R^2 value for each subsequent regression, and checking whether the adjusted R^2 increases more than 0.1%
- if not, terminating the addition of further explanatory variables to the regression model, and moving on to the next commodity.

This stepwise regression procedure is data-driven, as opposed to the theory-driven hierarchical multiple regression, where a model is specified based on purely theoretical considerations. The stepwise procedure was chosen because it is preferred if the purpose of regression is simple prediction of expenditure (Cramer 1969), and because a sound theoretical reason for a dependence of the consumption of a particular commodity on socio-demographic-economic variables can in general not be established *a priori*.

Structural path analysis

The general decomposition approach described in the following was introduced into economics and regional science in 1984 under the name *Structural Path Analysis* (Crama *et al.* 1984; Defourny and Thorbecke 1984), and applied in life-cycle assessment by Treloar and Lenzen (Treloar 1997; Treloar 1998; Treloar *et al.* 2000; Lenzen 2002). The total factor multipliers as in Equation 2 can be decomposed into contributions from structural paths, by 'unravelling' the Leontief inverse using its series expansion

$$\mathbf{Q}^{\mathrm{ind}}\,(\mathbf{I}\text{-}\mathbf{A})^{-1} = \mathbf{Q}^{\mathrm{ind}} + \mathbf{Q}^{\mathrm{ind}}\mathbf{A} + \mathbf{Q}^{\mathrm{ind}}\mathbf{A}^2 + \mathbf{Q}^{\mathrm{ind}}\mathbf{A}^3 + \ldots \quad . \qquad (4)$$

Expanding Equation 4, indirect requirements $Q^{\mathrm{emb}}{}_i \times Y_i$ as in Equation 1 can be written as

$$Q_i^{\mathrm{emb}} Y_i = Y_i \sum_{j=1}^{s} Q_j^{\mathrm{ind}} \left(I_{ji} + A_{ji} + (\mathbf{A}^2)_{ji} + (\mathbf{A}^3)_{ji} + \mathbf{...} \right)$$

$$= Y_i \sum_{j=1}^{s} Q_j^{\text{ind}} \left(I_{ji} + A_{ji} + \sum_{k=1}^{s} A_{jk} A_{ki} + \sum_{l=1}^{s} \sum_{k=1}^{s} A_{jl} A_{lk} A_{ki} + \ldots \right)$$

$$= Q_i^{\text{ind}} Y_i + \sum_{j=1}^{s} Q_j^{\text{ind}} A_{ji} Y_i + \sum_{k=1}^{s} Q_k^{\text{ind}} \sum_{j=1}^{s} A_{kj} A_{ji} Y_i + \sum_{l=1}^{s} Q_l^{\text{ind}} \sum_{k=1}^{s} A_{lk} \sum_{j=1}^{s} A_{kj} A_{ji} Y_i + \ldots \qquad (5)$$

where i, j, k, and l denote industries. $Q^{\text{emb}}{}_i Y_i$ is thus a sum over a direct factor input $Q^{\text{ind}}{}_i Y_i$, occurring in industry i itself, and higher-order input paths. An input path from industry j (domestic or foreign) into industry i of first order is represented by a product $Q^{\text{ind}}{}_j A_{ji} Y_i$, while an input path from industry k via industry j into industry i is represented by a product $Q^{\text{ind}}{}_k A_{kj} A_{ji} y_i$, and so on. There are s input paths of first order, s^2 paths of second order, and, in general, s^N paths of N^{th} order. An index pair (ij) shall be referred to as a *vertex*.

References

Albino, V. and Kühtz, S. (2002). Environmental footprint of industrial districts using input-output tables based on production processes. In: *14th International Conference on Input-Output Techniques*, Montréal, Canada, Internet site www.io2002conference.uqam.ca/abstracts_papers/new16janv03/Montreal_final_paper.doc

Aoyagi, M., Kondo, Y., Moriguchi, Y. and Shimizu, H. (1992). Analysis of differences of CO_2 emission structure by consumption expenditures of households. In: *9th Energy System/Economics Conference*, Tokyo, Japan, 307–12 (in Japanese).

Aoyagi, M., Moriguchi, Y., Kondo, Y. and Shimizu, H. (1995). Characteristics of households' energy consumption. *Energy and Resources* 16(6), 59–67 (in Japanese).

Australian Bureau of Agricultural and Resource Economics (1999). *Australian energy consumption and production.* ABARE Research Report 99.4, Commonwealth of Australia, Canberra, Australia.

Australian Bureau of Agricultural and Resource Economics (2000). Australian energy consumption and production, Table C1AUST, Historical data update. Electronic file (unpublished), Australian Bureau of Agricultural and Resource Economics, Canberra, Australia.

Australian Bureau of Statistics (1999a). *Australian National Accounts, Input-Output Tables, 1994–95.* ABS Catalogue No. 5209.0, Australian Bureau of Statistics, Canberra, Australia.

Australian Bureau of Statistics (1999b). Australian National Accounts, Input-Output Tables, 1994–95, Commodity Details. Electronic file (unpublished).

Australian Bureau of Statistics (2000a). *1998–99 Household Expenditure Survey: Detailed Expenditure Items.* ABS Catalogue No. 6535.0, Australian Bureau of Statistics, Canberra, Australia.

Australian Bureau of Statistics (2000b). 1998–99 Household Expenditure Survey: Detailed Expenditure Items, Confidentialised Unit Record File. Electronic file (unpublished), Australian Bureau of Statistics, Canberra, Australia.

Australian Bureau of Statistics (2001a). *Australian National Accounts, Input-Output Tables, 1996–97.* ABS Catalogue No. 5209.0, Australian Bureau of Statistics, Canberra, Australia.

Australian Bureau of Statistics (2001b). *Australian National Accounts, Input-Output Tables, Product Details, 1996–97.* ABS Catalogue No. 5215.0, Australian Bureau of Statistics, Canberra, Australia.

Australian Bureau of Statistics (2001c). Integrated Regional Data Base. Electronic database (unpublished), Australian Bureau of Statistics, Canberra, Australia.

Australian Greenhouse Office (1999). Australia's National Greenhouse Gas Inventory. Internet site www.greenhouse.gov.au/inventory, Australian Greenhouse Office.

Ayres, R.U. (2000). Commentary on the utility of the ecological footprint concept. *Ecological Economics* 32, 347–49.

Bagliani, M., Ferlaino, F. and Procopio, S. (2002). Ecological footprint and input-output methodology: the analysis of the environmental sustainability of the economic sectors of Piedmont Region (Italy). In: *14th International Conference on Input-Output Techniques*, Montréal, Canada, Internet site www.io2002conference.uqam.ca/abstracts.pdf

Barrett, J. (2001). Component ecological footprint: developing sustainable scenarios. *Impact Assessment and Project Appraisal* 19(2), 107–18.

Barrett, J. and Scott, A. (2001). An Ecological footprint of Liverpool: A Detailed Examination of Ecological Sustainability. Internet site www.york.ac.uk/inst/sei/footprint/Liverpool%20EF%20Report.PDF, Stockholm Environment Institute.

Bastianoni, S., Pulselli, F.M. and Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics* 49, 253–57.

Best Foot Forward and Imperial College (2001). Ecological footprint of the Isle of Wight. Internet site www.bestfootforward.com/island_form.htm, Best Foot Forward.

Bicknell, K.B., Ball, R.J., Cullen, R. and Bigsby, H.R. (1998). New methodology for the ecological footprint with an application to the New Zealand economy. *Ecological Economics* 27(2), 149–60.

Biesiot, W. and Noorman, K.J. (1999). Energy requirements of household consumption: A case study of The Netherlands. *Ecological Economics* 28(3), 367–83.

Breuil, J.-M. (1992). Input-output analysis and pollutant emissions in France. *Energy Journal* 13(3), 173–84.

Bullard, C.W., Penner, P.S. and Pilati, D.A. (1978). Net energy analysis: handbook for combining process and input-output analysis. *Resources and Energy* 1, 267–313.

Carlsson-Kanyama, A., Karlsson, R., Moll, H., Kok, R. and Wadeskog, A. (2002). *Household metabolism in the Five Cities: Swedish National Report, Stockholm*. Fms report 177, Forskningsgruppen för Miljöstrategiska Studier, Stockholm, Sweden.

Carter, A.P. and Petri, P.A. (1989). Leontief's contribution to economics. *Journal of Policy Modelling* 11(1), 7–30.

Close, A. and Foran, B. (1998). *Canberra's ecological footprint*. Working Paper Series 98/12, Resource Futures Program, CSIRO Wildlife and Ecology, Canberra, Australia.

Cohen, C.A.M.J., Lenzen, M. and Schaeffer, R. (2005). Energy requirements of households in Brazil. *Energy Policy* 55, 555–62.

Costanza, R. (2000). The dynamics of the ecological footprint concept. *Ecological Economics* 32, 341–45.

Crama, Y., Defourny, J. and Gazon, J. (1984). Structural decomposition of multipliers in input-output or social accounting matrix analysis. *Economie Appliquée* 37, 215–22.

Cramer, J.S. (1969). *Empirical Econometrics*. North-Holland Publishing Company Amsterdam, Netherlands.

Czamanski, S. and Malizia, E.E. (1969). Applicability and limitations in the use of national input-output tables for regional studies. *Papers of the Regional Science Association* 23, 65–77.

Darwin, R., Tsigas, M., Lewandrowski, J. and Raneses, A. (1996). Land use and cover in ecological economics. *Ecological Economics* 17, 157–81.

Defourny, J. and Thorbecke, E. (1984). Structural path analysis and multiplier decomposition within a social accounting matrix framework. *Economic Journal* 94, 111–36.

Dixon, R. (1996). Inter-industry transactions and input-output analysis. *Australian Economic Review* 3'96(115), 327–36.

Duchin, F. (1992). Industrial input-output analysis: implications for industrial ecology. *Proceedings of the National Academy of Science of the USA* 89, 851–55.

Environment Protection Authority (2003). *Extended Producer Responsibility Priority Statement*. Consultation Paper 2003/10, EPA NSW, Sydney, Australia.

Ferng, J.-J. (2001). Using composition of land multiplier to estimate ecological footprints associated with production activity. *Ecological Economics* 37, 159–72.

Folke, C., Jansson, Å., Larsson, J. and Costanza, R. (1997). Ecosystem appropriation by cities. *Ambio* 26(3), 167–72.

Foran, B., Lenzen, M. and Dey, C. (2005a). *Balancing Act: A Triple Bottom Line Account of the Australian Economy*. Internet site www.isa.org.usyd.edu.au, CSIRO Resource Futures and The University of Sydney, Canberra, ACT, Australia.

Foran, B., Lenzen, M., Dey, C. and Bilek, M. (2005b). Integrating Sustainable Chain Management with Triple Bottom Line Reporting. *Ecological Economics* 52(2), 143–57.

Forssell, O. (1998). Extending economy-wide models with environment-related parts. *Economic Systems Research* 10(2), 183–99.

Forssell, O. and Polenske, K.R. (1998). Introduction: input-output and the environment. *Economic Systems Research* 10(2), 91–97.

Gallego, B. and Lenzen, M. (2005). A consistent input-output formulation of consumer and producer responsibility. *Economic Systems Research* 17(4), 365–91.

George Wilkenfeld & Associates Pty Ltd and Energy Strategies (2002). *Australia's National Greenhouse Gas Inventory 1990, 1995 and 1999: end use allocation of emissions*. Australian Greenhouse Office, Canberra, Australia.

Gordon, P. and Ledent, J. (1980). Modeling the dynamics of a system of metropolitan areas: a demoeconomic approach. *Environment and Planning A* 12(2), 125–33.

Graetz, R.D., Wilson, M.A. and Campbell, S.K. (1995). *Landcover disturbance over the Australian continent*. Biodiversity Series, Paper No. 7, Department of the Environment, Sport and Territories Biodiversity Unit, Canberra, Australia.

Gretton, P. and Cotterell, P. (1979). The RAS method for compiling input-output tables - Australian Bureau of Statistics experience. In: *Eighth Conference of Economists*, La Trobe University.

Hawdon, D. and Pearson, P. (1995). Input-output simulations of energy, environment, economy interactions in the UK. *Energy Economics* 17(1), 73–86.

Herendeen, R. (1978a). Total energy cost of household consumption in Norway, 1973. *Energy* 3, 615–30.

Herendeen, R., Ford, C. and Hannon, B. (1981). Energy cost of living, 1972–1973. *Energy* 6, 1433–50.

Herendeen, R. and Tanaka, J. (1976). Energy cost of living. *Energy* 1, 165–78.

Herendeen, R.A. (1978b). Input-output techniques and energy cost of commodities. *Energy Policy* 6(2), 162–65.

Hirsch, W.Z. (1959). Interindustry relations of a metropolitan area. *Review of Economics and Statistics* 41(4), 360–69.

Hirsch, W.Z. (1963). Application of input-output techniques to urban areas. In: Barna, T., Ed. *Structural Interdependence and Economic Development*. MacMillan & Co Ltd, London, UK, 151–68.

Hubacek, K. and Giljum, S. (2003). Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* 44, 137–51.

Intergovernmental Panel on Climate Change (1995). *Climate Change 1995: Scientific-technical analysis of impacts, adaptations, and mitigation of climate change. Summary for*

Policymakers. Technical Summary of the Working Group II Report, Intergovernmental Panel on Climate Change, Bracknell, Berkshire, UK.

Isard, W., Choguill, C.L., Kissin, J., Seyfarth, R.H., Tatlock, R., Bassett, K.E., Furtado, J.G. and Izumita, R.M. (1972). *Ecologic-economic analysis for regional development*. The Free Press New York, NY, USA.

Joshi, S. (2001). Product environmental life-cycle assessment using input-output techniques. *Journal of Industrial Ecology* 3(2&3), 95–120.

Junius, T. and Oosterhaven, J. (2003). The solution of updating or regionalizing a matrix with both positive and negative entries. *Economic Systems Research* 15, 87–96.

Köllner, T. (2000). Species-pool effect potentials (SPEP) as a yardstick to evaluate land-use impacts on biodiversity. *Journal of Cleaner Production* 8(4), 293–311.

Kondo, Y., Moriguchi, Y. and Shimizu, H. (1996). Analysis of the trend of CO_2 emission structure by consumption expenditures of households. *Transactions of the Society of Environmental Science* 9(2), 231–40 (in Japanese).

Lenzen, M. (1998). The energy and greenhouse gas cost of living for Australia during 1993–94. *Energy* 23(6), 497–516.

Lenzen, M. (2001a). Errors in conventional and input-output-based life-cycle inventories. *Journal of Industrial Ecology* 4(4), 127–48.

Lenzen, M. (2001b). A generalised input-output multiplier calculus for Australia. *Economic Systems Research* 13(1), 65–92.

Lenzen, M. (2002). A guide for compiling inventories in hybrid LCA: some Australian results. *Journal of Cleaner Production* 10, 545–72.

Lenzen, M. and Murray, S.A. (2001). A modified ecological footprint method and its application to Australia. *Ecological Economics* 37(2), 229–55.

Lenzen, M. and Murray, S.A. (2003). *The ecological footprint: issues and trends*. ISA Research Paper 01-03, www.isa.org.usyd.edu.au/publications/documents/Ecological_Footprint_Issues_and_Trends.pdf, ISA The University of Sydney, Sydney, Australia.

Lenzen, M. and Treloar, G. (2005). Endogenising capital: a comparison of two methods. *Journal of Applied Input-Output Analysis* 10, 1–11.

Lenzen, M., Lundie, S., Bransgrove, G., Charet, L. and Sack, F. (2003). Assessing the ecological footprint of a large metropolitan water supplier - lessons for water management and planning towards sustainability. *Journal of Environmental Planning and Management* 46(1), 113–41.

Lenzen, M., Dey, C. and Foran, B. (2004). Energy requirements of Sydney households. *Ecological Economics* 49, 375–99.

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

Lenzen, M., Borgstrom Hansson, C. and Bond, S. (2007a). On the bioproductivity and land disturbance metrics of the Ecological Footprint. *Ecological Economics* 61(1), 6–10.

Lenzen, M., Murray, J., Sack, F. and Wiedmann, T. (2007b). Shared producer and consumer responsibility - theory and practice. *Ecological Economics* 61(1), 27–42.

Leontief, W. (1936). Quantitative input and output relations in the economic system of the United States. *Review of Economics and Statistics* 18(3), 105–25.

Leontief, W. (1941). *The Structure of the American Economy, 1919–1939*. Oxford University Press Oxford, UK.

Leontief, W. and Ford, D. (1970). Environmental repercussions and the economic structure: an input-output approach. *Review of Economics and Statistics* 52(3), 262–71.

Leontief, W. and Ford, D. (1971). Air pollution and the economic structure: empirical results of input-output computations. In: *Fifth International Conference on Input-Output Techniques*, Geneva, Switzerland, North-Holland Publishing Company, 9–30.

Levett, R. (1998). Footprinting: a great step forward, but tread carefully. *Local Environment* 3(1), 67–74.

Lindeijer, E. (2000a). Biodiversity and life support impacts of land use in LCA. *Journal of Cleaner Production* 8, 313–19.

Lindeijer, E. (2000b). Review of land use impact methodologies. *Journal of Cleaner Production* 8, 273–81.

McDonald, G. and Patterson, M. (2003). *Ecological Footprints of New Zealand and its Regions*. Internet site www.mfe.govt.nz/publications/ser/eco-footprint-sep03/index.html, Ministry for Environment New Zealand, Wellington, New Zealand.

Miller, R.E. and Blair, P.D. (1985). *Input-Output Analysis: Foundations and Extensions*. Prentice-Hall Englewood Cliffs, NJ, USA.

Miller, R.E., Polenske, K.R. and Rose, A.Z. (eds) (1989). *Frontiers of Input-Output Analysis*. Oxford University Press, New York, USA.

Moffatt, I. (2000). Ecological footprints and sustainable development. *Ecological Economics* 32, 359–62.

Moll, H.C. and Norman, K.J. (2002). Towards sustainable development at city level: evaluating and changing the household metabolism in five European cities. In: *Lifecycle Approaches to Sustainable Consumption*, Laxenburg, Austria, International Institute for Applied Systems Analysis (IIASA), National Institute for Advanced Industrial Science and Technology (AIST), and Sustainable Consumption and Production Unit of the United Nations Environment Programme (UNEP)

Morrison, W.I. and Smith, P. (1974). Nonsurvey input-output techniques at the small area level: an evaluation. *Journal of Regional Science* 14(1), 1–14.

Munksgaard, J., Pedersen, K.A. and Wier, M. (2000). Impact of household consumption on CO_2 emissions. *Energy Economics* 22, 423–40.

Munksgaard, J., Pedersen, K.A. and Wier, M. (2001). Changing consumption patterns and CO_2 reduction. *International Journal of Environment and Pollution* 15(2), 146–58.

Nichols, M. (2003). *An application of the Ecological Footprint method to an eco-tourism resort: A case study of Kingfisher Bay resort and Village, Fraser Island*. Bachelor of Science Thesis, University of the Sunshine Coast, Maroochydore, Australia.

Opschoor, H. (2000). The ecological footprint: measuring rod or metaphor? *Ecological Economics* 32, 363–65.

Peet, N.J., Carter, A.J. and Baines, J.T. (1985). Energy in the New Zealand household, 1974–1980. *Energy* 10(11), 1197–208.

Poulsen, M.F. and Forrest, J. (1988). Correlates of energy use: domestic electricity consumption in Sydney. *Environment and Planning A* 20, 327–38.

Proops, J.L.R. (1988). Energy intensities, input-output analysis and economic development. In: Ciaschini, M., Ed. *Input-Output Analysis: Current Developments*. Chapman and Hall, London, UK, 201–16.

Rapport, D.J. (2000). Ecological footprints and ecosystem health: complementary approaches to a sustainable future. *Ecological Economics* 32, 381–83.

Rees, W.E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* 4(2), 121–30.

Rees, W. and Wackernagel, M. (1996). Urban ecological footprints: why cities cannot be sustainable - and why they are a key to sustainability. *Environmental Impact Assessment Review* 16(4-6), 223–48.

Simmons, C. and Chambers, N. (1998). Footprinting UK households: how big is your ecological garden? *Local Environment* 3(3), 355–62.

Simpson, R.W., Petroeschevsky, A. and Lowe, I. (2000). An ecological footprint analysis for Australia. *Australian Journal of Environmental Management* 7, 11–18.

Smith, A. (1904). *An Inquiry into the Nature and Causes of the Wealth of Nations*. Methuen & Co Strand, UK.

Smith, P. and Morrison, W.I. (1974). *Simulating the urban economy*. Pion Limited London, UK.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G. (2004). System boundary selection in Life-Cycle Inventories. *Environmental Science & Technology* 38(3), 657–64.

Swan, G. and Pettersson, B. (1998). Land use evaluation in forestry. In: Swan, G. (ed.). *Evaluation of land use in Life Cycle Assessment, Center for Environmental Assessment of Product and Material Systems, CPM Report 1998:2*. Chalmers University of Technology, Göteborg, Sweden, 16–21.

Tarancon, M. and Del Rio, P. (2005). Projection of input-output tables by means of mathematical programming based on the hypothesis of stable structural evolution. *Economic Systems Research* 17(1), 1–23.

Tiebout, C.M. (1960). Regional and interregional input-output models: an appraisal. In: Pfouts, R.W. (ed.), *The techniques of urban economic analysis*. Chandler-Davis Publishing Co., West Trenton, NJ, USA, 395–407.

Treloar, G. (1997). Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. *Economic Systems Research* 9(4), 375–91.

Treloar, G., Love, P.E.D., Iyer-Raninga, U. and Faniran, O.O. (2000). A hybrid life cycle assessment method for construction. *Construction, Management and Economics* 18, 5–9.

Treloar, G.J. (1998). *A comprehensive embodied energy analysis framework*. Ph.D. Thesis, Deakin University, Geelong, Vic, Australia.

United Nations Department for Economic and Social Affairs, S.D. (1999). *Handbook of Input-Output Table Compilation and Analysis*. United Nations New York, USA.

van den Bergh, J.C.J.M. and Verbruggen, H. (1999). Spatial sustainability, trade and indicators: an evaluation of the ‘ecological footprint’. *Ecological Economics* 29(1), 61–72.

van Dobben, H.F., Schouwenberg, E.P.A.G., Nabuurs, G.J. and Prins, A.H. (1998). Biodiversity and productivity parameters as a basis for evaluating land use changes in LCA. In: IVAM Environmental Research, Ed. *Biodiversity and life support indicators for land use impacts, Publication Series Raw Materials Nr 1998/07*. Ministry of Transport, Public Works and Watermanagement, Delft, Netherlands, Annex 1.1–1.50.

van Kooten, G.C. and Bulte, E.H. (2000). The ecological footprint: useful science or politics? *Ecological Economics* 32, 385–89.

Vringer, K. and Blok, K. (1995). The direct and indirect energy requirements of households in the Netherlands. *Energy Policy* 23(10), 893–910.

Wackernagel, M. (1997). Ranking the ecological footprint of nations. Internet site www.ecouncil.ac.cr/rio/focus/report/english/footprint/ranking.htm, Centro de Estudios para la Sustentabilidad.

Wackernagel, M. (1998). The ecological footprint of Santiago de Chile. *Local Environment* 3(1), 7–25.

Wackernagel, M., Lewan, L. and Hansson, C.B. (1999). Evaluating the use of natural capital with the ecological footprint. *Ambio* 28(7), 604–12.

Wackernagel, M., Onisto, L., Linares, A.C., Falfan, I.S.L., Garcia, J.M., Guerrero, A.I.S. and Guerrero, M.G.S. (1997). *The Ecological Footprint of Nations*. Study for the Rio+5 Forum, Centro de Estudios para la Sustentabilidad, Xalapa, Mexico.

Wackernagel, M. and Rees, W. (1995). *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers Philadelphia, PA, USA.

Wackernagel, M. and Silverstein, J. (2000). Big things first: focusing on the scale imperative with the ecological footprint. *Ecological Economics* 32, 391–94.

Weber, C. and Fahl, U. (1993). Energieverbrauch und Bedürfnisbefriedigung. *Energiewirtschaftliche Tagesfragen* 43(9), 605–12.

Weber, C., Fahl, U., Schulze, T. and Voß, A. (1995). Freizeit, Lebensstil und Energieverbrauch. *VDI Berichte* 1204, 15–38.

Weber, C. and Perrels, A. (2000). Modelling lifestyle effects on energy demand and related emissions. *Energy Policy* 28, 549–66.

Wiedmann, T. and Lenzen, M. (2007). On the conversion from local hectares to global hectares in Ecological Footprint analysis. *Ecological Economics* 60(4), 673–77.

Wiedmann, T., Minx, J., Barrett, J. and Wackernagel, M. (2006). Allocating Ecological Footprints to final consumption categories with input-output analysis. *Ecological Economics* 56(1), 28–48.

Wier, M., Lenzen, M., Munksgaard, J. and Smed, S. (2001). Environmental effects of household consumption pattern and lifestyle. *Economic Systems Research* 13(3), 259–74.

Wood, R. and Lenzen, M. (2003). An application of an improved ecological footprint method and structural path analysis in a comparative institutional study. *Local Environment* 8(4), 365–84.