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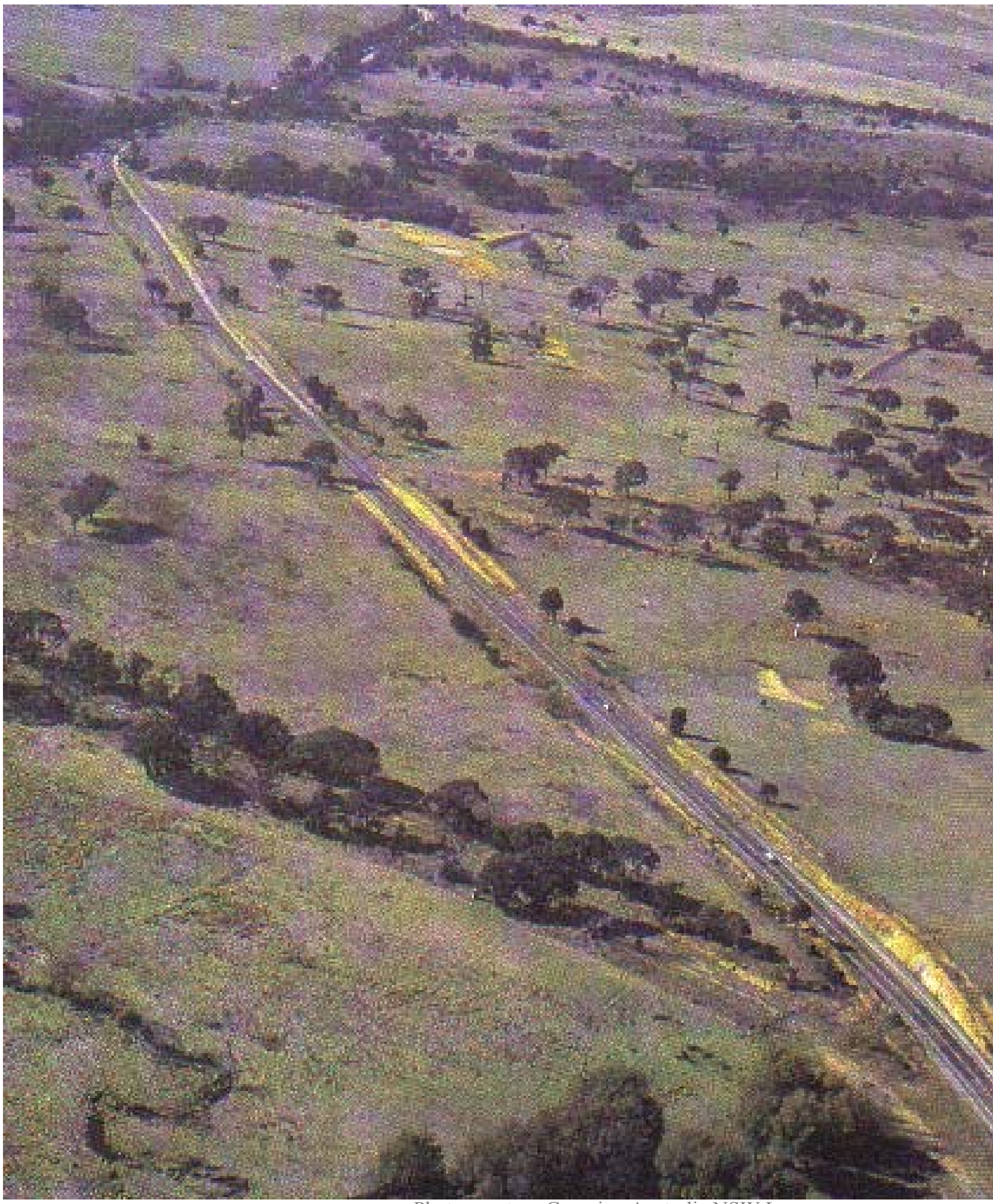
The Ecological Footprint – Issues and Trends



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ISA Research Paper 01-03

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The University of Sydney
Integrated Sustainability Analysis ™

The Ecological Footprint – Issues and Trends

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Executive Summary

The ecological footprint was originally conceived as a simple and elegant method for comparing the sustainability of resource use among different populations. Since the formulation of the ecological footprint, a number of researchers have mentioned the oversimplification in ecological footprints of the complex task of measuring sustainability of consumption. In particular, aggregated forms of the final ecological footprint make it difficult to understand the specific reasons for the unsustainability of the consumption of a given population, and to formulate appropriate policy responses. While generally acknowledged as a valuable educational tool that has enriches the sustainability debate, the original ecological footprint is limited as a regional policy and planning tool for ecologically sustainable development, because it does not reveal where impacts really occur, what the nature and severity of these impacts are, and how these impacts compare with the self-repair capability of the respective ecosystem. In response to the problems highlighted, the concept has undergone significant modification. These modifications include: use of input-output analysis, renewable energy scenarios, land disturbance as a better proxy for sustainability, and the use of production layer decomposition, structural path analysis and multivariate regression in order to reveal rich footprint details. Comprehensive input-output-based ecological footprints are now calculated in many countries, and applied to populations, companies, cities, regions and nations.

The Ecological Footprint – Issues and Trends

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1. Methodological issues and developments

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, a number of researchers have criticised 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 criticisms largely refer to the oversimplification in ecological footprints of the complex task of measuring sustainability of consumption, leading to comparisons among populations becoming meaningless[1], 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 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). While generally acknowledged as a valuable educational tool, the original ecological footprint is not seen as a regional policy and planning tool for ecologically sustainable development, because it does not reveal where impacts really occur, what the nature and severity of these impacts are, and how these impacts compare with the self-repair capability of the respective ecosystem (the temporal aspect, see Arrow *et al.* 1995 and Walker 1995). In response to the problems highlighted, the concept has undergone significant modification (Bicknell *et al.* 1998, Ferng 2001, Lenzen and Murray 2001). Development of and debate about the method are continuing.

In the first part of this chapter, we will describe the developments that have occurred, and explain how the differing results may be interpreted. We will also outline some of the areas where problems remain and where further research is needed. The second part of the chapter aims to illustrate with examples the most recent trends in the application of the ecological footprint concept on a national and local scale.

[1] 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 at least sustainably.

1.1 Original concept

The original ecological footprint is defined as the land area that would be needed to meet the consumption of a population and to absorb all their waste (Wackernagel and Rees 1995). Consumption is divided into 5 categories: food, housing, transportation, consumer goods, and services. Land is divided into 8 categories: energy land, degraded or built land, gardens, crop land, pastures and managed forests, and 'land of limited availability', considered to be untouched forests and 'non-productive areas', which the authors defined as deserts and ice-caps. The 'non-productive' areas are not included further in the analysis. Data are collected from disparate 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 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 that 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.

1.2 Including all areas of land

In the original ecological footprint, areas which were 'unproductive for human purposes', such as deserts and icecaps, are 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 (Simpson *et al.* 2000) all areas of land were included, irrespective of their productivity.

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 Fig. 1: the population to be examined represents the lowest level, or *production layer zero*. 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 number one, and their land requirements are called *first-order requirements*. The suppliers of these providers are production layer number two, and so on. The sum of direct and all indirect requirements, is called *total requirements*.

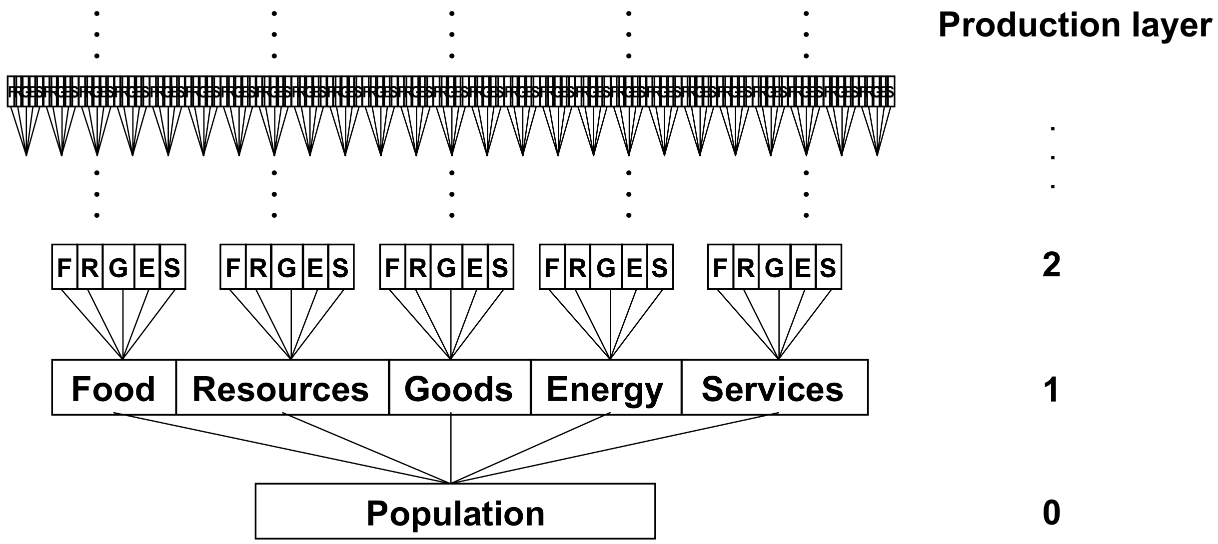

Fig. 1: Industrial interdependence in a modern economy:
a "tree" of upstream production layers.

A specific example for direct and indirect requirements in the ecological footprint of a family is shown in Fig. 2. Direct requirements in production layer zero are represented by the land required for the family's home and for the emissions caused by the burning of petrol, natural gas and other fuels in the household and the car. One item contributing to the family's ecological footprint could be a train journey. The family 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 layer 2) is a second-order requirement. Land and emissions associated with the steel plant producing the steel sheet (layer 3) for the train are third-order requirements, the land mined to extract the iron ore (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.

The supply chain 'iron ore for steel sheet for passenger train for train journey for family' (highlighted in red in Fig. 2) is called a *structural path* of fourth order. Since the production tree is ever-expanding in an upstream direction, the number of structural paths increases towards layers of higher order. On the other hand, higher-order paths also become less and less important, because at each stage only a part of the supplier's direct ecological footprint is "passed on" to the recipient. Nevertheless, Figs. 1 and 2 demonstrate that calculations that consider only layers zero and one underestimate the true ecological footprint. This will be shown in more detail in Section 2.5.

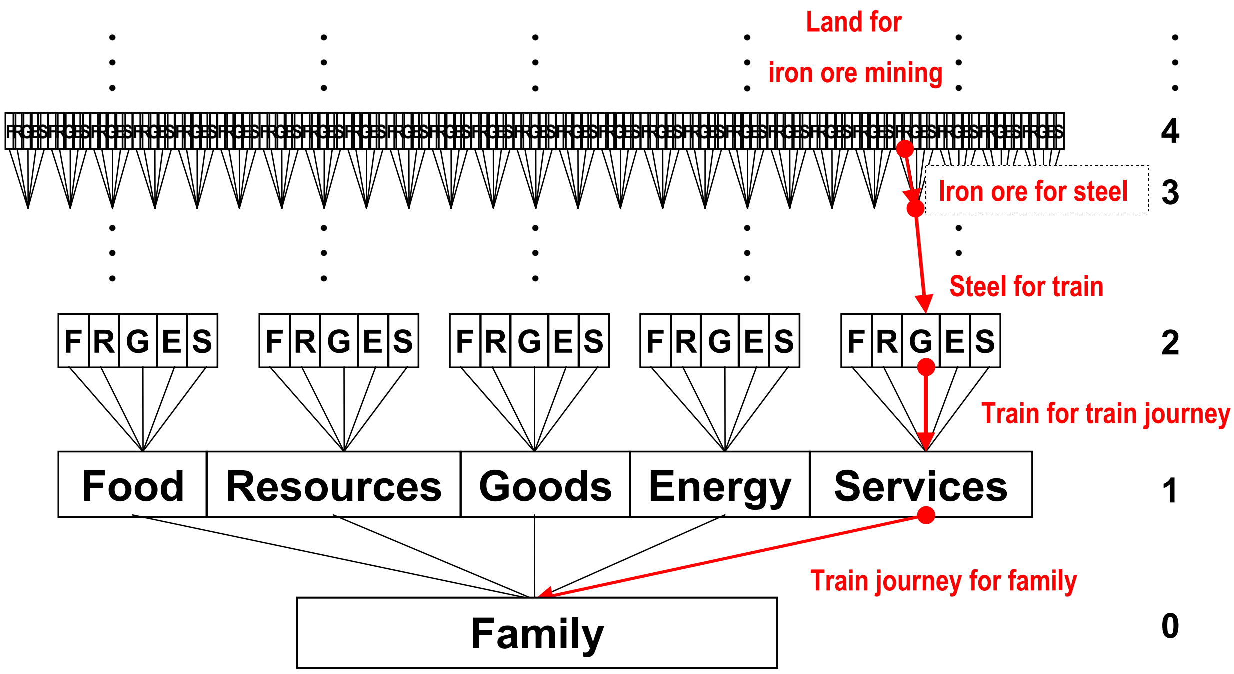

Fig. 2: Production layers and input paths in the ecological footprint of a family.

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, as documented for example in the Australian input-output tables compiled by the Australian Bureau of Statistics (2001). Since its introduction by Nobel Prize laureate Wassily Leontief (1936, 1941) input-output analysis has been applied to numerous economic, social and environmental issues.[2] It was first applied by Bicknell *et al.* in 1998 to calculate an ecological footprint for New Zealand.

Another advantage of using input-output analysis is that imports and exports can be easily accounted for. Ecological remainders or deficits cannot reveal whether the given population manages their land sustainably or not. For example, a population with an ecological remainder could use that remaining land unsustainably for producing exports, and therefore in reality not have any remaining ecological capacity. Also, an ecological deficit of a population may be due to imports of consumer items from countries practicing unsustainable production methods, with the environmental impacts occurring outside its borders, and the local ecosystems well preserved.

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 2001) and the household expenditure survey (Australian Bureau of Statistics 2000). Using Australian data, input-output-based ecological footprints can be calculated for more than 100

[2] For an introduction into input-output theory, see articles by Leontief and Ford (1970), Duchin (1992), and Dixon (1996). For examples and reviews of input-output studies applied to environmental issues, see for example Isard *et al.* (1972), Herendeen (1978b), Miller and Blair (1985), and Proops (1988). For a description of the assembly of an Australian input-output framework, see Lenzen (2001b).

industry sectors and product groups, for states, local areas and cities, and for companies and households.[3] Examples for such calculations are given in Sections 2.1 to 2.3.

Many teams around the world are now developing and applying input-output-based ecological footprints (see Bicknell *et al.* 1998, Ferng 2001, Albino and Kühtz 2002, Bagliani *et al.* 2002, Environment Waikato 2003, Hubacek and Giljum 2003, Ministry for Environment New Zealand 2003).

1.4 Using actual land areas, and assessing land disturbance

In the original ecological footprint method, the areas of forest, pasture and crop land do 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'.[4] Proceeding as such makes 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 makes it impossible to use an ecological footprint for formulating regional policies, because the latter always involve region-specific economic, political, technological, environmental and climatic aspects (Lenzen and Murray 2001).

In the original ecological footprint, land categories are weighted with equivalence and local yield factors (Wackernagel *et al.* 2002a) in order to express appropriated bioproductivity in world-average terms. However, the intensity of human-induced changes to land is independent of productivity (compare 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*, or the *deviation from a pristine state* is not captured in the productivity-based approach of the original concept.

For example, in the original method, the estimation of the ecological footprint for beef consumption by a population is simply the land area that would be needed for the corresponding amount of cattle if the grazing land had world average productivity. However, it is clear that in Australia, cattle farms in different parts of the country are subject to vastly different climates and soil types, and that individual farmers have very different management strategies for their cattle. In addition, some farmers have cleared their lands of natural vegetation much more extensively than others. More extensively cleared land has initially been impacted upon more greatly than less cleared land, and in addition, extensive land clearing is known to cause problems of soil salinity and erosion. Under the original method, it is not possible to distinguish these underlying parameters.

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[3] Simmons, Chambers, Lewis and Barrett (Simmons and Chambers 1998; Simmons *et al.* 2000; Barrett 2001; Best Foot Forward 2001; Chambers and Lewis 2001) calculate component ecological footprints, with the aim of capturing indirect effects in a life-cycle context. They deplore, however, a general lack of data, and methodological problems such as boundary selection and double-counting. In addition, they consider only embodied energy, but not embodied land (Simmons *et al.* 2000). Finally, these authors consider actual, but only bioproductive land.

[4] In order to express an ecological footprint at world-average productivity, the consumption of the reference population is assessed in weight units, which are subsequently translated into units of area by multiplication with world-average productivity factors. Different land types (pasture, crop land, forest) are then converted into a hypothetical land type at world-average biomass productivity by multiplying each land area with an equivalence factor reflecting biomass yield. Similarly, the 'bioproductive capacity' of the population's territory is converted to a world-average equivalent by applying local yield factors (Wackernagel *et al.* 1999).

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. Amongst others (see Lindeijer 2000a and 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 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).

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
SLIGHTLY DISTURBED	
Reserves and unused Crown land	
Slightly disturbed grazing land	0.0

Table 1. Basic weighting factors for land use, reflecting land condition in Australia.

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 Fig 3: the 100-hectare area shown in the photo includes a road (5 ha), a quarry (5 ha), cleared land (75 a), 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. In a disturbance-based approach, however, each area would be weighted with a land condition factor (see Fig. 3), 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. These figures demonstrate the effect of weighting: each part of the land receives a value that reflects both its area and its condition. An example of converting land use into land disturbance will be presented in Section 2.1.

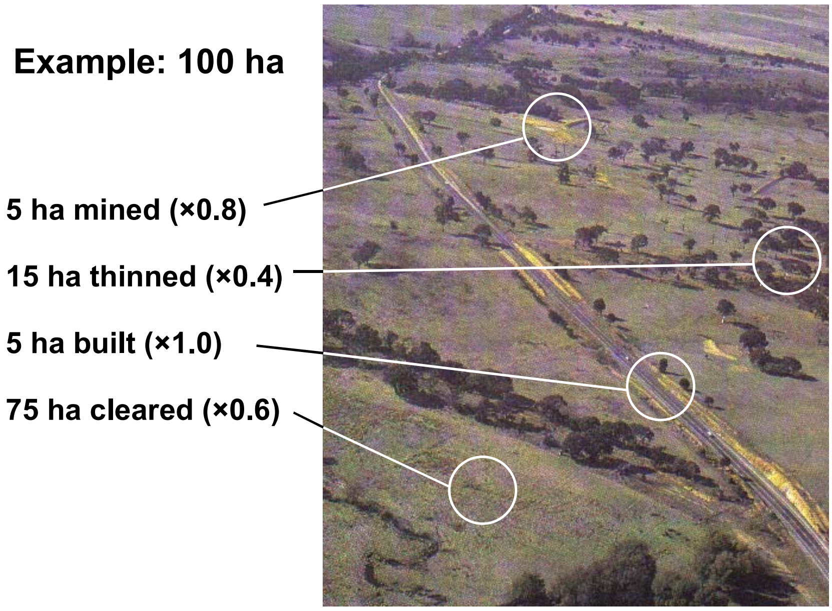

Fig. 3: Assessment of land disturbance
(photo courtesy of Greening Australia NSW Inc).

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, but not emissions of other greenhouse gases, and also not emissions due to other sources such as land clearing, enteric fermentation in livestock, industrial processes, waste, coal seams, venting and leakage of natural gas, which are particularly important in Australia. Therefore, an improvement was made to include other greenhouse gases (compare Ayres 2000)[5] 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. 'Energy land' is calculated conventionally using either a 'carbon sequestration' factor (Wackernagel and Rees 1995), or a 'fuelwood equivalence' factor (Wackernagel *et al.* 2002a). Hypothetical 'fuelwood' land is also responsible for the global 'overshoot' (Wackernagel *et al.* 2002b), or the "carbon sink deficit" (Rees, 2002, personal communication). 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 geographical, climatic and technological circumstances, there may be better options for a population to reduce or compensate its emissions (van den Bergh and Verbruggen 1999, Ferng 2002, Stöglehner 2003). Substituting renewable energy for fossil energy sources, improving energy efficiency, fuel mix changes or structural economic shifts are already existing 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). A national

[5] Greenhouse gases included in the analyses presented in Section 2 are methane (CH_4), nitrous oxide (N_2O), perfluoromethane CF_4, perfluoroethane C_2F_6, halofluorocarbon HFC 134a, and sulfur hexafluoride (SF_6).

greenhouse gas account could instead be presented as complementary to an ecological footprint account (see van Vuuren and Smeets 2000, and Lenzen and Murray 2001).

If it is considered important to produce a single-point indicator (that is, to combine land use and greenhouse gas emissions in the ecological footprint), a disturbance-based approach 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 populations' 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. It must be emphasised that climate change projections are highly uncertain. However, an advantage of a disturbance-based approach is that ecological footprints can be calculated for different abatement strategies and emissions scenarios, which can be compared to a business-as-usual baseline figure.

1.6 Remaining issues

A remaining issue, which has not yet been adopted into the calculation of ecological footprints, is how to accurately incorporate the ecological footprint of imported commodities. Current practice is to assume that industry sectors in the countries of imports origin apply the same production structure, and hence exhibit the same land disturbance characteristics as the respective domestic sectors. This is obviously not necessarily the case. Moreover, this assumption makes it impossible to identify opportunities where trade structures may be altered to reduce national ecological footprints (Bicknell *et al.* 1998). In order to obtain reasonable estimates for the ecological footprint embodied in imports, land disturbance and energy use figures for industries in the countries of imports origin have to be compiled and included in a multi-region ecological footprint framework.

The sustainability of regional land use is a further problem that cannot be addressed by ecological footprints as currently calculated (van den Bergh and Verbruggen 1999, Opschoor 2000, van Kooten and Bulte 2000). This is because productivity and land use are not directly related to sustainability. Ecosystems, climates, farming and forestry methods differ regionally: in some areas, the combination of climate, local ecosystems, and forestry or farming practices may ensure that even intensive land use activities may continue indefinitely. In other areas, local ecosystems could be more fragile, with the result that the land could become unsuitable for the current use, even if non-intensive farming or forestry methods were applied. In order for the ecological footprint to be a more useful and direct indicator of sustainability, detailed data on the unsustainability of various activities, and on the resilience of ecosystems, need to be collected, and a method developed by which to incorporate these data in the ecological footprint. However, while lacking explicit information on sustainability, focusing on land disturbance rather than productivity or land use is a first attempt to account for processes that contribute to unsustainability (Lenzen and Murray 2001).

2. Recent trends and applications

The following Sections contain some examples for recent developments and applications of the ecological footprint concept for Australia. These examples are organised as to proceed from a national Australian ecological footprint as shown in Figs. 4 and 5 towards the ecological footprint of a family, with each example dissecting the previous example into further detail. In particular, Section 2.1 presents an Australian national ecological footprint account at a detailed commodity level, and showing various final demand categories. The regional analysis in Section 2.2 "zooms in" on the Statistical Local Areas (SLAs) of Far North Queensland, which are subsequently broken down into samples of households of different socio-economic and demographic characteristics in Section 2.3. A representative family is then selected from the whole sample, and their ecological footprint split into land disturbance and greenhouse gas components in Section 2.4. In Sections 2.5 and 2.6, these components are then further dissected into production layers, and finally into structural paths as introduced in Figs. 1 and 2.

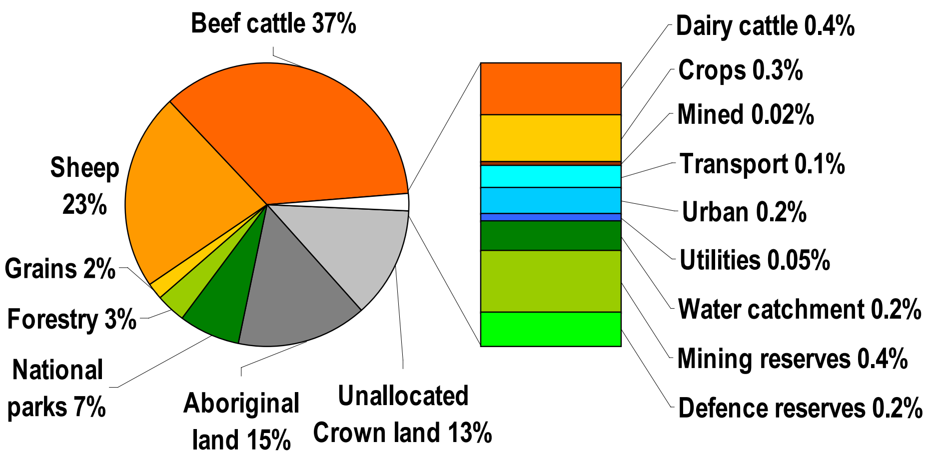

Fig. 4: Australian land use, by using industry.

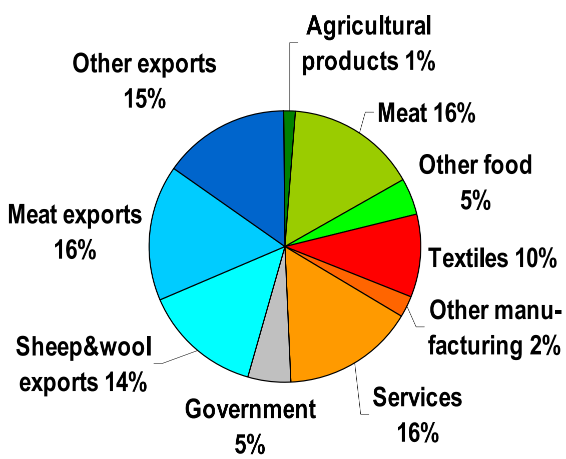

Fig. 5: Australian land disturbance, by commodity and final consumption category.

Figs. 4 and 5 illustrate the transition from land use to land disturbance, and from production to consumption, as facilitated by input-output analysis. Fig. 4 shows how the Australian continent is used or owned by various industries, groups of people, and the government. It is a remarkable fact that 60% of Australia is used for sheep and beef cattle grazing. Furthermore, mines – which are commonly perceived as strongly impacting on land – occupy only 0.02%. Note, however, that a considerable part of grazing land is only partially disturbed, while mining land is often highly degraded. The true impact of these activities can be more adequately described in terms of land disturbance. Moreover, the picture provided in Fig. 4 refers to production. The ecological footprint is, however, primarily concerned with consumption. As a result, Fig. 5 shows Australia's disturbance-based ecological footprint by commodity and final consumption category. The pie chart shows different items for the final consumption of Australian households (green: food, red: manufactured consumer items and services including electricity, gas and water), for the government (grey), and for export (blue). Obviously, a considerable part of land disturbance in Australia is caused for producing exports. Note also that the proportions of 'meat' and 'meat exports', and of 'textiles' and 'sheep and wool exports' compare roughly to the land use categories 'beef cattle' and 'sheep', respectively. The breakdown depicted in Fig. 5 will be decomposed into commodities and final demand categories in the following Section.

2.1 National ecological footprint account

The Australian National Accounts provide a systematic annual summary of national economic activity. They map key economic flows: production, income, consumption, investment, imports and exports (Australian Bureau of Statistics 1996). Currently, the most important measure of overall economic performance is the *Gross Domestic Product*, or GDP (for a criticism of GDP as a welfare indicator see Hamilton 1999). One way of measuring GDP is the *expenditure approach*, in which GDP is described as Gross National Expenditure, adjusted for the trade balance:

GDP = Gross National Expenditure + Exports – Imports.

Gross National Expenditure is in turn broken down into the following uses:

- private final consumption (households),
- government final consumption,
- gross fixed capital expenditure (investment) and
- changes in stocks.

The National Accounts are compiled using a detailed commodity-flow method, which is based on the Australian input-output tables (see Barbetti and De Zilva 1998), yielding classifications at a detailed commodity level. These are traditionally always expressed in monetary terms, but can be converted into a national ecological footprint account in area units by using input-output analysis. The result of such a conversion of the 1995 Australian National Account is shown in Tab. 2.

	PFC	+ GFC	+ Δst	= GNE	+ X	= GNT	- M	= GDP [a]
Sheep and shorn wool	0.23	0.00	-5.41	-5.2	35.18	30.0	0.00	30.0
Grains	0.33	0.00	-1.01	-0.7	4.91	4.2	0.40	3.8
Beef cattle	0.92	0.00	2.58	3.5	3.94	7.4	0.00	7.4
Other agriculture	1.39	0.04	-0.07	1.4	0.33	1.7	0.14	1.5
Forestry	0.11	3.50	-0.01	3.6	0.11	3.7	0.14	3.6
Fishing	0.21	0.02	0.00	0.2	0.11	0.3	0.01	0.3
Coal mining	0.00	0.00	-0.08	-0.1	1.71	1.6	0.00	1.6
Crude oil, natural gas and LPG	0.09	0.00	-0.11	0.0	0.49	0.5	0.47	0.0
Other mining	0.00	0.01	-0.07	-0.1	1.35	1.3	0.15	1.1
Meat products	38.30	0.00	0.97	39.3	40.37	79.6	0.95	78.7
Dairy products	2.09	0.00	-0.02	2.1	1.05	3.1	0.20	2.9
Sugar	3.75	0.00	0.01	3.8	2.25	6.0	0.97	5.0
Other food products	4.58	0.00	0.04	4.6	0.73	5.4	0.98	4.4
Alcohol and tobacco	0.84	0.00	0.09	0.9	0.36	1.3	0.46	0.8
Processed wool, yarns, fabrics	3.75	0.00	-0.09	3.7	6.11	9.8	12.64	-2.9
Textile products and footwear	19.83	0.00	0.44	20.3	4.36	24.6	10.54	14.1
Saw mill products	0.01	0.00	0.01	0.0	0.28	0.3	0.45	-0.2
Paper products	0.79	0.02	-0.06	0.7	0.13	0.9	1.57	-0.7
Refinery products	0.58	0.00	0.11	0.7	0.17	0.9	0.44	0.4
Chemical products	1.60	0.62	0.20	2.4	1.04	3.5	4.61	-1.1
Non-metal construction materials	0.06	0.00	0.02	0.1	0.05	0.1	0.25	-0.1
Basic iron and steel	0.00	0.00	0.04	0.0	0.44	0.5	0.47	0.0
Aluminium	0.00	0.00	0.02	0.0	1.02	1.0	0.01	1.0
Other non-ferrous basic metals	0.08	0.00	-0.01	0.1	1.09	1.2	0.23	0.9
Metal products	0.10	0.00	0.01	0.1	0.11	0.2	0.38	-0.2
Motor vehicles	0.83	0.00	0.13	1.0	0.18	1.1	1.50	-0.4
Other transport equipment	0.03	0.00	-0.01	0.0	0.10	0.1	0.22	-0.1
Other manufacturing	2.02	0.00	0.15	2.2	0.66	2.8	4.46	-1.6
Electricity supply	3.85	0.14	0.00	4.0	0.02	4.0	0.01	4.0
Gas supply	0.10	0.00	0.00	0.1	0.00	0.1	0.00	0.1
Water supply	0.52	0.01	0.00	0.5	0.00	0.5	0.00	0.5
Construction	0.00	0.25	0.00	0.3	0.07	0.3	0.02	0.3
Wholesale and retail trade	13.34	0.00	0.04	13.4	1.09	14.5	0.09	14.4
Accomodation and restaurants	9.00	0.00	0.00	9.0	0.98	10.0	0.65	9.3
Transport	1.57	0.17	0.00	1.7	1.45	3.2	0.99	2.2
Commercial services	7.74	0.57	0.00	8.3	0.56	8.9	0.60	8.3
Public administration and service	2.51	6.59	0.00	9.1	0.13	9.2	0.05	9.2
All industries	121.2	11.9	-2.1	131.0	112.9	244.0	45.1	198.9
Natural processes [b]	-5.3			-5.3		-5.3		-5.3
Residential Usage	2.0			2.0		2.0		2.0
Private Vehicle Usage	2.5			2.5		2.5		2.5
Ecological footprint	120.4	11.9	-2.1	130.2	112.9	243.1	45.1	198.1
Ecological footprint / cap	6.7	0.66	-0.11	7.2	6.25	13.5	2.5	11.0

Notes: all figures in Mha; [a] all figures include contributions from capital investment; [b] includes CO_2 sequestration, soil carbon uptake, prescribed burning, and wildfires; PFC = private final consumption; GFC = government final consumption; Δst = changes in stocks; GNE = Gross National Expenditure; X = exports; GNT = Gross National Turnover; M = imports; GDP = Gross Domestic Product.

Tab. 2: A national ecological footprint account.

Amongst other features, the ecological footprint account shows that almost half of Australia's (GDP) footprint is caused by producing exports of products from sheep and beef cattle grazing.[6] The total export-related footprint amounts to about 110 million hectares, which is more than the combined area of NSW and Victoria. The fact of Australia exploiting a considerable part of its natural assets for exports is the result of a history of economic planning: since the 1980s, Australia has sought to escape from increasing foreign debt and falling primary commodity prices by expanding the volume of meat, wool and other primary exports in order to maintain total export revenues and living standards (Daniels 1992; Muradian and Martinez-Alier 2001). Daly (1993) paraphrased this strategy as entering into an environmental 'race to the bottom'. Moreover, primary exports generally neither promote technological innovation and development of labour skills, nor positively influence economic growth, mainly because the respective producing industries are poorly linked back to other domestic, value-adding sectors (Fosu 1996; Lenzen 2003), and thus exert little economic impetus. In this respect, Australia is sharing the predicament of many developing countries that are locked into an environmental-economic dilemma through increasing dependency on environmentally degrading production and further erosion of environmental quality (Daniels 1992, Muradian and Martinez-Alier 2001). The environmental degradation associated with this situation is now slowly emerging, and will be exacerbated unless the national income is drawn from more sustainable production and trade, for example by internalising environmental cost into export prices, or by shifting towards alternative production structures, that is establishing strong value-adding secondary sectors through fostering education and research (Muradian and Martinez-Alier 2001).

2.2 Regional ecological footprints

Household expenditure surveys conducted by the ABS provide a detailed picture of the consumption of goods and services by representative households across Australia. Like the National Accounts, the survey data can be converted into ecological footprints of households, once again, by using input-output analysis.[7] The result of such a conversion is shown in the map in Tab. 3, which is based on the 1998-99 Household Expenditure Survey (Australian Bureau of Statistics 2000).

Tab. 3 also shows the *ecological footprint intensity*, that is the ecological footprint of one dollar spent by households, for all Far North Queensland Statistical Local Areas. Interestingly, the footprint intensity is low for regions with a high footprint, and vice versa. This is because households with a large footprint spend relatively more money on commodities with a low specific (per-dollar) footprint than households with a small footprint. This will be explained in more detail in the following Section.

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6 Note that the footprint of meat exports is probably even underestimated, because we have assumed that production of export meat occurs in intensive as well as on extensive land use zones. However, farmers in the intensive land use zones produce mainly for domestic final consumption, while the land clearing in Queensland is mainly directed towards exports.

7 This technique has been applied previously – mostly to energy consumption and emissions – by the following authors: Herendeen and Tanaka 1976; Herendeen 1978a; Herendeen *et al.* 1981; Peet 1986; Breuil 1992; Weber and Fahl 1993; Vringer and Blok 1995; Lenzen 1998; Biesiot and Noorman 1999; Munksgaard *et al.* 2000; Weber and Perrels 2000; Wier *et al.* 2001.

Statistical Local Area	EF (ha/cap)	EF intensity (ha/$)	Statistical Local Area	EF (ha/cap)	EF intensity (ha/$)
Atherton	6.6	0.42	Cook (excl. Weipa)	5.7	0.45
Aurukun	5.1	0.53	Croydon	6.7	0.48
Burke	5.7	0.51	Douglas	7.7	0.45
Cairns - Barron	7.1	0.41	Eacham	6.6	0.43
Cairns - Central Suburbs	6.9	0.38	Etheridge	7.7	0.46
Cairns - Mt Whitfield	8.2	0.41	Far North SD Bal[a]	6.2	0.43
Cairns - Northern Suburbs	7.5	0.43	Flinders	6.5	0.42
Cairns - Part B	5.5	0.40	Herberton	5.0	0.43
Cairns - Trinity	6.1	0.37	Johnstone	6.0	0.39
Cairns - Western Suburbs	7.2	0.40	Mareeba	6.2	0.43
Cairns City Part A	7.1	0.40	McKinlay	7.7	0.42
Cardwell	6.6	0.41	Mornington	6.0	0.51
Carpentaria	5.6	0.49	Mount Isa	6.5	0.39
Cloncurry	6.6	0.42	Richmond	6.8	0.43
Cook - Weipa only	7.1	0.37	Torres	5.1	0.47

Tab. 3: Ecological footprint for Statistical Local Areas in Far North Queensland ([a] Remainder of Statistical Division).

2.3 Socio-economic and demographic factors influencing ecological footprints

In addition to location, the data collected in Household Expenditure Surveys distinguishes families of different income, size, composition, age, and other socio-economic-demographic factors. This feature enables the investigation of the influence of these factors on the ecological footprint.

A technique which is commonly used to examine the relationship between a so-called *explained variable* (here the ecological footprint) and *explanatory variables* (here the socio-economic-demographic factors) is *multivariate regression*. The usefulness of this technique for policy design and urban planning is twofold: (1) it is possible to find out which factors are significant in explaining variations of the ecological footprint, and (2) it yields a quantitative formula that enables the prediction of the ecological footprint from these significant factors. Applying multivariate regression to the ecological footprint of households in the Statistical Local Areas of Far North Queensland as shown in Tab. 3 yields the following relationship:

$$\text{Ecological footprint per capita} = 2.00 \times X^{0.55} \times S^{-0.23} \times D^{-0.04} ,$$

where X is per-capita household expenditure in units of 1000 A$, S is the number of household members, and D is the population density in units of people per km^2.[8] The formula

[8] These factors were selected from available data. There may be factors that are more important for explaining the ecological footprint (such as education or house type), where data is not available on a household basis. Furthermore, the factors listed may themselves be the result of underlying socio-economic-demographic characteristics. For example, tenure type may be influenced by house type (in the sense that owners tend to occupy large detached houses, and not flats), which may be the true influencing factor for the ecological

states that the ecological footprint increases with increasing expenditure, and decreases with increasing household size and population density.

Using multivariate regression, a likely answer can be obtained, for example, for the question:

"What is the ecological footprint of a Far North Queensland family
- of four members, two working,
- living in a part of Cairns with a population density of 100 people/km^2,
- with a combined annual expenditure of 58,800 A$?"

by determining the per-capita expenditure: X = 58,800A$ / 4 = 14,700 A$, and then applying the multivariate regression formula given above. Inserting the values for X, S=4 and D=100 yields:

$$\text{Ecological footprint} = 2.00 \times 14.7^{0.55} \times 4^{-0.23} \times 100^{-0.04} = 5.87 \text{ hectares / capita.}$$

Amongst all explanatory variables, household expenditure has the strongest influence on the ecological footprint. However, the ecological footprint increases slightly less than proportionally with increasing expenditure (see the "flattening-out" of the solid line in Fig. 6a, representing Australian households), which is expressed in the exponent of X being 0.55 and thus smaller than one. This exponent is called the *expenditure elasticity of the ecological footprint*: an elasticity of 0.55 means that for a 10% relative increase in household expenditure, the associated ecological footprint increase is only 5.5%. As a consequence, the ecological footprint intensity decreases with increasing expenditure (see Fig. 6b).

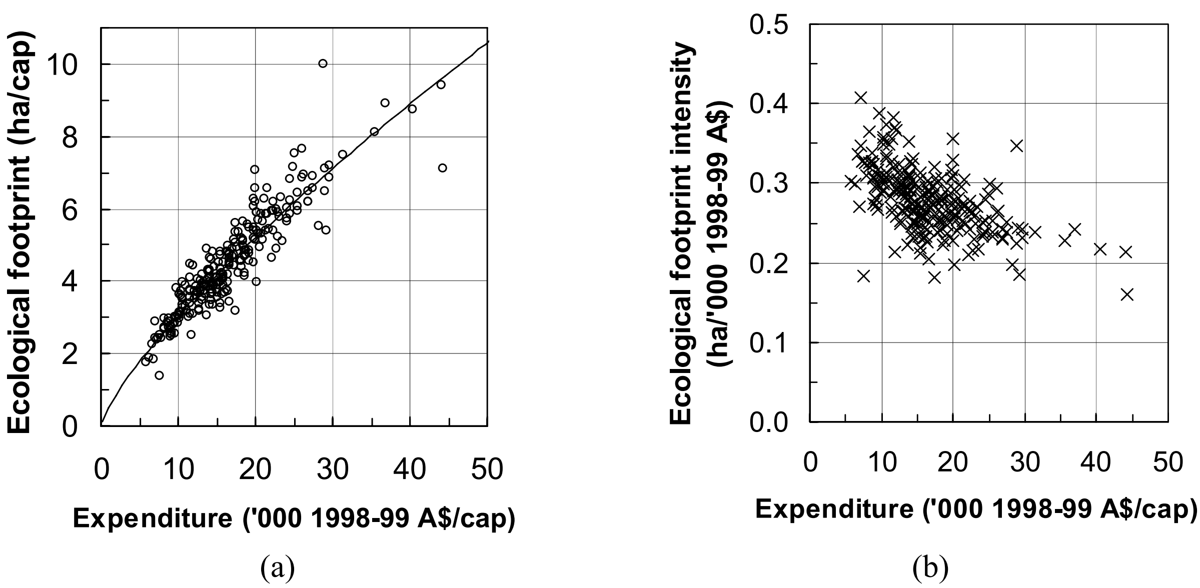

Fig. 6: Per-capita ecological footprint (a) and ecological footprint intensity (b) as a function of per-capita household expenditure for Australian households.

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footprint. Finally, factors may be correlated, and therefore influence each other. For example, expenditure increases with income, which in turn tends to increase with age.

This circumstance of wealthy households having a relatively smaller ecological footprint per dollar of expenditure is due to variations in the consumer basket: households with a low income consume relatively more items associated with a high ecological footprint intensity (such as food, energy, transport), and vice versa (see Fig. 7).

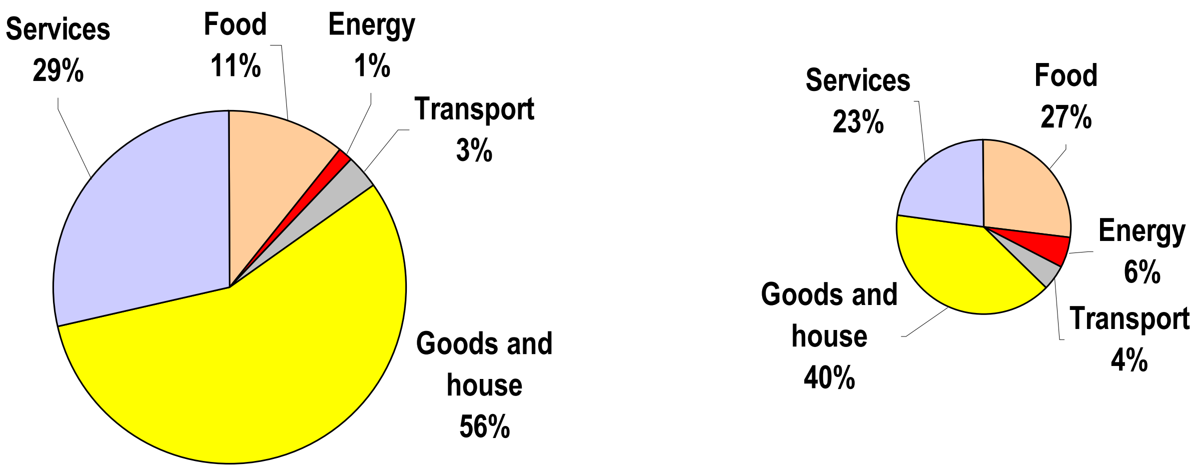

Fig. 7: Shares of consumer item categories in the total monetary household expenditure for Far North Queensland households with 2-3 members and an annual per-capita income of $60,000 (left pie chart) and $7,000 (right pie chart). Source: Australian Bureau of Statistics 2000.

2.4 Land use types and greenhouse gas emissions

As described in Section 1, the ecological footprint comprises impacts of various levels of disturbance, and also land disturbance through greenhouse gas emissions ("emissions land"). Tab. 4 shows a breakdown of the ecological footprint of the Far North Queensland family introduced in the previous Section into these categories (compare Tab. 1).

Consumed (C=1)	Degraded (C=0.8)	Replaced (C=0.6)	Significantly disturbed (C=0.4)	Partially disturbed (C=0.2)	Slightly disturbed (C=0)	Land disturbance	Emissions land
0.12	0.32	2.72	3.28	2.05	2.41	3.73	2.14

Tab. 4: Breakdown of the ecological footprint of the Far North Queensland family introduced in Section 2.3 into land of different disturbance level and emissions (in hectares).

Tab. 4 shows that this family exerts its footprint mainly on significantly disturbed and on replaced land. These disturbance types refer mostly to crop and grazing land across Australia. Moreover, a significant part of the ecological footprint is caused by greenhouse gas emissions. Consumed and degraded land plays only a minor role.

2.5 Production layers

An interesting question is: how much of the overall ecological footprint of 5.87 ha stated in Tab. 4 is caused by the family itself (in the house or while driving the private car), and how much is caused in industry and agriculture, through the provision of goods and services that the family acquires?

Fig. 8 shows a decomposition of the family's ecological footprint into *production layers*, as introduced in Section 1 (see Figs 1 and 2). If only such impacts are taken into account, which occur in the household or the car (layer 0), the ecological footprint would only be 0.05 ha/cap. Of this area, 0.03 ha/cap would be the land disturbed by the very existence of the (assumed about quarter-acre) property (25m×50m/4 persons ≈ 0.03ha). However, including the area of shops, supermarkets, workshops, garages, etc producing and selling goods and services (layer 1; apportioned to the fraction of items bought by the family) increases the ecological footprint to 1.0 ha/cap. If the area occupied by the suppliers of these shops, supermarkets etc is added (layer 2; steel works, power plants, farms etc), the footprint increases dramatically to 2.7 ha/cap. Suppliers of layer 3 (iron ore and coal mines, agricultural and mining machinery manufacturers etc) contribute another 2.0 ha/cap. With increasing order of production layer, proceeding towards further upstream suppliers, contributions become smaller and smaller, and the ecological footprint converges towards its final value of 5.9 ha/cap.

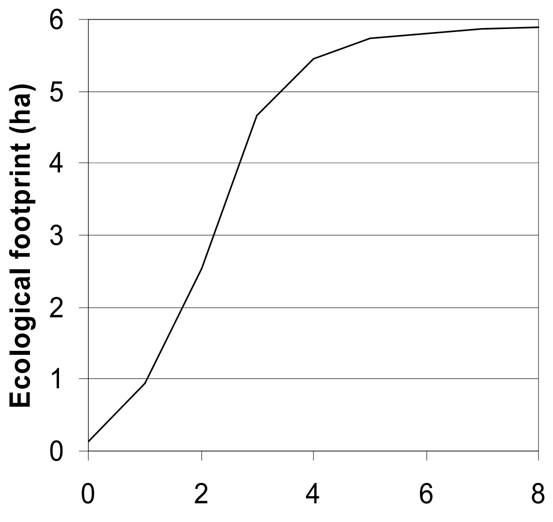

Fig. 8: Decomposition of the ecological footprint of the Far North Queensland family into contributions from production layers of increasing order.

2.6 Structural paths

The decomposition of the Far North Queensland family's ecological footprint into contributing production layers shown in Fig. 8 can be broken down further into detailed *structural paths* (as introduced in Section 1, see Fig. 2) by executing a path extraction algorithm (for further details see Treloar 1997 and Lenzen 2002).

In Tab. 5 on the following page, each of the top ecological footprint paths is characterised by a code, consisting of (1) a description of the *path type* and *path vertices*, (2) the *path order*, and (3) the *path value*. For the sake of brevity, the path vertices are assigned a sector code (see Tab. 6). The path E Bc Mp Ho (3; 1.3%) 0.021 (0.5%), for example, ranking 13th, describes the greenhouse gas emissions (E) caused by beef cattle grazing (Bc) supplying meat products (Mp) to hotels and restaurants (Ho) frequented by the family (see codes in Tab. 6). The path is of 3rd order. Its value is 0.021 ha, which constitutes a coverage of about 1.3% of emissions land (which is 0.4% of the family's total ecological footprint).

Tab. 5 illustrates the complexity of the inter-industry supply chains underlying the upstream requirements of the family: less than half of the top ecological footprint paths are of order 0 or 1, and all top paths constitute only 30% of the family's total ecological footprint. The remaining 70% are covered by numerous higher-order paths. Most of the paths refer to greenhouse gas emissions (E), followed by cleared (grazing and crop) land (R).

Tab. 5 shows that the family exerts its most important impact through CO_2 emissions due to electricity use (E El), followed closely by grazing land (condition R and S) for meat products (Mp). Paths occupying ranks 4, 5 and 13 also relate to greenhouse gas emissions for food consumption, this time in form of CH_4 from enteric fermentation in livestock for dairy (Dp) and meat (Mp) products, and food and beer consumed in hotels and restaurants (Ho). The (consumed) land for the family's dwelling (C Dw) ranks 8th. All subsequent paths, such as emissions from air travel (E At), from natural gas burned for hot water or cooking (E Ng), and petrol used in the private car (E Ap) contribute less than 1% to the total ecological footprint.

Ecological footprint paths	ha
E El (1; 17.2%)	0.274
R Bc Mp (2; 13.1%)	0.162
S Bc Mp (2; 14.8%)	0.144
E Dc Dp (2; 4.6%)	0.075
E Bc Mp (2; 4.5%)	0.075
E El Ho (2; 3.5%)	0.056
R Ba Bm Ho (3; 3.%)	0.037
C Dw (0; 35.5%)	0.031
R Ba Bm (2; 2.5%)	0.031
R Dc Dp (2; 2.5%)	0.030
R Wh Fc (2; 2.2%)	0.027
E At (1; 1.5%)	0.023
E Bc Mp Ho (3; 1.3%)	0.021
E Ng (0; 1.3%)	0.021
R Wh Fc Bp (3; 1.7%)	0.020
R Wh Fd (2; 1.6%)	0.020
D Bc Mp (2; 9.2%)	0.018
E El Rt (2; 0.9%)	0.014
E Fd (1; 0.8%)	0.013
E Ga (1; 0.8%)	0.013
E Pg (1; 0.8%)	0.013
E Wo Mp (2; 0.8%)	0.012
E Vf (1; 0.8%)	0.012
E Ap (0; 0.7%)	0.012

Tab. 5: Structural paths in the ecological footprint of the Far North Queensland family.

Symbol	Industry or land type
Ap	Automotive petrol
At	Air transport
Ba	Barley
Bc	Beef cattle grazing
Bm	Beer and malt
Bp	Bread and other bakery products
C	Consumed land (see Tab. 1)
D	Degraded land (see Tab. 1)
Dc	Dairy cattle grazing and untreated whole milk
Dp	Dairy products
Dw	Dwelling
E	Greenhouse gas emissions
El	Electricity
Fc	Flour, cereal foods, rice, pasta and other flour mill products
Fd	Seafoods, coffee, sugar, animal feeds and other foods
Ga	Gas production and distribution
Ho	Accommodation, cafes and restaurants
Mp	Meat and meat products
Ng	Natural gas
Pg	Pork
R	Replaced land (see Tab. 1)
Rt	Retail trade
S	Significantly disturbed land (see Tab. 1)
Vf	Vegetable and fruit
Wh	Wheat
Wo	Sheep and shorn wool

Tab. 6: Symbols used in Tab. 5.

In summary, these results show that decompositions of the ecological footprint into commodities, production layers, and structural paths provide an extremely detailed picture of environmental impact. In addition to a household, the analyses presented in Sections 2.1 to 2.6 can be applied to a nation, a state, a city, a council, a company, or any other institution. In any case, they enable identifying operational inputs that are most crucial in terms of their ecological footprint, and ultimately facilitate targeting opportunities and streamlining action for changes towards reducing environmental pressure.

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 http://www.io2002conference.uqam.ca/abstracts_papers/new16janv03/Montreal_final_paper.doc.

Arrow K., Bolin B., Costanza R., Dasgupta P., Folke C., Holling C.S., Jansson B.-O., Levin S., Mäler K.-G., Perrings C. and Pimentel D. (1995). Economic growth, carrying capacity and the environment. *Science* **268**(5210), 520-521.

Australian Bureau of Statistics (1996). *Measuring Australia's Economy*. ABS Catalogue No. 1360.0, Australian Bureau of Statistics, Canberra, Australia.

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

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

Ayres R.U. (2000). Commentary on the utility of the ecological footprint concept. *Ecological Economics* **32**, 347-349.

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 http://www.io2002conference.uqam.ca/abstracts.pdf.

Barbetti A. and De Zilva D. (1998). SNA93-based Input-Output Tables for Australia. In: *ANZRAI 22nd Conference*, Tanunda, South Australia, Australian Bureau of Statistics.

Barrett J. (2001). Component ecological footprint: developing sustainable scenarios. *Impact Assessment and Project Appraisal* **19**(2), 107-118.

Best Foot Forward (2001). Ecological footprint calculators. Internet site, Best Foot Forward, The Future Centre, 115 Magdalen Rd, Oxford OX4 1RQ, UK (electronic source).

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), 149-160.

Biesiot W. and Noorman K.J. (1999). Energy requirements of household consumption: a case study of The Netherlands. *Ecological Economics* **28**(3), 367-383.

Breuil J.-M. (1992). Input-output analysis and pollutant emissions in France. *Energy Journal* **13**(3), 173-184.

Chambers N. and Lewis K. (2001). *Ecological footprint analysis: towards a sustainability indicator for business*. Research Report No. 65, Association of Chartered Certified Accountants, London, UK.

Costanza R. (2000). The dynamics of the ecological footprint concept. *Ecological Economics* **32**, 341-345.

Daly H. (1993). The perils of free trade. *Scientific American* **269**, 24-29.

Daniels P.L. (1992). Barriers to sustainable development in natural resource-based economies: Australia as a case study. *Society and Natural Resources* **5**, 247-262.

Darwin R., Tsigas M., Lewandrowski J. and Raneses A. (1996). Land use and cover in ecological economics. *Ecological Economics* **17**, 157-181.

Dixon R. (1996). Inter-industry transactions and input-output analysis. *Australian Economic Review* **3'96**(115), 327-336.

Duchin F. (1992). Industrial input-output analysis: implications for industrial ecology. *Proceedings of the National Academy of Science of the USA* **89**, 851-855.

Environment Waikato (2003). *Regional Ecological Footprint*. Internet site http://www.ew.govt.nz/ourenvironment/indicators/community/sustainability/ecofoot/techinfo.htm, Waikato Regional Council, Hamilton East, New Zealand.

Ferng J.-J. (2001). Using composition of land multiplier to estimate ecological footprints associated with production activity. *Ecological Economics* **37**, 159-172.

Ferng J.-J. (2002). Toward a scenario analysis framework for energy footprints. *Ecological Economics* **40**, 53-69.

Fosu A. (1996). Primary exports and economic growth in developing countries. *World Economy* **19**, 465-475.

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.

Hamilton C. (1999). The genuine progress indicator: methodological developments and results from Australia. *Ecological Economics* **30**, 13-28.

Herendeen R. (1978a). Total energy cost of household consumption in Norway, 1973. *Energy* **3**, 615-630.

Herendeen R., Ford C. and Hannon B. (1981). Energy cost of living, 1972-1973. *Energy* **6**, 1433-1450.

Herendeen R. and Tanaka J. (1976). Energy cost of living. *Energy* **1**, 165-178.

Herendeen R.A. (1978b). Input-output techniques and energy cost of commodities. *Energy Policy* **6**(2), 162-165.

Hubacek K. and Giljum S. (2003). Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological Economics* **44**, 137-151.

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.

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.

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

Lenzen M. (2001). 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**, 545-572.

Lenzen M. (2003). Environmentally important linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics* **14**, 1-34.

Lenzen M. and Munksgaard J. (2001). Energy and CO_2 analyses of wind turbines - review and applications. *Renewable Energy* **26**(3), 339-362.

Lenzen M. and Murray S.A. (2001). A modified ecological footprint method and its application to Australia. *Ecological Economics* **37**(2), 229-255.

Leontief W. (1936). Quantitative input and output relations in the economic system of the United States. *Review of Economics and Statistics* **18**(3), 105-125.

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), 262-271.

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**, 313-319.

Lindeijer E. (2000b). Review of land use impact methodologies. *Journal of Cleaner Production* **8**, 273-281.

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

Ministry for Environment New Zealand (2003). *Ecological Footprints of New Zealand and its Regions*. Internet site http://www.dioxinplan.mfe.govt.nz/footprint/faq-about.html, Ministry for Environment New Zealand, Wellington, New Zealand.

Moffatt I. (2000). Ecological footprints and sustainable development. *Ecological Economics* **32**, 359-362.

Munksgaard J., Pedersen K.A. and Wier M. (2000). Impact of household consumption on CO_2 emissions. *Energy Economics* **22**, 423-440.

Muradian R. and Martinez-Alier J. (2001). Trade and the environment: from a 'Southern' perspective. *Ecological Economics* **36**, 281-297.

Opschoor H. (2000). The ecological footprint: measuring rod or metaphor? *Ecological Economics* **32**, 363-365.

Peet N.J. (1986). Energy requirements of output of the New Zealand economy, 1976-77. *Energy* **11**(7), 659-670.

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, 201-216.

Rapport D.J. (2000). Ecological footprints and ecosystem health: complementary approaches to a sustainable future. *Ecological Economics* **32**, 381-383.

Rees W.E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanization* **4**(2), 121-130.

Simmons C. and Chambers N. (1998). Footprinting UK households: how big is your ecological garden? *Local Environment* **3**(3), 355-362.

Simmons C., Lewis K. and Barrett J. (2000). Two feet - two approaches: a component-based model of ecological footprinting. *Ecological Economics* **32**, 375-380.

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

Stöglehner G. (2003). Ecological footprint - a tool for assessing sustainable energy supplies. *Journal of Cleaner Production* **11**, 267-277.

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.

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), 375-391.

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**, 385-389.

van Vuuren D.P. and Smeets E.M.W. (2000). Ecological footprints of Benin, Bhutan, Costa Rica, and the Netherlands. *Ecological Economics* **34**, 115-130.

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, Centro de Estudios para la Sustentabilidad (electronic source).

Wackernagel M., Lewan L. and Hansson C.B. (1999). Evaluating the use of natural capital with the ecological footprint. *Ambio* **28**(7), 604-612.

Wackernagel M., Monfreda C. and Gurarie E. (2002a). *Improvements to national footprint accounts since the Living Planet Report 2000*. Internet site http://www.redefiningprogress.org/, Redefining Progress, Oakland, CA, USA.

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., Schulz N.B., Deumling D., Callejas Linares A., Jenkins M., Kapos V., Monfreda C., Loh J., Myers N., Norgaard R. and Randers J. (2002b). Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences* **99**(14), 9266-9271.

Wackernagel M. and Silverstein J. (2000). Big things first: focusing on the scale imperative with the ecological footprint. *Ecological Economics* **32**, 391-394.

Walker B. (1995). National, regional and local scale priorities in the economic growth versus environment trade-off. *Ecological Economics* **15**, 145-147.

Weber C. and Fahl U. (1993). Energieverbrauch und Bedürfnisbefriedigung. *Energiewirtschaftliche Tagesfragen* **43**(9), 605-612.

Weber C. and Perrels A. (2000). Modelling lifestyle effects on energy demand and related emissions. *Energy Policy* **28**, 549-566.

Wier M., Lenzen M., Munksgaard J. and Smed S. (2001). Environmental effects of household consumption pattern and lifestyle. *Economic Systems Research* **13**(3), 259-274.