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ARTICLE

An Application of a Modified Ecological Footprint Method and Structural Path Analysis in a Comparative Institutional Study

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ABSTRACT *This paper presents an application of a modified ecological footprint method, using a regional, disturbance-based approach. In contrast to conventional institutional ecological footprint calculations, energy and land use resulting from all upstream production processes are explored by employing an input–output framework. Ecological footprints are calculated for two research institutions: the School of Physics (SoP) at the University of Sydney, and the Sustainable Ecosystems (CSE) Department of the Commonwealth Scientific and Industrial Research Organisation. These are broken down further in terms of land disturbance and greenhouse gas emissions, and as a function of production layer. To enable the use of the results in policy formulation, the ecological footprints are decomposed into detailed contributing paths, which are ranked according to their importance, using structural path analysis. The paper demonstrates that a considerable proportion of impacts occur upstream in industrial production. Thus a significant result of the study is the weight of obscure paths in the total footprints and, therefore, the importance of conducting an holistic assessment in order to ensure all upstream contributions are captured in the final impact of the institution.*

1. Introduction and Literature Review

The broad nature of sustainability makes it difficult to find indicators that not only encompass a wide range of aspects, but also remain specific enough to allow explicit policy formation. One indicator that seeks to address the full scope of consumptive sustainability is the ecological footprint, first proposed by Rees (1992) and expounded by Wackernagel & Rees (1995) and Simmons *et al.* (2000). It is noted for its intuitive simplicity and ease of understanding, and has helped to re-open the debate on human carrying capacity in the context of global sustainability.

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The EF of a population was defined by Rees (2001) as the total area of land and water ecosystems required to produce their resources and to assimilate their wastes, wherever these ecosystems are located. The concept as it was originally proposed has been criticised by a number of researchers and, as a result, significant modifications have been proposed. Two of these are the implementation of the economic tool of input–output analysis by Bicknell *et al.* (1998) and the incorporation of a regional, disturbance-based approach by Lenzen & Murray (2001).

Whilst the EF has been calculated previously for institutions (Anglian Water Group, 2001; Chambers & Lewis, 2001), studies have generally focused on regions and nations (see for example Wackernagel & Rees, 1995; Wackernagel *et al.*, 1997; Bicknell *et al.*, 1998; Simpson *et al.*, 2000; Lenzen & Murray, 2001; van Vuuren & Smeets, 2000; Loh, 2002). Such studies have highlighted the global impacts of consumption, but have not provided the intricate information at the local level needed for remediation. Detailed local information is particularly important for commercial and public organisations, which have the opportunity to mitigate their impacts by controlling and directing their own purchasing (see an ecological footprint study of a large water supplier by Lenzen *et al.*, 2003).

A case in point are universities which, along with exerting control over expenditure, have a particular responsibility in being role models for best environmental practice due to their significant influence on societal development (Viebahn, 2000a). Hence, the need for comprehensive environmental management systems (EMSs) in universities has recently been recognised (see Viebahn, 2002; Shriberg, 2002; Barnes & Jerman, 2002). In Germany, for example, Viebahn & Matthies (2000a) have pioneered a framework for 'eco-balancing' and environmental management of tertiary education institutions, which is documented in six research papers on the environmental management model of the University of Osnabrück, Germany (Viebahn & Matthies, 1999a); its energy balance (Viebahn & Matthies, 1999b); its transport balance (Viebahn *et al.*, 1999a); its waste balance and reduction programme (Viebahn *et al.*, 1999c); an environmental information system (Viebahn *et al.*, 1999b); and—summarising—its ecological balance (Viebahn & Matthies, 2000b). In the US, Venetoulis (2001) calculated the ecological footprint of the University of Redlands in California. An energy management system for the University of Melbourne in Australia was described by Pawsey (1980) and a more recent ecological footprint study for Australia was carried out at the University of Newcastle, New South Wales, by Flint (2001). All of the above authors employ (more or less) incomplete approaches for the calculation of ecological footprints and eco-balances. While Viebahn & Matthies (1999b) claim to capture upstream energy and CO_2 requirements of the university's energy supply, Venetoulis (2001) concedes that his study is not comprehensive and that exhaustive analyses must also include upstream impacts of material production. Only Flint (2001, p. 53) mentions Bicknell *et al.*'s (1998) input–output approach as enabling the overcoming of errors caused by the delineation of the assessment's system by a finite boundary. However, as with Simpson *et al.* (2000), Flint uses input–output-based intensities only for CO_2 (Common & Salma, 1992). A true input–output-based examination is Lichty & Jessweins (1978) study of the economic impact of the University of Minnesota at Duluth, US, on the local economy. An interesting interinstitutional comparison based on input–output analysis is presented in Lough's (1996) study of a university, a natural gas utility, a wastewater treatment facility and two private companies. The analysis is, however, only of the embodied energy. The application of the modified ecological footprint analysis (Bicknell *et al.*, 1998; Lenzen & Murray, 2001) in all the above systems would serve as both a more comprehensive environmental assessment and a feedback mechanism for the effectiveness of EMSs.

It is with this in mind that the paper presents calculations of the ecological footprint of the School of Physics at the University of Sydney (SoP) and the Commonwealth Scientific and Industrial Research Organisation's Sustainable Ecosystems Department (CSE). The SoP and the CSE were chosen in order to compare a research institution with a technological focus with a research institution more dependent on human resources.

This work presents the methodology, along with limitations and assumptions in Section 2; a summary of the results for the application of the method to the SoP and the CSE follows in section 3. A discussion of these results, in comparison, and with implications for policy is in section 4 and the paper concludes in section 5.

2. Methodology

2.1 Development of the Ecological Footprint Concept

In the original ecological footprint, the consumption of populations is converted into a single index: the land and sea area that would be needed to sustain that population indefinitely. In order to measure the sustainability of a given population, this land area is compared with the actual available land area. Unsustainable populations, in this analysis, are populations with a larger ecological footprint than their domestic land base.

Since its initial formulation, the ecological footprint has been criticised by a number of researchers (Levett, 1998; van den Bergh & Verbruggen, 1999; Ayres, 2000; Moffatt, 2000; Opschoor, 2000; Rapport, 2000; Lenzen & Murray, 2001; van Kooten & Bulte, 2000). The objections largely refer to the oversimplification of the complex task of measuring the sustainability of consumption and to perceived shortcomings in the method's impact weighting, sequestration scenario and spatial delineation (Ayres, 2000; Lenzen & Murray, 2001; Levett, 1998; van den Bergh & Verbruggen, 1999; Ferng, 2002). Many critics argue that ecological footprints are inadequate for (regional) policy design (Ayres, 2000; Lenzen & Murray, 2001; Moffatt, 2000; Opschoor, 2000; van den Bergh & Verbruggen, 1999; van Kooten & Bulte, 2000) and claim, but do not enable, the analysis of unsustainability (Lenzen & Murray, 2001; Rapport, 2000; van den Bergh & Verbruggen, 1999). 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 (for the temporal aspect, see Arrow *et al.*, 1995; and Walker, 1995, p. 145). In response to these issues, significant modifications have been proposed (Bicknell *et al.*, 1998; Ferng, 2002; Lenzen & Murray, 2001; Stöglehner, 2003).

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 & Verbruggen, 1999). In the use of appropriated world-average productivity, the original approach does not yield insights about regional impacts on land and ecosystem processes and therefore does not indicate the sustainability of regional land use (Lenzen & Murray, 2001; Rapport, 2000). Lenzen & Murray (2001) propose that the ecological footprint should be primarily concerned with *land disturbance* and that this approach would better reflect the image of a 'footprint' on land because it describes the effects of human land use on ecosystems, independent of productivity. They concede, however, that a disturbance-based approach still cannot address whether land use is practised sustainably. Nevertheless, land cover disturbance is a *contributor* to unsustainability in farming or forestry practices as it can be a precursor to soil erosion and other causes of land degradation (Graetz *et al.*, 1995). Until more detailed data are available on the unsustainability of various activities, land cover disturbance is the best indication available (compare van den Bergh & Verbruggen, 1999). For this reason, this paper uses modified Australian land types and a weighting system (land conditions C in Table 1) for these types, in order to reflect the degree of alteration of land from its natural state.

In the conventional ecological footprint, land needed for producing commodities consumed by populations is assessed in a bottom–up approach, covering only land used directly by the respective producer. Land used by suppliers of producers is not examined. In other words, the analysis is only *one production layer deep*.[1] While this approach is unproblematic at the national level, it leads to misallocation and systematic truncation errors at the component and regional levels (Lenzen & Murray, 2001; Ferng, 2002). The first authors to propose the use of input–output analysis for calculating comprehensive ecological footprints were Bicknell *et al.* (1998), who assessed the ecological footprint of the New Zealand population. Because of its intrinsic features, the input–output approach guarantees the complete coverage of upstream land and emissions requirements up to an infinite order (see section 2.2).

'Energy land' is calculated conventionally using either a 'carbon sequestration' factor (Wackernagel & 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' (W. E. Rees, personal communication, 2002). Rather than this bioproductivity measure for compensating emissions, and consistent with the disturbance-based land use approach, we consider the *projected disturbance* of terrestrial and aquatic ecosystems due to climate change and sea level rise for the incorporation of energy use and greenhouse gas emissions (including non-CO_2

TABLE 1. Weights C for land types (derived from Graetz *et al.*, 1995, Hobbs & Hopkins, 1990, Swan & Pettersson, 1998, van Dobben *et al.*, 1998, Köllner, 2000, Tab. 3 see also Lindeijer, 2000), area A affected in Australia, and resulting land disturbance $D = A \times C$

Land type	Affected area (A)	C	Disturbance (D)
CONSUMED	2.3	1.0	2.3
Built	2.3		2.3
DEGRADED	16.4	0.8	13.2
Degraded pasture	15.5		12.4
Degraded crop land	0.8		0.6
Mined land	0.2		0.1
REPLACED	101.1	0.6	60.7
Crop land	15.5		9.3
Cleared, ILZ	84.7		50.8
Non-native coniferous plantations	0.9		0.5
DISTURBED	162.8	0.4	65.2
Thinned, ILZ	47.1		18.8
Significantly disturbed, ELZ	115.2		46.1
Reversibly built	0.3		0.2
Native eucalypt plantations	0.2		0.1
PARTIALLY DISTURBED	102.1	0.2	20.4
Indeterminately disturbed, ILZ[a]	36.5		7.3
Substantially disturbed, ELZ[b]	65.6		13.1
SLIGHTLY DISTURBED	378.1	0.0	0.0
Uncleared, ILZ	85.9		0.0
Slightly disturbed, ELZ	8.3		0.0
Reserves and unused Crown Land	284.0		0.0
TOTAL	768.2		161.8

Notes: [a]Areas for which disturbance could not be assessed; [b]Disturbance below-critical for biotic erosion; C = Land condition.

gases and non-energy sources) into the ecological footprint. For doubled CO_2 equilibrium conditions, climate change scenarios (Darwin *et al.*, 1996; Intergovernmental Panel on Climate Change, 1995) yield a conversion factor of 68.5 ha/(kt $CO_2 - e/a$) (see Lenzen & Murray, 2001). Due to the substantial uncertainty in predicting impacts of climate change on land, these figures should be taken as a crude approximation. Combining present and potential future land disturbance, the ecological footprint EF is defined as a sum of areas A_i of $i = 1, \ldots, 7$ land types (6 in Table 1 plus 'emissions land') weighted with land condition factors C_i:

$$EF = \Sigma_i A_i C_i. \tag{1}$$

Finally, since the original approach was designed for national but not institutional ecological footprints, the paper follows Barrett (2001) and Simmons *et al.* (2000) and uses local (not world-average) land and emission figures in a detailed commodity approach.

2.2 Input–Output Analysis

This study employs a hybrid ecological footprint approach combining input–output analysis with an institutional audit. In this approach, the direct (on-site) land and emissions requirements of the SoP and the CSE are assessed in a detailed audit, while all remaining higher-order requirements (for materials extraction, manufacturing and services) are covered by input–output analysis. Such hybrid techniques have been applied in a number of life-cycle assessments (see Bullard *et al.*, 1978; Moskowitz & Rowe, 1985: Lave *et al.*, 1995; Treloar, 1997; Hendrickson *et al.*, 1998; Hondo & Sakai, 2000; Joshi, 2001; and Lenzen, 2001a).

Input–output analysis is a top–down economic technique which uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. Generalised input–output frameworks have been applied extensively to environmental analysis since the late 1960s (see for example Isard *et al.*, 1967; and Leontief & Ford, 1970). The result of generalised input–output analyses is a $f \times n$ matrix of *factor multipliers*—that is, embodiments of f production factors (here: land types and greenhouse gas emissions) per unit of final consumption of commodities produced by n industry sectors. A multiplier matrix $\mathbf{M}$ can be calculated from a $f \times n$ matrix $\mathbf{F}$ containing sectoral production factor usage, and from a $n \times n$ *direct requirements* matrix $\mathbf{A}$ according to

$$\mathbf{M} = \mathbf{F}\,(\mathbf{I} - \mathbf{A})^{-1} \qquad (2)$$

where, $\mathbf{I}$ is the $n \times n$ unity matrix. The $f \times 1$ land and emissions inventory $\mathbf{\Phi}$ of the SoP and the CSE ($f = 7$, 6 land types and greenhouse gas emissions) is then determined by multiplying the institution's annual operation cost (represented by a $n \times 1$ commodity inputs vector $\mathbf{y}$) with the multiplier matrix $\mathbf{M}$, and adding a $f \times 1$ vector $\mathbf{\Phi}_{\mathrm{d}}$ of direct (on-site) land and emissions

$$\mathbf{\Phi} = \mathbf{M} \times \mathbf{y} + \mathbf{\Phi}_{\mathrm{d}} \qquad (3)$$

$\mathbf{M} \times \mathbf{y}$ represents $f = 7$ indirect requirements—that is, land and emissions embodied in all inputs into the institution's operation. From the seven elements of $\mathbf{\Phi}$, land disturbance and the ecological footprint are calculated residually.

While being able to cover an infinite number of production stages in an elegant way, input–output analysis suffers from uncertainties arising from a number of areas such as source data sampling and reporting errors, assumptions about foreign industries, the assumption of proportionality between monetary and physical flow, the aggregation of input–output data over different producers and the aggregation of input–output data over different products supplied by one industry. These issues are described in a previous article (Lenzen, 2001a). The mathematical formalism used to derive equations (2) and (3) and some of the results presented in this article, is described in detail in a previous article (Lenzen, 2001b).

2.3 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 & Thorbecke, 1984) and applied in life-cycle assessment by Treloar and Lenzen (Lenzen, 2002; Treloar, 1997; Treloar *et al.*, 2000). The total factor multipliers as in equation (2) can be decomposed into contributions from structural paths, by 'unraveling' the Leontief inverse using its series expansion

$$\mathbf{F}\,(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{F} + \mathbf{FA} + \mathbf{FA}^2 + \mathbf{FA}^3 + \ldots \tag{4}$$

Expanding equation (4), indirect land and emissions requirements $M_i \times y_i$ as in equation (3) can be written as

$$\begin{aligned} M_i y_i &= y_i \sum_{j=1}^{n} F_j(\delta_{ji} + A_{ji} + (\mathbf{A}^2)_{ji} + (\mathbf{A}^3)_{ji} + \ldots) \\ &= y_i \sum_{j=1}^{n} F_j(\delta_{ji} + A_{ji} + \sum_{k=1}^{n} A_{jk}A_{ki} + \sum_{l=1}^{n}\sum_{k=1}^{n} A_{jl}A_{lk}A_{ki} + \ldots) \\ &= F_i y_i + \sum_{j=1}^{n} F_j A_{ji} y_i + \sum_{k=1}^{n} F_k \sum_{j=1}^{n} A_{kj}A_{ji}y_i + \sum_{l=1}^{n} F_l \sum_{k=1}^{n} A_{lk} \sum_{j=1}^{n} A_{kj}A_{ji}y_i + \ldots \end{aligned} \tag{5}$$

where, i, j, k, and l denote industries, and $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ otherwise. $M_i y_i$ is thus a sum over a direct factor input $F_i y_i$, 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 $F_j A_{ji} y_i$, while an input path from industry k via industry j into industry i is represented by a product $F_k A_{kj} A_{ji} y_i$, and so on. There are n input paths of first order, n^2 paths of second order and, in general, n^N paths of N^{th} order.

2.4 Data Sources and Processing

The ecological footprints of the SoP and CSE were obtained through a three-step process in which the financial data of the institutions (SoP: financial records, financial data from the University Statistics Office, records from the Facilities Management Office; CSE: financial records) were

(1) reclassified and compressed into a commodity vector **y**, corresponding to the Australian input–output product classification (IOPC, Australian Bureau of Statistics, 1999b). These were then
(2) re-evaluated from purchasers' prices to basic values (see Lenzen, 2001b); and then
(3) multiplied by emissions or land use and disturbance multipliers (**M**, equation (2)) determined from 1994/95 Australian input–output tables (Australian Bureau of Statistics, 1999a), the National Greenhouse Gas Inventory (National Greenhouse Gas Inventory Committee, 1998) and land use and condition data from various sources (see Lenzen & Murray, 2001).

This procedure yields an indirect land and emissions inventory ($\mathbf{M} \times \mathbf{y}$, see equation (3)). The on-site impact vector $\boldsymbol{\Phi}_{\mathrm{d}}$ was obtained through direct measurement of the SoP's premises and from GIS measurement of CSE's on-site land disturbance.

TABLE 2. Summary: SoP's and CSE's ecological footprints (in hectares)

	SoP	CSE
On-site	4.2	76.6
Industrial	789	1343
Total	794	1420
Land disturbance	371	620
GHG	423	800
No. of employees	116	295
EF per employee	6.8	4.8
EF per \$m spent	116.2	224.4

Note that salaries (and hence travel to work) were excluded from the institutions' input vector **y**, since expenditure from salaries is commonly assumed to be a variable exogenous to the production system—that is, benefiting the household and not producers (Herendeen, 1988, p. 262). Lough (1996, p. 135) adds to this point, that including salaries would mean that some costs are counted twice: "for a factory manufacturing TV sets, the energy cost of payroll includes the energy costs of employees' TV sets".

Finally, equation (5) was evaluated by sequential backwards scanning of the production chain tree from final demand to the various locations of production factor usage as described by Mateti & Deo (1976). The result of one execution of this algorithm for a particular production factor is a ranking of input paths for each of the n (135 in this work) sectors in terms of their contribution to the total ecological footprint.

3. Results

3.1 Ecological Footprint

The ecological footprints of the SoP and the CSE are presented in Table 2. The rows represent on-site impacts (occupied land and on-site emissions) and indirect industrial impacts, with a final breakdown of the total footprints for actual land and projected emissions land. In 1997, the total ecological footprint of the SoP was about 794 ha, whilst the CSE had an ecological footprint of about 1420 ha. However, the CSE employs 295 people, whilst the SoP has only 116 employees (on a full-time-equivalent basis and not including students) and, as a result, the SoP has a significantly larger per-employee footprint (6.8 ha) than the CSE (4.8 ha). Of these, both institutions show similar breakdowns into emissions and land disturbance, with only slightly higher footprints resulting from emissions than from land disturbance. The CSE had a considerably higher on-site footprint due to its larger site areas. Finally, since the annual expenditures of both institutions are about equal, the CSE appears to consume—on average—items that have

TABLE 3. Summary: SoP's ecological footprint according to various approaches and using various emissions-to-land conversion factors (in hectares)

Conversion factor	RWSBCL Bioproductivity 0.0163 gha/GJ[a,b]	S&al Bioproductivity 0.0163 gha/GJ[a,b]	B&al Land use 0.01 ha/GJ[b]	L&M Land disturbance 68.5ha/kt
On-site	12.0	12.0	6.1	4.2
First and second order	636.1	639.0		
All industrial		926.4[c]	1653.8	789.4
Total	648.1	938.5	1659.9	793.6
Land[d]	34.3	37.3	989.7	370.5
GHG	613.8	901.2	670.2	423.1

[a] fuelwood method.
[b] energy-related CO_2 emissions only.
[c] bioproductivity up to second order, energy-related CO_2 emissions for all orders.
[d] in terms of bioproductivity, land use or disturbance, as described in header.
Notes: RWSBCL = Rees, Wackernagel, Simmons, Barrett, Chambers, Lewis; S&al = Simpson *et al.*; B&al = Bicknell *et al.*; L&M = Lenzen and Murray; gha = global hectares.

larger specific ecological footprints than those consumed by the SoP. This will be examined in more detail in section 3.4.

For comparative purposes, the results for the SoP were also calculated according to the methods of Rees (1992), Wackernagel & Rees (1995), Simmons *et al*. (2000), Barrett (2001), Chambers & Lewis (2001),[2] Simpson *et al.* (2000) and Bicknell *et al.* (1998) (see Table 3). Rows show ecological footprint contributions for on-site activities; first- and second-order industrial requirements (which are assumed to be the limits of the approach taken by Rees, Wackernagel, Simmons, Barrett, Chambers and Lewis[3] and Simpson *et al.*[4]); all industrial requirements (as obtained by Bicknell *et al.*; and Lenzen & Murray); and the total ecological footprint, in terms of both greenhouse gases and land use/disturbance. The value of the energy/emissions-to-land conversion factor is found in the header row. Comparing the results, it becomes clear that the original ecological footprint underestimates the appropriation of land bioproductivity, as major impacts occur in third- and higher orders of production.

3.2 Breakdown into Land Types and Greenhouse Gas Emissions

As a first step in decomposing the aggregate results presented in Table 2 for use in decision-making and policy design, the footprints are broken down into the six land types, their composite land disturbance and greenhouse gas emissions (see Table 4).

Most on-site impacts are the result of the land occupied by the buildings of the institutions (SoP: 0.5 ha; CSE: 1.9 ha) and the surrounding landscaping (SoP: 2.3 ha; CSE: 122.1 ha). For the CSE, this contributes a significant amount to its total footprint (5.2% of total). The first-order impacts mostly result from

TABLE 4. Land disturbance types and greenhouse gas emissions caused by the SoP and the CSE

	Consumed land ($C=1$) (kha)	Degraded land ($C=0.8$) (kha)	Replaced land ($C=0.6$) (kha)	Significantly disturbed land ($C=0.4$) (kha)	Partially disturbed land ($C=0.2$) (kha)	Land disturbance (kha)	GHG emissions (t)
SoP							
On-site	0.5	0	2.3	0	0	1.9	34
First and second order	15.3	0.5	2.9	2.8	1.0	18.7	3626
All industrial	20.9	35.1	230.8	346.1	213.7	368.6	6142
Total	21.5	35.1	233.1	346.1	213.7	370.5	6176
CSE							
On-site	1.9	0	122.1	0	0	75.1	22
First and second order	27.3	3.8	11.0	20.0	11.8	47.4	8396
All industrial	34.5	52.5	335.7	510.3	317.0	545.4	11650
Total	36.3	52.4	457.7	510.3	317.0	620.5	11672

consumed land, with the larger components being from major airports for air transport, reservoirs for hydro-electricity and transmission lines for electricity, and are the same for both institutions. However, when all upstream requirements are taken into account, the higher-order inputs of land-intensive agricultural industries become important and the greatest land disturbance occurs in the replaced, significantly and partially disturbed land types. This is shown more quantitatively in the structural path analysis in section 3.4.

Greenhouse gas emissions differ from land disturbance in that a far greater portion of the total occurs in the first two orders. Emissions from electricity use is by far the greatest contributor for both institutions (SoP: 1561 kt; CSE: 5672 kt), although air travel (SoP: 388 kt; CSE: 718 kt) and landfill emissions (SoP: 202 kt; CSE: 339 kt) are also significant. It is remarkable that the greenhouse gas emissions of each employee caused at work are twice as high (SoP: 53.2 t; CSE: 42.6 t) as the emissions caused at home (about 26 t; Lenzen & Murray, 2001). These emissions are considerably larger than those of the University of Osnabrück (5.6 t; Viebahn & Matthies, 1999b; Viebahn, 2000b), which is partly due to the application of nuclear energy in the German power system and more efficient energy use in their buildings, but also partly due to greater completeness in the methodology employed for the CSE and SoP. In contrast, using input–output analysis, Lough (1996) arrives at about 80 t CO_2 per employee at an unspecified US state university.[5]

3.3 Decomposition into Production Layers

The graphs in Figures 1 and 2 illustrate the decomposition of land disturbance and greenhouse gas emissions, respectively, into upstream production layers via the series expansion of the Leontief inverse (see equations (4) and (5)). The difference in the site areas of the two institutions places the CSE at a higher starting position at 0th order. The discontinuity in the graph is largely a result of land-intensive third-order impacts of agricultural industries that provide goods to industries such as hospitality that attract greater expenditure from CSE than SoP.

In contrast to the decomposition of land disturbance, greenhouse gas emissions show a much more immediate convergence to system completeness, with most impacts occurring in the first few orders for both the SoP and CSE. The major components of these impacts are similar for both institutions, with electricity generation, air transport and landfill emissions being the major first-order contributors.

3.4 Structural Path Analysis

The decomposition of the land and emissions requirements into structural paths was obtained by running an extraction algorithm, evaluating equation (5). The sorted paths are presented in Table 5. The components of the path code represent

(1) the type of land disturbance (E = emissions, C = consumed, D = degraded, R = replaced, S = significantly disturbed, P = partially disturbed);

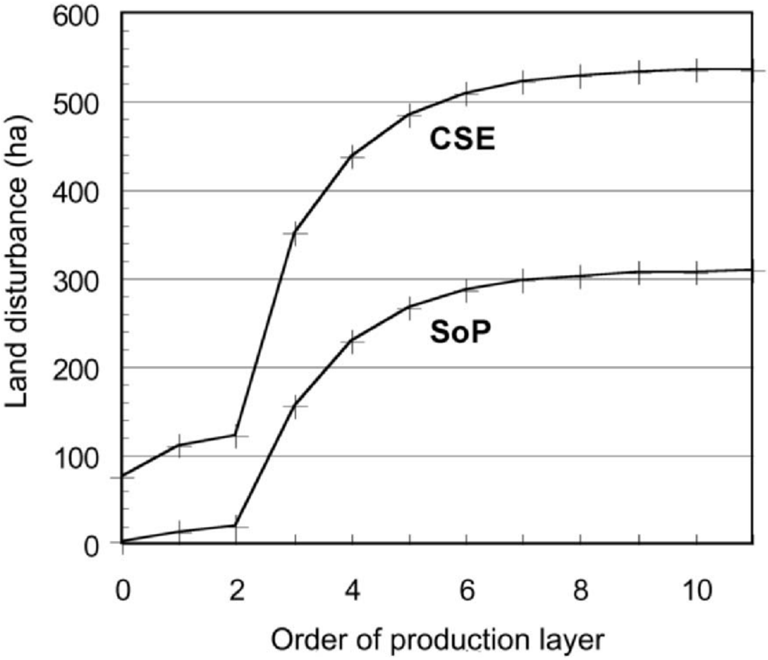

FIGURE 1. Land disturbance as a function of production layer order for the SoP and the CSE.

(2) the industries—abbreviated as in Table 6;
(3) the path order; and
(4) the path coverage, or the relative contribution of the path to the emissions or land disturbance type.

For example, the path E El En (2, 1.6%) denotes the land projected to become disturbed as a consequence of climate change, due to greenhouse gas emissions (E) caused by the production of electricity (El) that was used by the electronics industry (En) to produce goods purchased by the SoP. The path is of second order and contributes 1.6% to the total greenhouse gas emissions caused by the SoP. The path value is 6.64 ha and contributes 0.8% to the SoP's total ecological footprint. The reader should bear in mind that the values of these paths are only indicative and that the ranking's primary function is the identification and prioritisation of targets for action on environmental impact abatement (Lenzen, 2002). Hence, path values should not be interpreted as giving accurate figures for the absolute impact of the institutions along particular supply chains.

The largest path for both institutions is that of emissions from electricity generation (first-order path to power plants—SoP: 107 ha; CSE: 389 ha). This path is also high for consumed land (hydro-electricity reservoirs, transmission lines—SoP: 2.5 ha; CSE: 9.2 ha). The combined land disturbance of the electricity represents 15% of the total footprint for the SoP and 28% for the CSE. The CSE footprint is also affected by the large area of the sites it occupies (73 ha, 5.2%), unlike that of the SoP (1.4 ha, 0.2%). An immediately non-intuitive significant path for both institutions is Bc Mp Ho, ranking second, third, sixth

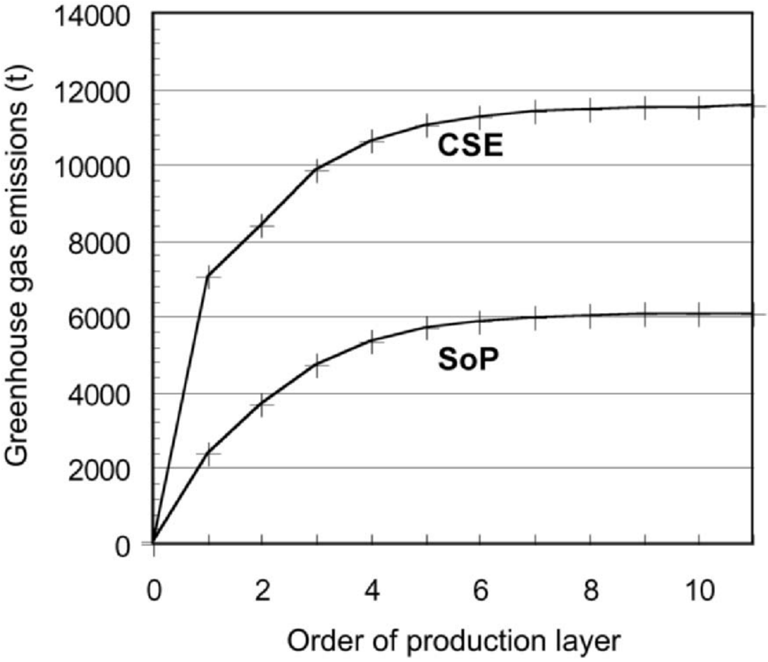

FIGURE 2. Greenhouse gas emissions caused by the SoP and the CSE, as a function of production layer order.

and seventh for the SoP for S, R, P, E land types respectively and ranking third, fifth, seventh and eighth for the CSE for the same land types. Considering that only 2.9% of the hospitality industry's inputs come from the meat industry, these paths serve to illustrate just how land-intensive beef cattle farming is in Australia. Another important path common to both institutions is air transport (SoP: E 26.5 ha, C 4.2 ha; CSE: E 49.2 ha, C 7.8 ha). The SoP also has important paths for emissions resulting from electricity for campus activities such as student administration and the running of computers and other electricity-dependent services (E El Ed 23.6 ha) and for emissions from electricity consumed in the production of electronic equipment for the SoP (E El En 6.6 ha).

Subject to methodological discrepancies, the above values are in agreement with findings for other universities. Venetoulis (2001) identified electricity consumption as the largest part (32%) of the University of Redlands' ecological footprint, followed by air travel (25%) and space heating (19%). The latter is also a substantial source of emissions at the University of Osnabrück, Germany (Viebahn & Matthies, 1999b). Similarly, Flint (2001) finds that energy use (41.9%, after subtracting private travel and food) and air travel (19.0%) significantly influence the total ecological footprint. As with the SoP and the CSE, the University of Newcastle's site is responsible for only a small impact (3.7%). Impacts of catering and meals out were also found to be of surprisingly high importance in a study of a German passenger car by Keimel *et al.* (2001).

TABLE 5. Structural path analysis of SoP's and CSE's ecological footprints (E = land-disturbance equivalent of greenhouse gas emissions; C = consumed; D = degraded; P = partially disturbed; R = replaced; S = significantly disturbed).

	Ecological Footprint SoP			Ecological Footprint CSE		
Rank	Path	Area (ha)	% of total	Path	Area (ha)	% of total
1	E E1 (1; 25.3%)	106.9	13.5%	E E1 (1; 48.6%)	388.6	27.4%
2	S Bc Mp Ho (3; 23.4%)	32.40	4.1%	R Ts (0; 26.7%)	73.23	5.2%
3	R Bc Mp Ho (3; 19.0%)	26.58	3.3%	S Bc Mp Ho (3; 27.7%)	56.61	4.0%
4	E At (1; 6.3%)	26.51	3.3%	E At (1; 6.2%)	49.19	3.5%
5	E El Ed (2; 5.6%)	23.63	3.0%	R Bc Mp Ho (3; 16.9%)	46.46	3.3%
6	E Gd (1; 3.3%)	13.77	1.7%	E Gd (1; 2.9%)	23.24	1.6%
7	P Bc Mp Ho (3; 24.0%)	10.28	1.3%	P Bc Mp Ho (3; 28.3%)	17.95	1.3%
8	E Bc Mp Ho (3; 1.6%)	6.85	0.9%	E Bc Mp Ho (3; 1.5%)	12.04	0.8%
9	E El En (2; 1.6%)	6.64	0.8%	R Ba Bm Ho (3; 3.5%)	9.75	0.7%
10	R Ba Bm Ho (3; 4.0%)	5.58	0.7%	E Bl El (2; 1.2%)	9.36	0.7%
11	E El Ho (2; 1.1%)	4.75	0.6%	C El (1; 25.2%)	9.16	0.6%
12	C At (1; 19.6%)	4.20	0.5%	E El Ho (2; 1.0%)	8.30	0.6%
13	D Bc Mp Ho (3; 13.8%)	3.92	0.5%	C At (1; 21.5%)	7.79	0.5%
14	S Wo Mp Ho (3; 2.7%)	3.72	0.5%	D Bc Mp Ho (3; 16.2%)	6.79	0.5%
15	E Rt (1; 0.6%)	2.71	0.3%	E Nb (1; 0.8%)	6.77	0.5%
16	E Wt (1; 0.6%)	2.59	0.3%	S Wo Mp Ho (3; 3.2%)	6.54	0.5%
17	E Bl El (2; 0.6%)	2.58	0.3%	S Wo (1; 2.8%)	5.62	0.4%
18	R Wo Mp Ho (3; 1.8%)	2.52	0.3%	R Wo Mp Ho (3; 1.6%)	4.43	0.3%
19	C El (1; 11.7%)	2.50	0.3%	R Wo (1; 1.4)	3.81	0.3%
20	E Nb (1; 0.6%)	2.49	0.3%	E Rt (1; 0.5%)	3.67	0.3%
21	E El Rt (2; 0.5%)	2.19	0.3%	S Wo Tx Cl (3; 1.6%)	3.25	0.2%
22	E El Cu (2; 0.4%)	1.79	0.2%	R Wh Fc Ho (3; 1.1%)	3.00	0.2%
23	R Wh Fc Ho (3; 1.2%)	1.74	0.2%	E El Ts (2; 0.4%)	2.97	0.2%
24	E Ap At (2; 0.4%)	1.53	0.2%	E El Rt (2; 0.4%)	2.97	0.2%
25	R Tsl (0; 1.0%)	1.38	0.2%	E Ap At (2; 0.4%)	2.84	0.2%
26	E Lg (0; 0.3%)	1.36	0.2%	E Is Nb (2; 0.3%)	2.73	0.2%
27	P Wo Mp Ho (3; 2.8%)	1.18	0.1%	E Wt (1; 0.3%)	2.64	0.2%
28	D Wo Mp Ho (3; 4.1%)	1.12	0.1%	E El En (2; 0.3%)	2.56	0.2%
29	R Dc Dp Ho (3; 0.8%)	1.08	0.1%	R Wo Tx Cl (3; 0.8%)	2.20	0.2%
30	S Bc Mp Ed (3; 0.7%)	1.04	0.1%	P Wo Mp Ho (3; 3.3%)	2.07	0.1%

Paper consumption (through paths for printed material and for printing services) is notably absent from the top 30 paths for each organisation. Whilst intuitively, paper may be thought to be of importance, the highest paper-using path is R Sw Pp Pr (replaced land for the growing of softwoods, supplying timber to the pulp and paper industry, which supplies paper for printing), ranking only 44th for the SoP (0.8 ha, 0.1%). This result may be explained by the increasing use of electronic equipment instead of paper as a means both of communication and for the dissemination of literature and other information, and

TABLE 6. Codes used for IOPC industry groups in the vertex descriptions in Table 5

Symbol	IOPC industry groups
Ap	Automotive petrol
At	Air and space transport
Ba	Barley, unmilled
Bc	Beef cattle
Bl	Black coal
Bm	Beer and malt
Cl	Clothing
Cu	Libraries, parks, museums and the arts
Dc	Dairy cattle and untreated whole milk
Dp	Dairy products
Ed	Education
El	Electricity supply
En	Electronic equipment, photocopying, gaming machines
Fc	Flour, cereal foods, rice, pasta and other flour mill products
Gd	Sanitary and garbage disposal services
Ho	Accommodation, cafes and restaurants
Is	Basic iron and steel, pipes, tubes, sheets, rods, bars & rails
Lg	Liquefied natural gas, liquefied natural petrol
Mp	Meat and meat products
Nb	Non-residential buildings, roads and other construction
Pd	Property developer, real estate & other property services
Rt	Retail trade
Ts	Scientific research, technical and computer services
Tx	Processed wool, textile fibres, yarns and woven fabrics
Wh	Wheat, legumes for grain, oilseeds, oats and other grains
Wo	Sheep and shorn wool

the intensive rather than extensive nature of forestry. In comparison, Flint (2001) found forest land to be 2.5% of the total footprint for the University of Newcastle. However, Flint was not able comprehensively to cover all of the consumption at the University of Newcastle and thus forest land (being included) has a relatively higher percentage.

3.5 Speed of Convergence towards System Completeness

The cumulative ecological footprint as a function of the number of extracted paths is shown in Figure 3. The value of the cumulative ecological footprint is on the vertical axis, with the total number of extracted paths counted on the horizontal. The total ecological footprint is also indicated for each institution near the right-hand border of the diagram. After extracting 15 000 paths, the system completeness for the CSE and SoP is only 65% and 56% respectively.

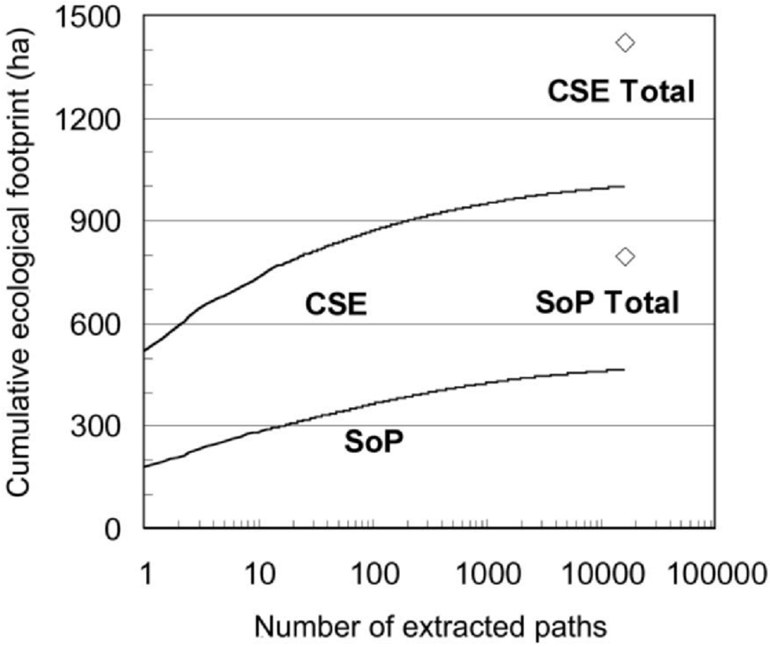

FIGURE 3. Cumulative ecological footprint by path rank.

4. Discussion

The paper has been limited by space in providing detailed results on errors, but it can be shown indicatively that the total errors of ecological footprint figures are quite low. Taking a conservative estimate of relative errors of multipliers (elements of **M** in equation (3)) of 100% and using the number of IOPC-classification entries in the account breakdown (SoP: 40; CSE: 30), the application of the common relationship for the propagation of stochastic errors yields total errors for the ecological footprints of $\Delta(EF_{\mathrm{SoP}}) \approx 100\%/\sqrt{40} \approx 16\%$ and $\Delta(EF_{\mathrm{CSE}}) \approx 100\%/\sqrt{30} \approx 18\%$. This result holds under the assumption of accurate financial data and on-site impacts, as these quantities are well known by the institutions. For a more detailed analysis of errors associated with input–output analysis, see Lenzen (2001a).

Using the structural path analysis, electricity consumption can be identified as an area most in need of address (SoP: 15% of total; CSE: 28%). Counter to intuition, CSE has a higher reliance on electricity, even though the SoP is more dependent on energy-intensive laboratories for research in areas such as plasma and high-energy physics. This implies that a large proportion of electricity use is in fact conventional electronic equipment such as lights, computers and photocopiers, although some of the difference would be attributable to the mitigation of greater climatic variations experienced by CSE. As it is common in many institutions for computers and lights to be left on when not in use, this is an area that could be easily investigated further as a means to reduce resource wastage. Another option would be the installation of energy-saving globes and devices on the replacement of existing fluorescent tubes, or the sourcing of green power.

Whilst the structural path analysis also identifies hospitality as having large emissions and land disturbance impacts occurring through the provision of meat products, the land disturbance impacts may be slightly inflated due to the nature of the Australian cattle industry. This is because exported beef products are largely sourced from grazing pastures in Queensland, where cattle farming disturbs a larger area per head of cattle than in the southern part of Australia which, in general, supplies the domestic beef industry. Thus future work in regionalising data would result in a reduction in the areas disturbed by the institutions.

High-ranking emissions from landfills (Gd) (sixth) for both institutions, may also be partly artificial, as the institutions studied have only a small organic waste content in their garbage, compared with the national average. This inflates their emissions, as it is organic waste that is the most significant contributor of greenhouse gas emissions from the anoxic decay in landfills.

Expenditure on travel costs is an area of potential review. Air travel alone accounts for a significant percentage of the institutions' footprints (SoP: 3.8%; ranking E fourth, C 12th; CSE 4%, ranking E fourth, C 13th). Because Australia is a large and also an isolated country, air travel is often the only viable form of transport but, over shorter distances, other less resource-intensive modes such as bus or railway could be utilised to a greater extent.

The site area of the CSE (73 ha of replaced land) is another area that could come under scrutiny. Ranking second in the structural path analysis, this area could be used, for example, to mitigate the institution's greenhouse gas emissions by re-establishing native vegetation on the site.

An important result from this study is the weight of the footprint occurring in obscure paths and at higher-order production layers. After emissions from electricity, which are by far the most important contributor, there were only six other paths for each institution contributing more than 1% to the respective total footprints. Coupled with the result that counting 15 000 paths only represented 56% of the SoP and 65% of the CSE totals, the analysis constitutes a strong case for the use of input–output analysis, which covers infinite paths of industrial transactions automatically, compared with process- and audit-type methods, which involve manual tracing of paths. The number of paths which practitioners can reasonably follow is limited by available human, time and financial resources, and will usually be smaller than a few thousand. Thus, the speed of convergence presented in Figure 3 is testament to shortcomings inherent in process analysis.

Thus, these results question the completeness of ecological footprints calculated according to the original approach applied to institutions such as the Anglian Water Group (2001) or the company Best Foot Forward (Chambers & Lewis, 2001), as well as to cities (Santiago de Chile; Wackernagel, 1998) and regions (Malmöhus county, Sweden; Wackernagel *et al.*, 1999). Similarly, ecological footprint calculators for household and office (Best Foot Forward, 2001; Redefining Progress, 2001; Simmons & Chambers, 1998) based on the initial method are likely to underestimate the true environmental impact. This finding is independent of whether appropriated bioproductivity or land disturbance is the quantity under consideration.

5. Conclusions

In this study, a comprehensive picture was obtained by applying input–output analysis to the ecological footprint methodology. As a result, the School of Physics at the University of Sydney has been found to cause about 794 ha of land disturbance (including emissions), whilst the Sustainable Ecosystems Department of the CSIRO caused about 1420 ha of land disturbance (including emissions). A significant result of this study was the importance of conducting an holistic assessment in order to capture all contributing industrial paths into the final impact of an institution. If only a limited number of contributions are considered, a serious underestimation of the ecological footprint is likely to occur, thus resulting in a picture of the institution's impacts and flows that is far from comprehensive.

As Viebahn (2000b) and Viebahn & Matthies (1999a, 2000a) emphasise, the assessment of an institution's environmental pressure—whether in terms of the ecological footprint or another set of indicators—should ideally serve a number of purposes. It should

(1) provide a comprehensive picture of the institution's impact and present material and energy flows in a transparent way;
(2) suggest ways in which the institution's organisational structure can be optimised in order to increase the efficiency of an EMS, especially in view of lacking environmental regulations and economic incentives;
(3) highlight areas where environmental abatement is accompanied by cost reductions ('no-regret measures');
(4) generate internal environmental guidelines, benchmarks and an action programme, while guaranteeing adherence to external environmental regulations;
(5) lead to the implementation of an environmental information system, instructive staff education and regular environmental reporting;
(6) support effective public relations work and marketing; and
(7) foster staff motivation, communication and involvement.

Most aspects in points 2–7 are not addressed in this article, partly because of limitations in space and partly because this work has a methodological focus. Nevertheless, shortcomings in conventional assessments of environmental impacts (point 1) such as outlined in this work could significantly flaw the basis for subsequent action on points 2–7.

The incorporation of this work into a time series of an institution's operation, with an environmental management plan such as outlined by Viebahn above, would serve as an interesting future application of this methodology and would give valuable insight into the effectiveness of such a management plan on the less sizeable paths that are nonetheless a significant component of the institution's impact.

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Notes

[1] Barrett (2001) and Simmons *et al*. (2000) examine regional, component-based ecological footprints using local data and considering some upstream impacts such as from car manufacturing. The present authors, however, were unable to determine the boundary conditions of their life-cycle approach and hence the degree of completeness of the figures.

[2] The original fuelwood-equivalent approach is used for converting energy into land.

[3] See note 1.

[4] Except for CO_2 emissions, which are assessed using input–output analysis.

[5] The emissions value was converted from Lough's 'operations and maintenance' energy figure via 1080×10^6 Btu/employee $\times$ 1055 GJ/10^6 Btu $\times$ 0.07 t CO_2/GJ. The latter CO_2 coefficient was taken from Kreith *et al*. (1990).

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