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A comparative study of some environmental impacts of conventional and organic farming in Australia

Richard Wood [a], Manfred Lenzen [a], Christopher Dey [a,*], Sven Lundie [b]

[a] *School of Physics, A28, The University of Sydney, Sydney, NSW 2006, Australia*
[b] *Centre for Water and Waste Technology, School of Civil and Environmental Engineering, University of New South Wales, Kensington, NSW 2060, Australia*

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Abstract

The provision of food causes environmental impacts that range from local through to global in scale. Organic farming, used in general here to mean farming practices with a greater emphasis on long-term sustainability, is one general approach to reduce these impacts. Whilst organic farming may be argued to be superior to conventional farming on the basis of local impacts, it is not often clear how organic farming performs relative to conventional farming in terms of wider, global impacts. In this paper we present a comparative assessment of on-farm and indirect energy consumption, land disturbance, water use, employment, and emissions of greenhouse gases, NO_x, and SO_2 of organic and conventional farming in Australia. A hybrid input-output-based life-cycle technique is employed in order to ensure a complete coverage of indirect requirements originating from all upstream production stages. Using data from a detailed survey of organic farms, the results show that direct energy use, energy related emissions, and greenhouse gas emissions are higher for the organic farming sample than for a comparable conventional farm sample. Direct water use and employment are significantly lower for the organic farms than for the conventional farms. However, the indirect contributions for all factors are much higher for the conventional farms, leading to their total impacts

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[*] Corresponding author. Tel.: +61 2 9351 5979; fax: +61 2 9351 7726.
E-mail address: c.dey@physics.usyd.edu.au (C. Dey).

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being substantially higher. This shows that indirect effects must be taken into account in the consideration of the environmental consequences of farming, in particular for energy use and greenhouse gas emissions, where the majority of impacts usually occur off-farm. Subject to yield uncertainties for organic versus conventional farming, from the sample here we can conclude that in addition to their local benefits, organic farming approaches can reduce the total water, energy and greenhouse gases involved in food production.

Keywords: Organic farming; Environmental impact; Input-output analysis; Structural path analysis; Agricultural energy use

1. Introduction

In many parts of the world, agriculture causes environmental pressure that is significant on national scales. This is particularly true in terms of land degradation, water use and greenhouse gas emissions. Amongst the most prominent impacts of agriculture on the global environment are (Pimentel, 1994; Kendall and Pimentel, 1994):

- during the past 40 years almost one third of the world's cropland has been abandoned because of erosion and degradation,
- agriculture accounts for 80% of deforestation, and
- 40% of the world's population live in regions where water resources are overdrafted and stressed, and where users compete for water.

An often-cited aspect of the global agriculture-environment nexus is that the largest environmental impacts are associated with non-rangeland livestock production, which is also the most inefficient way to convert resources into food (Pimentel et al., 1975, 1980; Goodland, 1997). The increase of environmental pressure from agriculture is unlikely to reverse in the near future, since the world population continues to increase faster than global food supply, and diets continue to shift towards animal products (Goodland, 1997; Pimentel, 1994; Kendall and Pimentel, 1994). This so-called "livestock revolution" is projected to involve meat consumption in developing countries increasing by nearly 3% per year to at least 2020 (IFPRI, 1999).

1.1. Energy for agriculture in the food supply system

Agriculture is only the first stage of the food supply system: the post-harvest system includes processing, distribution (transport and storage) and preparation. It is interesting to obtain a perspective of the importance of these stages in terms of primary energy consumed directly during the various activities. Depending on the degree of regional processing and different cooking efficiencies, agriculture represents between 20% and 50% of the energy consumed in the whole supply chain (see Table 1). In developed countries agriculture comprises on average about 25% of the direct

Table 1
Estimates of the share of different stages in the direct energy requirement of the food supply chain (%)

	Agriculture	Processing	Distribution	Preparation	References
Africa	21	8	3	69	Parikh and Syed, 1986[a]
Latin America	42	18	5	36	Parikh and Syed, 1986[a]
Middle East	50	6	3	41	Parikh and Syed, 1986[a]
Far East	30	13	3	55	Parikh and Syed, 1986[a]
USA	24	27	23	25	Steinhart and Steinhart, 1974
USA	24	39	[b]	37	Cambel and Warder, 1976
USA	22	36	10	32	Fluck and Baird, 1980
USA	31	14	24	31	Organisation for Economic Co-operation and Development, 1982
Australia	25	21[c]	17[d]	38[e]	Watt, 1979
Australia	29	26	10	35	Organisation for Economic Co-operation and Development, 1982
UK	21	31	12	35	
Canada	18	32	20	30	
UK	38	27	8	27	Leach, 1976
OECD	29	29	18	24	Organisation for Economic Co-operation and Development, 1982[a]

[a] End-use energy, not primary.

[b] Included in processing.

[c] Consists of 24% packaging, 11% buildings and equipment, 17% transport and 48% energy use.

[d] 6% Packaging, 7% buildings and equipment, 7% transport and 80% energy use.

[e] 55% Refrigerators, 34% stoves, 8% other appliances and 4% transport.

energy requirement. There is also a general long-term trend towards using more energy to provide food, although there are notable exceptions and caveats. Schroll (1994) shows that total energy per hectare for Danish agriculture increased steadily between the 1940s and 1990. This was also observed as a decrease in the output/input energy ratio. Similar results were found by Ozkan et al. (2004a) for Turkish agriculture between 1975 and 2000. From 1940 to the mid-1970s, fuel-to-food energy ratio in the US almost doubled, while the labour-to-food ratio has declined four-fold (Steinhart and Steinhart, 1974; Cambel and Warder, 1976). In contrast, from about 1977 the energy intensity of French agriculture has *decreased*, particularly for large-scale wheat production, representing a departure from a general increasing trend in France since 1959 (Bonny, 1993). Similar behaviour in the US has been noted, with total energy use for agriculture peaking in about 1980, then declining (Cleveland, 1995).

1.2. Life-cycle analysis (LCA) of agriculture

As is evident from some of the trends discussed above, the oil price shocks of the 1970s were of great importance for agriculture and triggered a number of investigations of the energy intensity of conventional farming, and organic alternatives (Pimentel et al., 1973; Steinhart and Steinhart, 1974). Most of these studies restrict themselves to primary energy used on the farm. However, as well as impacts arising directly out of on-farm activities, agriculture also causes environmental pressure indirectly through the usage of goods and services for farm operations. The provision of these goods and services entails resource use and pollutant emissions in industries that are located "upstream" of agriculture in economies, such as power plants, chemical and steel making plants, etc. These resources and pollutants are called *indirect requirements*. In addition to overall *impacts*, indirect effects also indicate the potential *susceptibility* of agricultural operations with regard to resource shortages, price increases, or environmental taxes.

Many studies on agriculture have aimed at incorporating a limited range of indirect effects, particularly in terms of energy. However, in most cases, a *process analysis* is applied, which covers usually one, but at most two or three production stages (supplier levels) upstream of the farm (see for example Pimentel, 1980; Gifford, 1984; Cowell and Clift, 1997; Klepper et al., 1977; Singh, 1992; Carlsson-Kanyama, 1998; Carlsson-Kanyama et al., 2003; Geier and Köpke, 1998; Refsgaard et al., 1998; Cederberg and Mattsson, 2000). Typically, only obvious inputs such as fertilisers, pesticides, irrigation and machinery are included in such studies. However, farms also require insurance, financial services, repairs and maintenance, veterinary and other services, and so on (see Fluck and Baird, 1980, p. 59–60). It has been demonstrated in a number of comparative studies that the omission of higher production stages in process analyses causes a systematic error that is due to the truncation of the production system by a finite boundary, and that this error can be in the order of 50% (Suh et al., 2004). Furthermore, the degree of incompleteness in process analyses varies considerably (Fluck and Baird, 1980), so that results are often not even comparable.

In this work we employ input–output analysis in order to ensure a complete coverage of indirect requirements originating from all upstream production stages. This technique has been applied extensively for energy analysis of agriculture to within-farm energy flows by Zucchetto and Bickle (1984), to energy required for US agriculture by Cleveland (1995), to Swiss agriculture by Kytzia et al. (2004), to Swedish agriculture by Uhlin (1998), and to energy in Turkish agriculture by Ozkan et al. (2004a,b) and Karkacier and Goktolga (2005), for example.

Most previous agricultural studies, when applying input–output analysis to environmental factors, are restricted to the analysis of energy issues, or, when considering more factors, usually employ process analysis. Gerbens-Leenes et al. (2003) give a good overview of indicators for environmental sustainability in food production, from local to region to global scale. They propose a method for sustainability measurement using basic indicators for land use, water use and energy use that combine the on-site (corporate) impacts of farms with shared responsibility of the impacts in the (corporate) supply chain that is part of the wider food production system.

In this paper we present an input–output analysis of energy consumption, land disturbance, water use, employment, and emissions of greenhouse gases, NO_x, and SO_2 of some organic farms and comparable conventional farming in Australia. We focus on the indirect, off-farm generation of environmental pressure through farm operations. The novelty and significance of this work lies in its comprehensive perspective: while some of the advantages of organic farming on a local and regional scale have been documented (e.g. for soil quality – Reganold et al., 2001, biodiversity

– Hole et al., 2005, and general environmental performance – Pacini et al., 2003), global impacts, for example on climate change or general resource depletion, are less often examined. One recent study was of the energy and greenhouse gas emissions from sugar beet production in the UK (Tzilivakis et al., 2005). Twelve variations of conventional and one organic production system were compared. In terms of the energy requirement, an analysis that did include some indirect energy use, the organic farm performed worse (in part because of the extra distance that the organic beet had to transported to the factory). In terms of contribution to climate change (tonnes of CO_2-e per ha of beet grown) the organic option was better than about two-thirds of the conventional farms.

Clearly there are many factors influencing the relative performance of organic versus conventional farming, particularly in terms of global impacts such as greenhouse gas emissions. Without rigourous calculations of both direct and indirect effects, incorrect conclusions may be drawn. The paper is organised as follows: Section 2 outlines the methods (survey and input–output analysis) used to obtain the results, which are described in Section 3. Conclusions are then drawn in Section 4.

2. Methods

2.1. Survey design

The goal of the survey was to obtain quantitative information on all direct and indirect inputs of some Australian organic farms. The survey design included the selection of the sample, choice of survey methodology, creation of the questionnaire, the survey itself and analysis of survey data. For this survey a two-stage method was employed, in line with previous surveys carried out in the context of determining societal values on environmental impacts (Lindeÿer, 1996; Walz et al., 1996). The first survey asked for information on the overall physical characteristics of the farm, the products, and the labour force, as well as for a detailed breakdown of the typical expenditure of the farm in categories consistent with the Australian input–output tables. It was sent out to 105 organic farmers, of whom 15 responded.

Because of feedback from farmers about the first survey, in particular in relation to the detail and relevance of the questions, the second stage was refined in three ways. First, a more detailed introduction and covering letter were included to make clear the motivations of the study and the background to the work. Second, a short qualitative survey was included that attempted to gauge the relative importance of different environmental issues for organic farmers. Third, the quantitative part of the survey was reduced in size slightly from the first survey. The second round of surveys was sent to the organic farmers who did not reply to the first survey, and a further 93 farmers from the National Association of Sustainable Agriculture Australia survey database. In the second round 35 responses were received. The overall response rate was approximately 25% (50 of 198).

From the 50 responses, 21 were not used for quantitative analysis, as they either did not contain comprehensive data of all inputs and outputs of the farm, or did not report any output for the year (often because of being in organic conversion). Thus, there were 29 high-quality responses to the quantitative surveys, the data of which are used in the analysis reported here. These responses represent about 1.5% of the 2000-odd organic farms in Australia at the time of the survey, which are also about 1.5% of the total number of Australian farms (Kondinin Group, 2000; DAFF, 2005). The 29 farms for which quality data were obtained range in annual output in monetary terms from AUS$ 5000 to AUS$ 580,000, and covered such diverse agricultural types as organic egg production to large-scale grazing to a wide variety of fruit and vegetable horticulture. Of the 29 farms, 17 were primarily producing fruit, four vegetables, one purely free-range eggs, one purely field crops, three a mixture of field crops and livestock, two sheep and cattle, and one purely cattle. Six of these farms were located in Queensland, a further six in Victoria, five in New South Wales, two each in South Australia, the Northern Territory and Tasmania, and one in Western Australia. The location of the remainder of the farms is unknown. Only one farm was located in the extensive land use zone (ELZ), which covers roughly two-thirds of the Australian continent but which has only low pressures from grazing and clearing (Graetz et al., 1995). On average, the farms had been following organic practices for 8.5 years, but ranged between 33 years, and less than one year of certification.

Whilst the sample size of this study is not large, this is due to the immature nature of the organic farming industry in Australia. With such a small sample, comparisons between an average organic farm and an average conventional farm are not possible. However, because of the nature of this study, in which the calculation of environmental inputs required to produce a unit of output was the focus, it is appropriate to aggregate the survey data to produce a hypothetical mixed-produce organic farm (for brevity, hereafter called "the organic farm"). A comparative hypothetical conventional farm ("the conventional farm") was then constructed with the same output as the organic farm. The input ratio for the output mix of the conventional farm was extracted from the Australian input–output tables to give comprehensive Australian average data. Thus two data sets were used in the comparison, the first being the average input–output ratio across all produce of the surveyed organic farms, and the second being the input–output ratio for Australian average agriculture. Thus, in the aggregate organic farm we rely on the variations in the general organic farm sample (of different farm types) to produce results that can be better-compared with the average (conventional) farm. Financial rather than physical characteristics were chosen as the means of output comparison so as to capture the greater value embodied in organic produce (assumed to be due to the premium prices consumers are prepared to pay for the claimed lower chemical content and higher content of some nutrients). Findings are thus reported as impact per $ or million-$ of output.

2.2. Input–output analysis

We employ a hybrid LCA approach combining input-output and process analysis. In this approach, the direct factor requirements (for farm operations) are assessed in a detailed process analysis based on the survey described in the previous section, while remaining indirect requirements (e.g. for materials extraction, manufacturing, and services) are covered by input–output analysis. In this way, the advantages of both analysis techniques, completeness and specificity, are combined. Moreover, the selection of a boundary for the production system becomes obsolete (compare Suh et al. (2004), and for agricultural systems, Uhlin (1998) and Tellarini and Caporali (2000)).

Input–output analysis is a top-down economic technique that uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies. The result of generalised input–output analyses is a $f \times n$ matrix of *factor multipliers*, that is, embodiments of f production factors (such as water, labour, energy, resources and pollutants) per unit of final consumption of commodities produced by n industry sectors. A multiplier matrix $\mathbf{M}$ is 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

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

where $\mathbf{I}$ is the $n \times n$ unity matrix. $\mathbf{A}$ comprises requirements from current as well as capital intermediate demand of domestically produced and imported commodities.

The $f \times 1$ *factor inventory* $\mathbf{\Phi}$ of a given functional unit (for example the operation of a farm) represented by a $n \times 1$ commodity inputs vector $\mathbf{y}$ and a $f \times 1$ vector $\mathbf{\Phi}_{\mathrm{d}}$ of direct factor usages is then simply

$$\mathbf{\Phi} = \mathbf{M}\mathbf{y} + \mathbf{\Phi}_{\mathrm{d}}. \tag{2}$$

$\mathbf{M}$, $\mathbf{y}$ represents the indirect usage of factors embodied in all inputs into the functional unit. Note that in agreement with previous studies (for example Cleveland, 1995; Refsgaard et al., 1998 and Herendeen, 1988), human labour is excluded from $\mathbf{y}$, and hence $\mathbf{\Phi}$ neither includes metabolic energy nor the employment of family members. Similarly, solar energy is excluded from energy requirements, since only non-biological energy use is at present able to be consistently accounted in a way that is useful for decision-making (compare Jones, 1989, p. 345, who discusses the eMergy concepts developed by Odum, 1984). We recognise the importance of ecosystem energy flows compared with fossil energy flows, but at the moment there are difficulties in combining these two viewpoints.

An introduction into the input–output method and its application to environmental problems can be found in papers by Leontief and Ford (1970) and Proops (1977). Fluck (1992) summarises the principles of input–output analysis applied to agriculture. The mathematical formalism used to derive Eqs. (1) and (2) and some of the results presented here are described in detail in a previous paper (Lenzen, 2001a).

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 and Thorbecke, 1984), and applied in life-cycle assessment by Treloar and Lenzen (Treloar, 1997; Treloar et al., 2000; Lenzen, 2001b). The total factor multipliers as in Eq. (2) can be decomposed into contributions from structural paths, by "unraveling" the Leontief inverse using its series expansion

$$\mathbf{F}(\mathbf{I}-\mathbf{A})^{-1} = \mathbf{F} + \mathbf{FA} + \mathbf{FA}^2 + \mathbf{FA}^3 + \cdots. \tag{3}$$

Expanding Eq. (3), for indirect requirements in terms of factor usages $M_i \times y_i$ as in Eq. (2) can be written as

$$\begin{aligned} M_i y_i &= y_i \sum_{j=1}^{n} F_j(\delta_{ji} + A_{ji} + (\mathbf{A}^2)_{ji} + (\mathbf{A}^3)_{ji} + \cdots) \\ &= y_i \sum_{j=1}^{n} F_j\left(\delta_{ji} + A_{ji} + \sum_{k=1}^{n} A_{jk}A_{ki} + \sum_{l=1}^{n}\sum_{k=1}^{n} A_{jl}A_{lk}A_{ki} + \cdots\right) \\ &= F_i y_i + \sum_{j=1}^{n} F_j A_{ji} y_i + \sum_{k=1}^{n} F_k \sum_{j=1}^{n} A_{kj}A_{ji}y_i + \sum_{l=1}^{n} F_l \sum_{k=1}^{n} A_{lk} \sum_{j=1}^{n} A_{kj}A_{ji}y_i + \cdots, \end{aligned} \tag{4}$$

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 Nth order. An index pair (ij) shall be referred to as a *vertex*.

2.4. Uncertainties

The results of this comparative study are limited to organic farms with the particular characteristics of the survey sample. We have not made an attempt to evaluate the representativeness of this sample for organic farming in general, and the variability of production methods within organic farming. The results are also based entirely on the farmers' responses, assessments and perceptions; no independent measurements were made of environmental and economic quantities. Moreover, since organic farms constitute a small fraction of all Australian farms, and since we compute average rather than marginal resource use quantities under fixed-price conditions, the results presented below do not describe resource pressure changes that would arise from substantial switching to organic practices. Nevertheless, the results give an indication of major trends that would occur if organic farming became more widespread (compare Lockeretz et al., 1981, p. 541).

Major sources of uncertainty in the surveys include discrepancies between (1) the total reported cost and the breakdown of the cost, and (2) the base year of the input–output framework and the farm data. Cost differences (1) were covered by extrapolating conventional inputs, excluding chemicals and fertiliser inputs. As the year of reference was 1994–1995, surveys that reported figures for different years were adjusted by applying consumer price indices.

In addition to survey-related uncertainties, there are a number of methodological shortcomings. While being able to cover an infinite number of production stages in an elegant way, input-output analysis suffers from uncertainties arising from the following sources: (1) uncertainties of basic source data due to sampling and reporting errors, (2) uncertainties resulting from the assumption made in single-region input–output models, that foreign industries producing competing imports exhibit the same factor multipliers as domestic industries, (3) the assumption that foreign industries are perfectly homogeneous, (4) the estimation of flow tables for domestically produced and imported capital commodities, (5) the assumption of proportionality between monetary and physical flow, (6) the aggregation of input–output data over different producers, (7) the aggregation of input–output data over different products supplied by one industry, and (8) the truncation of the "gate-to-grave" component of the full life cycle. Error source (7) especially applies to agriculture, because many farms produce a commodity mix, and because the degree of specialisation and vertical integration varies considerably. As a consequence, quite diverse transactions become aggregated in intra-sector transactions of the respective input–output table (Fox, 1963).

Standard errors ΔM_{ij} of elements in the multiplier matrix $\mathbf{M}$ due to the above sources defy analytical treatment, and can therefore only be determined using stochastic analysis. The ΔM_{ij} as used in this work were calculated by Monte–Carlo simulations of the propagation of numerical perturbations from $\mathbf{F}$ and $\mathbf{A}$ through to $\mathbf{M}$. The application of this technique to Australian data is described in detail in a previous article (Lenzen, 2001b). Given the standard errors ΔM_{ij}, and the standard errors Δy_j and $\Delta\Phi_{d,i}$ of $\mathbf{y}$ and $\mathbf{\Phi}_\mathrm{d}$, the total standard error $\Delta\Phi_i$ of an element in the factor inventory vector $\mathbf{\Phi}$ is

$$\Delta\Phi_i = \sqrt{\sum_{k=1}^{n}(y_k\Delta M_{ik})^2 + \sum_{k=1}^{n}(M_{ik}\Delta y_k)^2 + \Delta\Phi_{\mathrm{d},i}^2}\,. \tag{5}$$

It should be emphasised that, in our input–output-based LCA, the standard errors ΔM_{ij}, Δy_j, and $\Delta\ \Phi_{\mathrm{d},i}$ are stochastic. This feature enables the total standard error $\Delta\Phi_i$ to decrease with increasing number of non-zero entries in $\mathbf{y}$, that is, with increasing detail of the breakdown of the inputs into the farms. This can be seen as follows: let $\Phi_{\mathrm{d},i} \ll \Phi$, and y_j, $j = 1, \ldots, m$ be m non-zero entries in $\mathbf{y}$, so that for factor i

$$\Phi_i \approx \sum_{k=1}^{m} M_{ik}y_k. \tag{6}$$

Let all y_k, M_{ik}, Δy_k, and ΔM_{ik} be approximately of the same order, that is

$$y_k \approx \bar{y}, \quad M_{ik} \approx \overline{M_i}, \quad \Delta y_k \approx \overline{\Delta y}, \quad \text{and} \quad \Delta M_{ik} \approx \overline{\Delta M_i}\forall k = 1, \ldots, m. \tag{7}$$

The relative standard error $\Delta\Phi_i/\Phi_i$ of Φ_i is then

$$\frac{\Delta\Phi_i}{\Phi_i} \approx \frac{\sqrt{\sum_{k=1}^{m}(y_k\Delta M_{ik})^2 + \sum_{k=1}^{m}(M_{ik}\Delta y_k)^2}}{\sum_{k=1}^{m} M_{ik}y_k} \approx \sqrt{\frac{m(\overline{y}\overline{\Delta M_i})^2 + m(\overline{\Delta y}\overline{M_i})^2}{(m\overline{y}\overline{M_i})^2}}$$
$$= \frac{1}{\sqrt{m}}\sqrt{\left(\frac{\overline{\Delta M_i}}{\overline{M_i}}\right)^2 + \left(\frac{\overline{\Delta y}}{\overline{y}}\right)^2}. \tag{8}$$

In order to minimise the relative standard error of the factor inventory, it is therefore important to (1) obtain a breakdown of the farm inputs that is as detailed as possible (large m), and (2) obtain important direct factor inputs with low relative standard errors $\Delta\Phi_{d,i}/\Phi_{d,i}$. Note that in conventional, process-type LCA, strategy (1) is not applicable, because process-type multipliers carry systematic errors due to the truncation of the system boundary (see Suh et al., 2004). For these non-stochastic errors, a decrease in the overall error with increasing detail does not occur.

2.5. Data sources

This study assesses environmental pressures in terms of the factors of energy, land disturbance, water use, employment, and emissions of greenhouse gases, NO_x, and SO_2. The term ‘land disturbance’ aims at describing impacts of human activity on land, rather than simply area of use. The idea is to group land use into disturbance classes that are quantified by a land condition factor between 0 and 1, which in turn is based on vegetation coverage, species diversity, and bioproductivity. A measure of land disturbance in units of hectares (ha) can be obtained by a weighted sum containing products of the affected area and the respective land condition factor (for further information see Lenzen and Murray, 2001). This selection of factors is based purely on data availability and quality, and does not necessarily reflect the societal importance of environmental and health impacts, or appropriate life-cycle features of agricultural systems (for a review of life-cycle impact categories for agriculture see Haas et al., 2000). Nevertheless, land disturbance, water use, and greenhouse gas emissions are among the most crucial environmental factors in the case of Australia (Whetton et al., 1993; Glanznig, 1995; Murray-Darling Basin Ministerial Council, 1995), and for agriculture in general (Kendall and Pimentel, 1994).

Elements in **F** containing sectoral production factor usage were obtained partly from well-documented sources such as the National Greenhouse Gas Inventory (National Greenhouse Gas Inventory Committee, 1998), energy statistics (Australian Bureau of Agricultural and Resource Economics, 1997a), employment statistics in full time employment equivalent years (emp-y) (Australian Bureau of Statistics, 1999) and water accounts (Australian Bureau of Statistics, 2000a). Further sectoral disaggregation was achieved by using supplementary reports (Wilkenfeld and Associates Pty Ltd, 1998) and unpublished estimates on these factors (Australian Bureau of Agricultural and Resource Economics, 1997b; Australian Bureau of Agricultural and Resource Economics, 1999; Australian Bureau of Statistics, 2000b). However, no comprehensive data exist for Australian land use, let alone land disturbance, so that a range of disparate sources had to be used (Lenzen and Murray, 2001).

Emissions of CH_4 from enteric fermentation in animals as well as emissions of N_2O from soil processes and fertilisers were excluded from the greenhouse gas calculations because of their dependence on feeding strategies and subsequent high variability (compare Lewis et al., 1999; Cederberg and Mattsson, 2000).

3. Results

3.1. Direct and indirect impacts

The environmental and employment impacts of the aggregate organic farm, and its conventional equivalent, are presented in Table 2. The columns represent on-site impacts (including land, water, labour and fuels used); first-order requirements for the farm (e.g. electricity, products and services used on the farm); impacts from further upstream production stages of farm inputs; and total impacts, respectively. Figures are expressed as intensities (per Australian $ or $m of output).

On-site energy requirements were found to be slightly higher for organic farming (org 2.2 MJ/A$, conv 1.8 MJ/A, and are largely due to the use of diesel and petrol products on the farm. The higher on-site energy use on the organic farm is probably related to weed control, manure spreading and the lower employment intensity. The replacement of herbicides requires more frequent physical cultivation, particularly in the transition to organic farming. The results are consistent with Tzilivakis et al.,

Table 2
Summary of on-site, indirect and total factor intensities (physical factor per Australian dollar or million Australian dollar A$m) for the aggregate organic and conventional farm

	Units	Organic farm				Conventional farm			
		On-site	Indirect		Total	On-site	Indirect		Total
			1st Order	Higher-order			1st Order	Higher-order	
Energy intensity	MJ/A$	2.2	2.6	4.0	8.8	1.8	3.7	8.3	13.8
Greenhouse gas intensity	kg/A$	0.2	0.2	0.5	0.9	0.1	0.8	1.0	1.9
Water intensity	L/A$	22.4	1.9	22.5	46.8	149.2	14.0	57.7	220.9
Land dist. intensity	kha/A$m	3.9	0.0	0.0	4.0	4.1	0.2	0.1	4.5
NO_x intensity	g/A$	1.0	1.3	1.8	4.0	0.7	1.8	3.6	6.1
SO_2 intensity	g/A$	0.2	0.4	1.7	2.3	0.1	0.4	3.6	4.2
Employment intensity	emp-y/A$m	9.7	2.3	4.5	16.5	12.6	4.7	8.9	26.3

All units of the factors are standard, except perhaps kilo-hectares (kha) for land disturbance and full-time equivalent employment-years (emp-y).

2005, Table 2; Flessa et al., 2002, Table 5; Clements et al., 1995, Table 5; Lal, 2004, Table 8. However, as higher orders of input are explored (see Section 3.3), the conventional farm requires greater indirect energy (13.8 MJ/A$ total energy intensity) than the organic farm (8.8 MJ/A$). This result is also reflected in the greenhouse gas, NO_x, and SO_2 intensities. Whilst the constituents of these intensities will be explored later, the divergence of the intensities is mainly due to the conventional farm being more dependent on products with high indirect energy requirements, such as machinery, fertilisers, chemicals and pesticides. An advantage of organic farms in terms of overall energy requirements has also been reported by Klepper et al. (1977) for corn and soybean production in the US Midwest, by Pimentel (1993) for US maize production, by Refsgaard et al. (1998) for Danish dairy farms, by Cederberg and Mattsson (2000) and Uhlin (1998) for Swedish dairy farms, by Haas et al. (1995, 2001) for German mixed farms, by Reganold et al. (2001) for apple production, by Mäder et al. (2002) for Swiss wheat, grass-clover and potato production, and by Kytzia et al. (2004) for Swiss agriculture in general (see Fig. 4 for an international comparison of the distribution of energy requirements).

Of note from Table 2 is the considerable difference in water dependence, with conventional farms using 149 L/A$ on-site, over six times more than that of organic farms (22 L/A$). This may be a result of the accumulation of a number of factors, including the lower grazing and cropping concentration of organic farming, resulting in a greater catchment area per tonne of crops; and/or a philosophy apparent amongst organic farmers of the importance of self-sufficiency of water use (which was evident from some of the response to the qualitative questions that were part of the survey). However, there was insufficient information in the surveys to be able to make any conclusions such as that the reduced water use on the organic farms is due to the increased use of mulch or the higher organic matter in soil. Much of Australian agriculture is severely constrained by rainfall so it is difficult to compare the water results here with international studies on organic farm water use.

On-site land disturbance is similar for the organic and conventional farms (3.9 and 4.1 kha/A$m, respectively), and is principally due to land for livestock rather than crops. Stocking rates were factored into the calculation of land disturbance: whilst organic farms *used* a larger area, the number of livestock per hectare was fewer, resulting in a similar level of disturbance. However, it should be noted that this calculation could not be done for crops. Thus, the organic land disturbance intensity is likely to be a slight overestimate (at greatest ~0.1 kha/A$m) due to greater periods of fields being left fallow for cropping areas. Indirect land disturbance impacts are minor in comparison with on-site land disturbance because of the greater land requirements generally inherent in agriculture as opposed to other industries.

The on-site employment intensity of organic farms (9.7 employment-years/A$m) is lower than that of conventional farms (12.6 emp-y/A$m). This result is independent of scale of output, with both large and average scale organic farms reporting similar on-site employment requirements. For comparison, Klepper et al. (1977), Lockeretz et al. (1981) and Pimentel (1993) report labour intensities (on-farm component only) that are similar for both farm types (8.5–9.5 emp-y/US$m for broadacre farming), with that for organic farming being slightly higher. The higher indirect employment intensity of conventional farming is consistent with greater indirect energy use, and results largely from a higher dependence of conventional farming on such inputs as the manufacture of agricultural machinery. However, the difference between the two farming practices was found to be dependent on produce type, with the total employment intensity of organic horticultural crops being higher than that of conventionally grown crops, but this was outweighed by a significantly lower total employment intensity for organic sheep farming (org 0.7 emp-y/A$m, conv 2.8 emp-y/A$m). This finding is reflected in a corresponding higher energy dependence of organic sheep farming in comparison with both conventional and other produce, and is explored further in Section 3.5.

In relation to the discussion of uncertainties in Section 2.4, an indicative relative standard error $\Delta\Phi_i/\Phi_i$ of Φ_i, is obtained by evaluating Eq. (8). Using very conservative estimates of 100% of relative errors in multipliers and relative errors in the commodity inputs, and a count of 58 commodity entries, we obtain an estimate of relative standard errors of about 20%.

3.2. Scale dependence of total energy requirements and costs

Fig. 1 shows the total energy intensity and costs as a function of output. Costs and sales are as reported from the survey, in units of million Australian dollars (A$m). Economies of scale are observed for organic farms, with an elasticity of $\eta = 0.94$. The correlation between energy intensity and sales, whilst not as strong, shows the effect of scale on energy requirements, with the larger farms (inclusive of both hor-

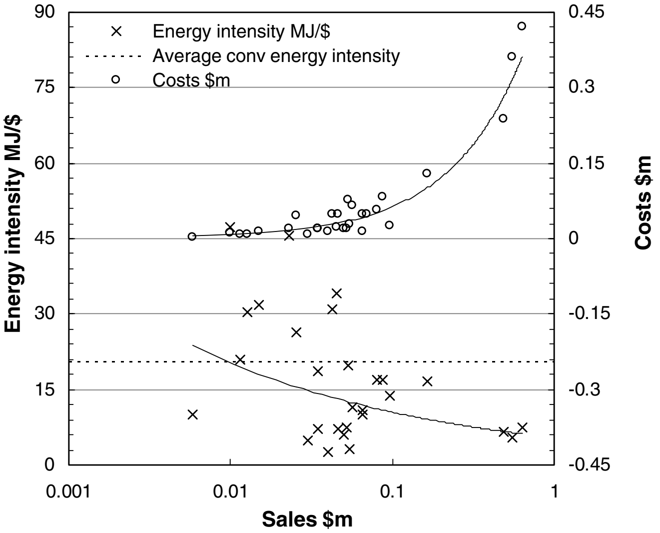

Fig. 1. Energy intensity (total energy requirement of each farm per dollar of output) and costs versus sales of each organic farm. The average energy intensity of conventional farms is 21 MJ/$.

ticulture and grazing) requiring significantly less energy per dollar of output. The average energy intensity of organic farms in the survey is less than the average of conventional agriculture, re-iterating the greater self-sufficiency of organic farms. Scale information for conventional farms was not available for comparison.

The financial performance in terms of gross operational surplus of organic farms surveyed in this study is comparable to that of their conventional counterparts (30–50% of total sales; Australian Bureau of Statistics, 2001). This result is consistent with observations of chemical-free cereal/livestock farms in South East Australia by Wynen and Edwards (1990), who report somewhat lower per-hectare yields for organic farms, but also significantly lower per-hectare inputs than for conventional farms (compare Lockeretz et al., 1981, p. 543), so that the farm cash operating surplus of organic farms (≈60% of sales) exceeded that of conventional farms (≈50%).

3.3. Decomposition into production layers

Fig. 2 illustrates the decomposition of energy intensity into upstream production layers via the series expansion of the Leontief inverse (see Eq. (3)). The gradual approach to system completeness demonstrates the importance of addressing impacts beyond the first-, second- or third-order. Whilst, as reported, on-site energy requirements are slightly higher for organic farming, Fig. 2 shows a cross-over between the 0th (on-site) and 1st order of production (direct suppliers). This stems mainly from higher direct energy requirements for the supply of fertiliser to the

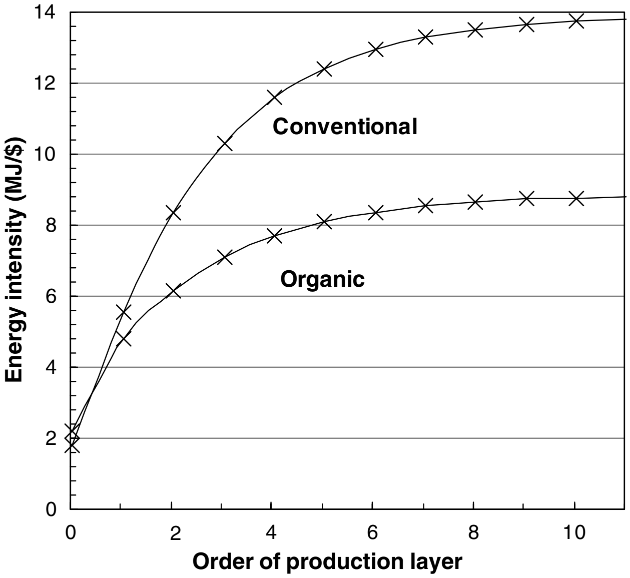

Fig. 2. Energy intensity by production layer of the aggregated organic farm, and the equivalent conventional farm.

conventional farm (see Section 3.4). An increasing disparity is also observed through the industrial production layers, with the organic farm approaching system completeness at a faster rate. This shows a significantly greater localisation of impacts within the industrial production system for organic farming. These results contradict assumptions made by Haas et al. (2000) who expect no differences between farms regarding the primary energy needed for farm buildings, machinery, etc., and the conclusion of Trewavas (2004) (p. 774) that organic and conventional farming were similar in energy efficiency.

3.4. Structural path analysis

The decomposition of impacts into structural paths was obtained by running an extraction algorithm evaluating Eq. (4). The sorted paths are presented in Table 3. The components of the path code represent (1) the input industries – abbreviated as in Table 4; (2) the intensity of the impact (eg MJ/A\$); (3) the path order (0 = on-site, 1 = first supplier level, and so on); (4) the path coverage, or the relative contribution of the path to the total impact by factor. For example, in the energy use for the conventional farm, the path Is Ma 0.37 (2; 2.6%) denotes the energy required to produce iron and steel that is used for agricultural machinery (Ma). The path value is 0.37 MJ/A\$, is of second-order, and contributes 2.6% to the total energy requirement of conventional farming. The reader should bear in mind that the values of these paths are only indicative, and that the primary function of the ranking is to identify and prioritise targets for action (Lenzen, 2001b). Hence, individual path values should not be interpreted as giving highly accurate figures for the absolute impact of the farms along particular supply chains.

Of note in the detailed structural path analysis is the higher energy impact of conventional farming due to reliance on (particularly synthetic) fertilisers and chemicals in agricultural production (conv Fe 1.7 MJ/A\$; org Fe 0.29 MJ/A\$). This difference is partially due to greater use of manures and compost (with lower than average embodied energy[1]) on the organic farm, as both types of farm have similar expenditure on fertiliser. Similar large differences are evident in energy requirements of iron and steel production for machinery (conv Is Ma 0.37 MJ/A\$; org Is Ma 0.088 MJ/A\$). This finding is consistent with results obtained by Klepper et al. (1977) and Pimentel (1993) in their comparative studies of commercial-size cereal/livestock farms in the US Corn Belt (Iowa, Illinois, Minnesota, Missouri and Nebraska), and of US maize and potato production, respectively. Klepper et al. (1977) report that conventional farms are more than twice as energy-intensive as their organic equivalents, whether in per-dollar, per-acre, or per-bushel terms. Lockeretz et al. (1981) and Pimentel (1993) arrive at the same conclusion, but with less pronounced differences. The difference between the two farm types is caused mainly by the use of inorganic fertilisers (particularly nitrogen) and pesticides by conventional farmers.

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[1] Embodied energy of manure and compost (1.9 l fuel/tonne compost) includes transport and application, see Pimentel et al., 1983, p. 360 and Pimentel, 1993.

Table 3
Structural path analysis results for energy intensity (MJ/\$), land disturbance intensity (kha/\$m), water intensity (ML/\$), greenhouse gas emissions intensity (kg CO_2-e/\$), and employment intensity (emp-y/\$m) for the conventional and organic farm

Rank	Organic energy (MJ/\$)	Conventional energy (MJ/\$)	Organic land disturbance (kha/\$m)	Conventional land disturbance (kha/\$m)	Organic water use (L/\$)
1	Fo 1.3 (0; 15.0%)	**Fe 1.7 (1; 12.1%)**	Wo 2.2 (0; 54.4%)	Wo 2.8 (0; 63.%)	Vf 21.8 (0; 68.4%)
2	El 0.98 (1; 11.0%)	Fo 1.3 (0; 9.0%)	**Bc 1.5 (0; 38.2%)**	**Bc 1.2 (0; 26.3%)**	Sc Cg1 5.1 (2; 16.1%)
3	Fo 0.62 (1; 6.9%)	El 0.89 (1; 6.4%)	Wh 0.18 (0; 4.6%)	Wh 0.12 (0; 2.8%)	Vf 1.1 (1; 3.4%)
4	Ap 0.43 (0; 4.8%)	Fo 0.42 (1; 3.0%)	**Vf 0.059 (0; 1.5%)**	Bc 0.12 (1; 2.8%)	Wo 0.27 (0; 0.9%)
5	Hw 0.33 (0; 3.7%)	**Is Ma 0.37 (2; 2.6%)**	Pe 0.004 (0; 0.1%)	Wh 0.038 (1; 0.8%)	Wh 0.27 (0; 0.9%)
6	**Fe 0.29 (1; 3.2%)**	Ap 0.31 (0; 2.2%)	Ba 0.0034 (0; 0.09%)	Wo 0.037 (1; 0.8%)	Wa 0.18 (1; 0.6%)
7	Sp 0.14 (1; 1.6%)	Fe Fe 0.26 (2; 1.9%)	Bc 0.0025 (1; 0.06%)	**Vf 0.021 (0; 0.5%)**	Sc Cg Sc Cg 0.11 (4; 0.3%)
8	Rd 0.13 (1; 1.4%)	*Fe* Fe 0.24 (2; 1.7%)	Wo *Tx* Cl 0.0025 (3; 0.06%)	Bc Mp 0.018 (2; 0.4%)	Wp 0.1 (1; 0.3%)
9	Lg 0.1 (0; 1.1%)	El Fe 0.18 (2; 1.3%)	Wo Tx Cl 0.0023 (3; 0.06%)	Fr 0.012 (1; 0.3%)	Sc Cg Vf 0.077 (3; 0.2%)
10	Ap 0.098 (1; 1.1%)	Rd 0.14 (1; 1.%)	Dc 0.0022 (0; 0.06%)	Bc Bc 0.0058 (2; 0.1%)	Vf Sc Cg 0.053 (3; 0.2%)
11	**Is Ma 0.088 (2; 1.0%)**	Vf 0.12 (1; 0.9%)	Sc Cg 0.0021 (2; 0.05%)	Wh Wh 0.005 (2; 0.1%)	Bc 0.053 (1; 0.2%)
12	Ce 0.088 (1; 1.0%)	Br 0.097 (0; 0.7%)	Sw Ti 0.00094 (2; 0.02%)	Sc Cg 0.005 (2; 0.1%)	Fo 0.048 (1; 0.1%)
13	El El 0.086 (2; 1.%)	El Ma 0.089 (2; 0.6%)	Wh 0.00078 (1; 0.02%)	Bc Mp Fe 0.0029 (3; 0.06%)	Dc 0.047 (1; 0.1%)
14	Is 0.077 (1; 0.9%)	Is Is Ma 0.084 (3; 0.6%)	Bc Mp Fe 0.00076 (3; 0.02%)	Bc Mp Fd 0.0022 (3; 0.05%)	Fe 0.039 (1; 0.1%)
15	Fe Fe 0.045 (2; 0.5%)	El El 0.078 (2; 0.6%)	Wo 0.00076 (1; 0.02%)	Wo Mp 0.0021 (2; 0.05%)	Pp Pa 0.038 (2; 0.1%)

Conventional water use (L/\$)	Organic greenhouse gas emissions (kg/\$)	Conventional greenhouse gas emissions (kg/\$)	Organic employment (emp-y/m\$)	Conventional employment (emp-y/m\$)
Vf 103.6 (0; 56.4%)	Fo 0.13 (0; 13.9%)	**Fr 0.33 (1; 17.1%)**	Vf 8.5 (0; 51.5%)	Vf 8.3 (0; 31.4%)
Bc 24.4 (0; 13.3%)	El 0.087 (1; 9.4%)	**Bc 0.16 (1; 8.3%)**	**Wo 0.66 (0; 4.%)**	**Wo 2.7 (0; 10.2%)**
Wo 18.4 (0; 10.%)	Fo 0.044 (1; 4.7%)	Fe 0.1 (1; 5.2%)	Wh 0.42 (0; 2.5%)	**Ma 0.91 (1; 3.4%)**
Sc Cg 12. (2; 6.5%)	Ce 0.03 (1; 3.3%)	Fo 0.088 (0; 4.5%)	Rd 0.26 (1; 1.6%)	**Bc 0.91 (0; 3.4%)**
Vf 5.8 (1; 3.2%)	Ap 0.029 (0; 3.2%)	El 0.079 (1; 4.1%)	Cg 0.22 (1; 1.3%)	Wh 0.57 (0; 2.1%)
Wh 2.8 (0; 1.5%)	Fe 0.017 (1; 1.9%)	Sc Cg 0.036 (2; 1.9%)	**Ma 0.22 (1; 1.3%)**	Cg 0.52 (1; 2.%)
Bc 2.6 (1; 1.4%)	Sc Cg 0.015 (2; 1.7%)	Is Ma 0.031 (2; 1.6%)	Rv 0.19 (1; 1.1%)	Vf 0.47 (1; 1.8%)
Dc 2.3 (1; 1.2%)	Oi Fo 0.014 (2; 1.5%)	Fo 0.029 (1; 1.5%)	Nb 0.18 (1; 1.1%)	Sc Cg 0.29 (2; 1.1%)
Su 0.88 (1; 0.5%)	*Oi* Fo 0.013 (2; 1.4%)	Fr Fr 0.026 (2; 1.4%)	Sc Cg 0.12 (2; 0.8%)	Rd 0.28 (1; 1.1%)
Wh 0.84 (1; 0.5%)	Sw Ti 0.012 (2; 1.3%)	Bc Mp 0.024 (2; 1.2%)	Wp 0.12 (1; 0.7%)	Nb 0.27 (1; 1.%)
Ri Fc 0.62 (2; 0.3%)	Sp 0.011 (1; 1.1%)	Vf 0.023 (1; 1.2%)	Vf 0.087 (1; 0.5%)	Mv 0.22 (1; 0.8%)
Sc Cg Vf 0.41 (3; 0.2%)	Lg 0.01 (0; 1.1%)	Ap 0.02 (0; 1.%)	Ti 0.075 (1; 0.5%)	Wh 0.17 (1; 0.7%)
Ri 0.4 (1; 0.2%)	Rd 0.0088 (1; 0.9%)	Fe Fe 0.017 (2; 0.9%)	In 0.075 (1; 0.5%)	Ms 0.16 (1; 0.6%)
Bc Mp 0.38 (2; 0.2%)	El El 0.0077 (2; 0.8%)	El Fe 0.016 (2; 0.8%)	Ms 0.072 (1; 0.4%)	Rv 0.15 (1; 0.6%)
Wa 0.34 (1; 0.2%)	Is Ma 0.0075 (2; 0.8%)	Wo 0.015 (1; 0.8%)	Mv 0.069 (1; 0.4%)	Bk 0.15 (1; 0.6%)

The meaning of the figures is explained in Section 3.4. The abbreviations for the industries supplying the farms are listed in Table 4. Items in bold are discussed specifically in the text. Imported paths are shown in bold italics.

Table 4
Input–output industry symbols used in Table 3

Symbol	IOPC industry groups
Ap	Automotive petrol
Ba	Barley, unmilled
Bc	Beef cattle
Bk	Banking
Br	Brown coal, lignite
Ce	Cement
Cg	Services to agriculture, ginned cotton, shearing and hunting
Cl	Clothing
Dc	Dairy cattle and untreated whole milk
El	Electricity supply
Fc	Flour, cereal foods, rice, pasta and other flour mill products
Fd	Raw sugar, animal feeds, seafoods, coffee and other foods
Fe	Mixed fertilisers and chemicals
Fo	Gas oil, fuel oil
Fr	Forestry and services to forestry
Hw	Hardwoods, brushwoods, scrubwoods, hewn and other timber
In	Insurance
Is	Basic iron and steel, pipes, tubes, sheets, rods, bars and rails
Lg	Liquefied natural gas, liquefied natural petrol
Ma	Agricultural, mining and construction machinery
Mp	Meat and meat products
Ms	Legal, accounting, marketing and business managemt services
Mv	Motor vehicles and parts, other transport equipment
Nb	Non-residential buildings, roads, and other construction
Oi	Crude oil
Pa	Paper containers and products
Pe	Poultry and eggs
Pp	Pulp, paper and paperboard
Rd	Road freight transport services
Ri	Rice, in the husk
Rv	Repairs of motor vehicles, agricultural and other machinery
Sc	Seed cotton
Sp	Water transport
Su	Sugar cane
Ti	Sawn timer, woodchips and other sawmill products
Tx	Processed wool, textile fibres, yarns and woven fabrics
Vf	Vegetable and fruit growing, hay, plant nurseries, flowers
Wa	Water supply, sewerage and drainage services
Wh	Wheat, legumes for grain, oilseeds, oats and other grains
Wo	Sheep and shorn wool
Wp	Plywood, window frames, doors and other wood products

The energy requirements for 1 kg of nitrogen fertiliser and pesticide are in excess of 100 and 200 MJ, respectively (Pimentel, 1992, pp. 20–24; Organisation for Economic Co-operation and Development, 1982, p. 16). In contrast, the characteristics of the machinery and equipment used differed less between the two groups. Finally, the energy needed to transport fertiliser to the farms was less than 1% of the energy used during fertiliser manufacture. In the Netherlands, Denmark and the UK, imported cattle feed represents a substantial portion of the energy embodied in agricultural products (Organisation for Economic Co-operation and Development, 1982). In contrast, imported cattle feed is negligible for Australian agriculture.

Land disturbance of sheep farming is about 20% lower for organic farms than for conventional farms. However, the land disturbance of beef cattle grazing (org: Bc 1.5 kha/A$m, conv: Bc 1.3 kha/A$m) is about 15% higher for the organic case, and is due to the extensive grazing on a surveyed organic farm (situated in the ELZ). The land disturbance of vegetable and fruit growing for the organic farm (Vf 0.059 (0; 1.5%)) is nearly three times that of the conventional farm (Vf 0.021 (0; 0.5%)). This could be due to the larger areas used in organic farming in crop rotation and left fallow, and shows the less intensive, albeit broader, impacts, that organic crops have on the land.

Water use is shown to have a similar breakdown for both organic and conventional farms, but with much lower overall intensities for organic farms. Of note in the greenhouse gas structural paths are the emissions due to forestry as a service to conventional agriculture (Fr 0.33 (1; 17.1%)). This path is highly dependent on regional circumstances, however, as most land clearing takes place in northern Australia for new grazing lands of conventionally grown cattle (Australian Greenhouse Office, 2004). This is reflected in the emissions resulting from cattle of Bc 0.16 (1; 8.3%). Thus these paths may not be applicable for direct comparisons. Apart from this, most other impacts reflect those of energy requirements.

As mentioned previously, the employment intensity of vegetable and fruit growing is similar for both conventional and organic farming, but for livestock, it is significantly lower in the organic system (org: Wo 0.66 emp-y/A$m, Bc ~0.06 emp-y/A$m; conv: Wo 2.7 emp-y/A$m, Bc 0.91 emp-y/A$m). The greater dependence on off-site materials for conventional farms is also shown through the direct employment in the machinery industry, which is considerably higher for conventional farms (conv Ma 0.91 emp-y/A$m; org Ma 0.22 emp-y/A$m).

Whilst the structural path analysis shows each third and higher-order paths to be comparably small, the large number of these paths results in their non-negligible contribution to total impacts, as can be seen in the production layer decomposition in Fig. 2.

3.5. Structure of energy requirement of different products

To show the energy dependence of different agricultural products, the energy requirements stemming from on-site energy use, fertiliser, chemicals and pesticides, and machinery were calculated for farms producing primarily fruit, vegetables, wheat and sheep, and general livestock (sheep and cattle). The results are presented in Fig. 3.

Generally, as previously identified, the total energy embodied in the range of organic produce is lower than in conventional produce (for some products, however, the difference is not large, and the uncertainty estimate of 20% may take these differences into account). There is a notable exception in organic sheep and wheat

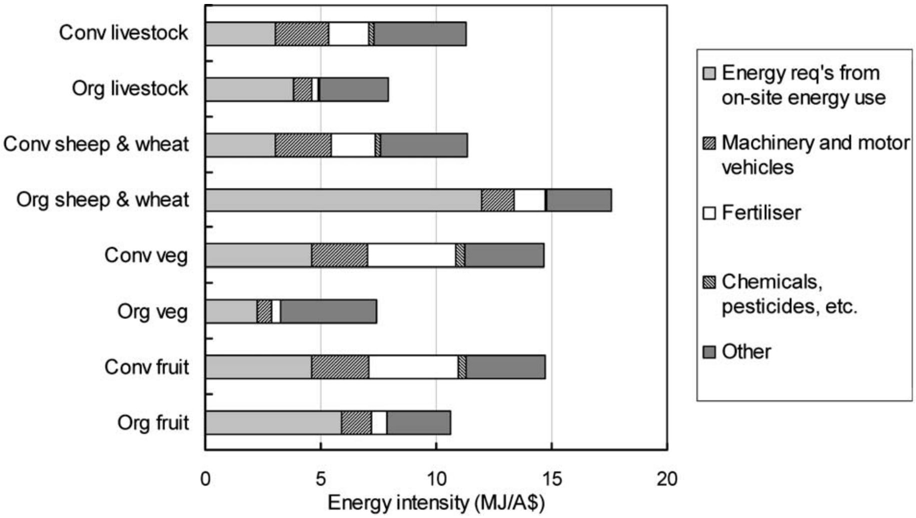

Fig. 3. Structure of total (embodied) energy requirement for different types of produce.

production, however. This category has an energy requirement due to on-site fuel uses of 12 MJ/A$, significantly higher than that for conventional sheep and wheat production (3.1 MJ/A$). This result is principally due to large amounts of diesel and petroleum products being used on these farms, are based on four high-quality surveys of sheep- and wheat-producing farms, and are consistent with figures for on-site fuel use found by Wynen (2001).

Across the range of products, however, the ratio of on-site to total energy intensity is higher for organic farms. This shows a greater localisation of energy use for organic farming. Of note is the lower energy dependency for fertilisers across all products excepting wheat and sheep. This is again due to greater localisation of energy impacts stemming from local sources of manure and compost making up around 50% of the organic expenditure on fertiliser.

It is also interesting to note that across both conventional and organic farming (excluding sheep and wheat), fruit and vegetable production has a higher energy intensity than livestock production. However, in terms of land disturbance the opposite is the case.

An international comparison of the structure of energy requirements (Fig. 4) yields a unanimous picture of organic farms exhibiting (1) a higher proportion of on-site energy use, and (2) a lower proportion of energy embodied in synthetic fertilisers. Both components make up mostly between 40% and 70% of the total energy requirement, with the remainder varying strongly between studies. Note also that the component ‘other’ is considerably larger in the results of this study, which is due to the more comprehensive coverage of the input–output method as opposed to that obtained by the process analysis used in most other studies.

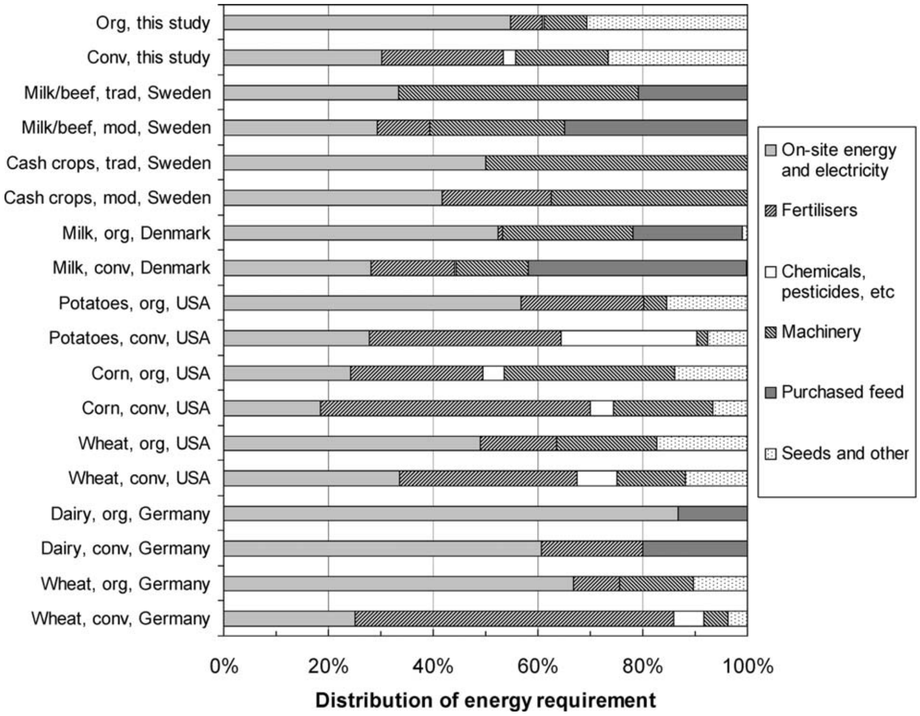

Fig. 4. Distribution of energy requirements of organic and conventional farming in an international comparison (after Pimentel et al., 1983, 1989; Pimentel, 1993; Haas et al., 1995; Refsgaard et al., 1998; Uhlin, 1998 and Haas et al., 2001).

4. Conclusions

In order to calculate the full environmental impacts of agriculture, it has been shown that off-site effects must be taken into account. This is particularly the case with energy use and greenhouse gas emissions, in which greater than five times the on-site impact occurs off-site. The importance of addressing these indirect impacts is obvious in the need to move towards a more sustainable food production system. As the results show organic production to have smaller indirect impacts than conventional production, a transition to organic farming could be a viable way of reducing energy use and greenhouse gas emissions. Larger-scale farms also show an alternate way to reduce energy dependency, whilst still maintaining the social benefits of higher employment levels per dollar of output.

Significant energy use occurs in the use of fuels on-site, and this would be an obvious area that could be addressed by organic farmers especially, possibly by reverting to a higher reliance on labour as opposed to machinery. However, given the nature of Australian agriculture with many relatively isolated farms, which may mean increasing the labour demands on the current farmers, this is not without its problems (see Loake (2001) for a discussion on human energy in organic and conventional farms).

Synthetic chemicals and fertilisers are another major source of energy use, and the transition to organic agriculture, being less reliant on these inputs, would see a reduction in these impacts.

The area of land disturbance is generally localised to the farm, and, in a global "footprint" context, is not considered to be a major area in need of review. Water use, in contrast, appears to be much lower on organic farms, and is possibly a result of organic philosophy as well as practice. This finding is worthy of further investigation, given the highly stressed nature of Australia's water resources. Conventional farmers could reduce their water use by adopting some of the attitudes of organic farmers.

It is also clear that whilst organic farmers are more concerned with local environmental issues, they are also aware of, and prepared to address, impacts that occur at the global level. In summary, some ways of easing these global environmental pressures could involve: (1) the increased use of labour, as opposed to machinery, as outlined above, (2) technological change, involving efficiency improvements of machinery and irrigation systems, (3) conservation measures and installation of renewable energy, (4) reforestation to sequester greenhouse gas emissions and (5) systemic change towards more sustainable farm practices (as set out for example by the National Association for Sustainable Agriculture Australia; NASAA).

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