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Methods

Giving the consumer the choice: A methodology for Product Ecological Footprint calculation

Elena Alexandra Mamouni Limnios [a,*], Anas Ghadouani [a], Steven G.M. Schilizzi [b], Tim Mazzarol [c]

[a] School of Environmental Systems Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[b] School of Agricultural and Resource Economics, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia
[c] UWA Business School, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

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ABSTRACT

As global consumption increases we are faced with a major threat; exceeding the Earth's capacity to create new resources and absorb waste. In the present study we develop a self-improving, market-driven process of ecological footprinting of products, proposed as a means to give consumers a real choice in actively monitoring and reducing their ecological impact. We conduct a small scale case study to illustrate first stage calculations. A wider market application of higher accuracy second or third stage calculations changes market information dynamics, as ecological information is internalized for consumers. Potential impacts on purchasing behavior, demand and eco-technological innovation are discussed.

1. Introduction

Climate change, air and water pollution, soil degradation and species extinction constitute major environmental threats caused directly or indirectly by human activities. The urgency for more extensive technological and cultural change to mitigate pressing ecological issues and reduce vulnerability to future climate change is constantly affirmed and is gradually being quantified (IPCC, 2007). Evidence is now available that a portfolio of adaptation and mitigation measures, including a shift towards sustainable energy sources and technologies, needs to be made within the next five years in order to halt climate change without major loss of biodiversity; otherwise the shift will increase expenses and the risk of failure (Mallon et al., 2007). In this process it is important to recognize that the responsibility for change lies only partially with policymakers and industry leaders. An effective solution can only be found in the interaction between consumers, companies and governments (United Nations, 1992).

Private industry and NGO's are leading the way through research and investment in sustainable technology and practices, the establishment and advancement of corporate environmental reporting, the development of international sustainability self-reporting guidelines (Global Reporting Initiative), and the formation of private, national and international sustainability assessment initiatives and organizations (e.g., Dow Jones Sustainability Index, Ethical Investor). Despite available information technology and rising consumer environmental awareness, only a small portion if this information is directly related to the product or service provided by the company and becomes available to the consumer at the product outlet. The vast majority of corporate sustainability information is provided at an aggregate level for all products and processes, in a reporting format that targets special interest stakeholder groups. Information at the product level is driven by national and international policies and commonly takes the form of “seal-of-approval” type of environmental labelling (Green Seal, Blue Angel), product hazard warnings and product durability labelling. In these cases quantitative information collected in the assessment and awarding phase of the ecolabel is not communicated to the consumer and therefore the label assumes a qualitative character. Quantitative environmental information, such as energy efficiency, chlorofluorocarbons use and recycled content, is less frequent and applies only to specific categories of products not allowing comparisons across categories. As a result, consumers are not conscious of the environmental impacts of conventional products, which can be misperceived as relatively benign to the environment.

A typical example can be found in the aquaculture industry, where the common misconception is that fish farming methods reduce the stress on world fisheries. Consumers are unaware that high-trophic level fish require a large volume of fishmeal inputs. Shrimp and salmon aquaculture products require two to four times their volume

* Corresponding author. School of Environmental Systems Engineering, The University of Western Australia, M015, 35 Stirling Highway, Crawley, WA 6009, Australia. Tel.: +61 404 554854; fax: +61 8 6488 1015.
E-mail addresses: mamouni@sese.uwa.edu.au, elenamamouni@msn.com (E.A. Mamouni Limnios).

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in fish products as inputs, which contributes to the exhaustion rather than augmentation of fisheries resources (Naylor et al., 1998). It is predicted that by 2015 the global aquafeed industry will require 70% of the average historical fishmeal supply and 145% of the fish oil supply (Tyedmers et al., 2007). Furthermore, aquaculture activities can be highly pollutant and detrimental to coastal nursery areas and adjacent ecosystems. Shrimp farming ponds have an average life span of 7 to 15 years after which abandonment due to productivity loss, occurrence of algal blooms or disease outbreaks is common (Dierberg and Kiattisimkul, 1996; Paez-Osuna, 2001). In many cases ponds have become so polluted that conversion to other uses is not economically feasible (Naylor et al., 1998). In addition to this, organic labelling can be misleading, as current standards for organic aquaculture fail to reduce the environmental impacts of feed production for a variety of impact categories in the salmon industry (Pelletier and Tyedmers, 2007). As a result, consumers of the imported aquaculture products are largely unaware of the ecological damage that occurs in the place of origin.

Significant steps forward are being initiated in Europe, such as the carbon labelling program run by The Carbon Trust in the UK (Carbon Trust, 2007b). A draft carbon footprint measuring methodology has been developed, aiming at the provision of a public measure of product carbon emissions from source to store. The methodology is currently being applied to a number of pilot industry case studies (Carbon Trust, 2007a). Atmospheric concentration of carbon and other greenhouse gases is an important environmental concern. However, a more holistic approach is needed to account for the complex impacts of human actions on the environment and ensure long-term survival of local and global socio-ecological systems.

The ecological footprint (EF) method, developed by Rees and Wackernagel (Rees, 1996; Wackernagel and Rees, 1996; Wackernagel and Rees, 1997), is a tool that has been used to compare the sustainability of resource use among populations, by converting the flows of energy and matter into corresponding land areas. The EF aims to estimate the biologically productive area that is needed to produce the yearly resource flows, absorb wastes or emissions and host the built infrastructure of a region (Haberl et al., 2001). This widely applicable methodology for measuring environmental impact provides a partial solution to the sustainability aggregation problem by expressing environmental impacts in a single measurement unit. If applied at the product level, it could allow for consistent measurement, labelling and comparative evaluation across products and industries.

The EF has been commonly applied to measure and compare the footprint of various groups of populations and regions. Examples include China (Chen and Chen, 2006; Chen et al., 2006; Cui et al., 2004; Du et al., 2006; Wang et al., 2006), New Zealand (Jollands et al., 2004; Mcdonald and Patterson, 2004), North America (Senbel et al., 2003), Australia (Lenzen, 2001; Lenzen and Murray, 2001) Slovenia (Medved, 2006), Austria, Philippines and Korea (Haberl et al., 2001; Wackernagel et al., 2004a). Calculations of specific product, enterprise or industry ecological footprints have also taken place; they are however very case specific with a number of publications focusing on aquaculture industry (Bunting, 2001; Chopin et al., 2001; Kautsky et al., 1997; Roggenbauer, 2005; Roth et al., 2000) and the fuel and transportation industry (Azar et al., 2006; Chi and Stone, 2005; De Oliveira and Vaughan, 2006; De Oliveira et al., 2005; Holden and Hoyer, 2005; Wood, 2003). Notable exceptions to the above are a life-cycle analysis of mobile phones ecological footprint (Frey et al., 2006) and the recent work by Huijbregts et al. (2008) that aims to fill the existing information gap by applying the EF methodology to a wide range of products. These applications commonly aggregate direct land occupation and indirect land occupation related to carbon dioxide emissions from fossil fuel energy use or other production and distribution activities. Additional contributors depend on the specific industry and may vary from area required to remove nitrogen, phosphorous and mangrove detritus (Kautsky et al., 1997), to area needed for safe deposits of nitrogen and sulphur (Holden and Hoyer, 2005) and land occupation related to nuclear energy use (Huijbregts et al., 2008).

Although the need to account for the efficiency of natural resource use (instead of only relating it to the area occupied by the manufacturing facility) has been stressed in the literature (Bunting, 2001; Lenzen and Murray, 2001), this rarely takes place in product ecological footprint calculations. Furthermore, calculations of the productive land required to absorb the carbon from burning fossil fuels through afforestation have attracted great criticism, both because the calculation is based on an economically and socially unfeasible option (afforestation) and because the aggregate EF and the estimated EF deficits are largely dominated by the energy land component (Ayres, 2000; Van den Bergh and Verbruggen, 1999; Huijbregts et al., 2008). Finally, since its conception, the EF methodology relies on third (research) parties to collect and analyse data. Long-term, cross industry, national or international applications (e.g. work conducted by the Global Footprint Network) require aggregation of information and costly maintenance of detailed databases at an aggregate level.

We develop a market-driven consumer information process, based on product ecological footprinting, while aiming to address some of the above mentioned limitations of the ecological footprint method. We propose a staged, self-improving approach for the computation of product ecological footprints (PEF), which will require the maintenance of international databases at early stages of application, substituting aggregate data averages at later stages with more accurate, product-specific data sourced directly from the supply chain. We aim at transforming PEF from a theoretical and research methodology, to a practical market tool that can become both a means to educate and empower consumers, but also a management tool for the comparison of economic and environmental cost, and thus a driver of eco-technological innovation.

2. Product ecological footprint methodology

We have developed a methodology for Product Ecological Footprint (PEF) calculation that can be applied by manufacturers consistently across industries, using data initially available in international databases and subsequently directly sourced from the supply chain. In order to successfully trace the ecological impact of the supply, production and distribution of each product we utilize an accounting methodology called Activity Based Costing (ABC), adjusted to account for ecological impacts instead of financial costs.

2.1. Activity based costing: an accounting concept

The Activity Based Costing (ABC) methodology emerged in the late 1980s and became very popular in the 1990s (Bjørnenak and Mitchell, 2002). Traditional accounting cost categories of fixed and overhead costs were replaced by a detailed activity analysis of all the actions that take place to transform process inputs into outputs. The value of resources was allocated to each activity, resulting in a much more accurate definition of output (product or service) costs. Activity based costing has allowed for the definition of cost drivers within each activity and the identification of the value added by each activity to the end product or the consumer, providing opportunities for multiple managerial gains. A 1999 survey of UK firms showed that ABC applications extended from cost reduction (90.3% of users) to include product or service pricing (80.6%), performance measurement or improvement (74.2%), cost modelling (64.5%), budgeting (54.8%), customer profitability analysis (51.6%), output decisions (51.6%) and new product or service design (41.9%) (Innes et al., 2000).

The great majority of ABC users express very positive views on the importance and success of the method (Innes et al., 2000) and a positive association between ABC use and firm profitability has been identified under certain conditions (Cagwin and Bouwman, 2002). ABC has in numerous cases been transformed into corporate philosophy, guiding strategic decision making, cross functional teams and employee empowerment (Hooshang, 2004). Furthermore, it has been successfully used concurrently with process and quality management techniques such as "Total Quality Management", "Just-In-Time" and "Balanced ScoreCard" applications (Cagwin and Bouwman, 2002; Maiga and Jacobs, 2003). In other cases ABC has been gradually abandoned, as most lessons have been successfully internalized by users and the cost focused data collection processes have gradually been replaced by other financial and non-financial measurements (Geri and Ronen, 2005). In conclusion, ABC has transformed cost measuring, product pricing and managerial accounting as it was known in the late 1980s.

2.2. Ecological Activity Based Costing (e-ABC)

In order for the ABC methodology to be adjusted to account for ecological impacts (EIs), we need to conceptualize product ecological impacts by applying an input–output conceptual model (Fig. 1).

Any activity, which is defined as a group of actions that transform inputs into outputs, may have direct and indirect EIs. Direct impacts take the form of waste, water, soil or air pollution, biodiversity, and ecosystem productivity impacts. Indirect ecological impacts can be embedded in activity inputs (materials, labor, energy). Materials and energy will carry an embedded EI as outputs of previous activities, in which case the output's Type C ecological impact from each previous activity will equal the input's Type A ecological input in the following activity. Embedded EI of labor includes obvious work-related activities, such as paper consumption and pollution due to daily commuting to work, or work-related travel. Recycled materials carry embedded EI only due to the recycling processes and not as outputs of their previous production and consumption cycle. The materials have been through the complete cycle and their EI as consumable outputs of that cycle have already been accounted for.

2.3. PEF equations

One can calculate the end product's ecological footprint using the following staged approach, following the mapping of each activity's ecological impacts. This approach is designed to result in a gradual increase in the accuracy of the calculations and in the demand for information gathering at the industry level, while reducing reliance on international databases.

2.3.1. 1st stage calculations

First stage calculations will result in a PEF estimate (PEF^1) and should only be used as such. For this reason we recommend that ecological impacts are aggregated for each end-product that the company provides and PEF calculations are conducted at that aggregate level and not at intermediate activity output levels. The EIs accounted for in PEF^1 include materials-embedded (EF_M^1), land-embedded, biodiversity and productivity impacts (EF_A^1), and labor embedded impacts (EF_L^1).

$$\mathrm{PEF}^1 = \frac{EF_M^1 + EF_A^1 + EF_L^1}{\text{Product Units}}\left(\frac{\text{ha}}{\text{unit}}\right) \tag{1}$$

Where:

$$EF_M^1 = \sum_M \left[\frac{\mathrm{M}\left(\frac{\text{units}}{\text{yr}}\right)}{\text{Global M yield}\left(\frac{\text{units}}{\text{ha}\cdot\text{yr}}\right)} \cdot \text{Equiv factor}\left(\frac{\text{gha}}{\text{ha}}\right)\right] \tag{2}$$

$$EF_A^1 = \sum_{\text{Area type}} \left[\begin{array}{l}\text{Area(ha)} \cdot \text{Dist factor}(-) \cdot \text{Yield factor}(-) \\ \cdot\ \text{Equiv factor}\left(\frac{\text{gha}}{\text{ha}}\right)\end{array}\right] \tag{3}$$

$$EF_L^1 = \sum_{\text{Pr Activity, Nation}} \left[\begin{array}{l}\frac{\text{National } EF}{\text{population}} \cdot \text{Number of Employees} \\ \cdot\ \frac{\text{average working hours in a week}}{168}\end{array}\right] \tag{4}$$

Materials and energy embedded EI (EF_M^1) is calculated for processed inputs that are not extracted or collected directly from the land or sea. The primary materials (M) that constitute the processed product can easily be defined (usually from the product label) and a weight, volume or energy unit can be used for the calculations depending on the available format of respective national, or if not available, global yields. It becomes evident that PEF^1 calculations for primary industry products will be of higher accuracy in comparison to secondary industry products (processed), as the materials component at first stage calculations is based on national or global average yields.

The ecological footprint methodology does not take into account regional and local features of land types and land use (Van den Bergh and Verbruggen, 1999). As directly stated in the paper used by the Global Footprint Network to calculate nations' EF accounts, "a primary product will have an identical Footprint regardless of its origin" (Monfreda et al., 2004). This is due to their calculation methodology that utilizes tons of output and then translates this into a land value applying the global crop yield. In order to address this limitation we are using direct land area usage rather than land area derived from the volume of outputs in Eq. (3). The area component (EF_A^1) is an assessment of direct land use, taking into consideration long-term biodiversity and productivity impacts that are caused by current production methods. As a result, differences in productivity

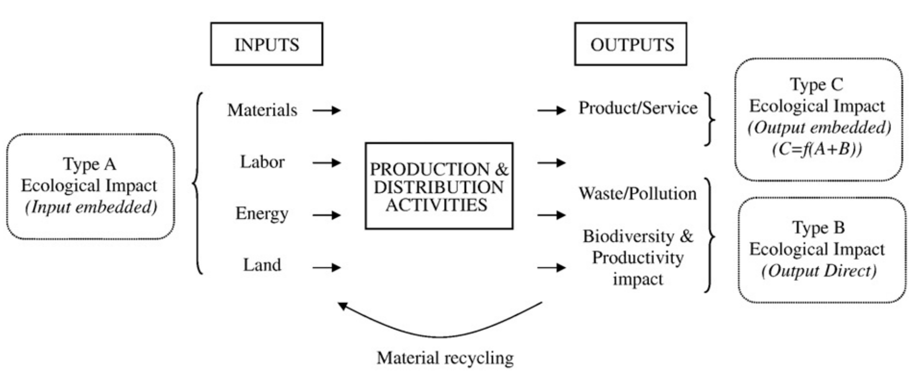

Fig. 1. Product ecological impacts model.

between various primary producers will surface even from first stage calculations.

EF values are not measures of physical land, rather an equivalent of land area assumed to have world average bioproductivity. The Yield and Equivalence factors in Eq. (3) are adopted from Monfreda et al. (2004). The Yield factor is the ratio between the country's and world average land yields for a specific land/area type. It is used to account for differences in biological productivity of the same land category in different world regions. The Equivalence factors are global values for each land category that represent the world average bioproductivity of each land type relative to the world average bioproductivity of all bioproductive areas. It is used to transform each land type area in a hypothetical number of global hectares (gha) of world average bioproductivity (Monfreda et al., 2004). The combination of these two factors results in assigning a weighting to each area based on its bioproductive capacity, in order to allow for aggregation across nations and different land types. Yield and Equivalence factors are annually computed by the Global Footprint Network (www.footprint-network.org). In their calculations the Global Footprint Network differentiates between seven land categories (Cropland, Primary, Marginal, Pasture, Forest, Fisheries and Built-up area).

The Global Footprint Network method (Monfreda et al., 2004) does not account for unsustainable resource use or any type of land disturbance or degradation (Van den Bergh and Verbruggen, 1999). An unsustainable agricultural method that could increase production output in the short-term with long-term productivity impacts would result in a short term, deceiving decrease of EF. The introduction of the Disturbance factor, that accounts both for current and potential land disturbance, addresses this concern. Something similar has been applied by Lenzen and Murray (2001), who have expressed land disturbance within the yield factor. The Disturbance factor is calculated as follows:

$$\text{Disturbance factor} = \text{Current Disturbance factor} \times \text{Potential Disturbance factor} \quad (5)$$

The Current Disturbance factor will fluctuate between 0 (for slightly disturbed land), 0.2 (partially disturbed land), 0.4 (disturbed land), 0.6 (replaced land), 0.8 (degraded land) and 1 (consumed land = built). See Lenzen and Murray (2001) for an analysis of each land type and correlations with intensive land zone (ILZ) and extensive land zone (ELZ). The Potential Disturbance factor will fluctuate from 1 and over, assessing the potential future impact of the production method on the occupied and adjacent land and ecosystem. Further research is required within each industry to categorize production methods in terms of their potential future ecological impact on biodiversity and soil degradation. For all non-classified or sustainable production methods the Potential Disturbance factor will take the value of 1. It is important to note that firstly, in order to eliminate seasonal variations, and secondly, because Yields and Equivalence factors are computed annually, it is suggested to conduct these calculations on an annual basis.

Finally, in order to derive a first approximation of the labor component (EF_L^1) for first stage calculations, the value of the average EF per capita (National EF/population) (available from the Global Footprint Network) is used as a proxy for the average EF per employee. The EF of all the employees working in product related activities (within the firm in question) is then calculated by multiplying by the number of employees and then adjusted by the ratio (average working hours in a week/168) (Eq. (4)). The ratio is used to derive an estimate of the total employee EF that can be attributed to work related activities. It represents the average working hours in a week over total week hours (7*24 = 168).

Due to great criticism of the methodology that is being applied in transforming carbon emissions in land equivalents (Ayres, 2000; Van den Bergh and Verbruggen, 1999) we shall not integrate this component in first stage calculations (also note that carbon contributions need to be excluded from national footprint measures used in the EF_L equation). The EF fails to account for any other types of emissions or wastes and therefore it seems selective to account only for CO_2 emissions. We propose instead that first and second stage calculations be accompanied by a list of major waste and pollutant outcomes from the manufacturing and distribution processes. Released gases can be assessed based on their contribution to atmospheric disruptions, categorized as global warming, ozone depletion and acidification, or toxic/carcinogenic related. Furthermore, waste generation can also be categorized as non-, moderately or highly hazardous for the environment (Lesourd and Schilizzi, 2001). It is important to establish a single categorization scheme that will be followed internationally and across industries to allow for comparisons. The proposed methodology allows for inclusion of some or all of these factors in the aggregate PEF if scientific consensus can be reached regarding their respective contributions to land degradation (even from first stage calculations through the Disturbance factors) and once commonly accepted absorption or sequestration rates can be developed (third stage calculations).

2.3.2. 2nd stage calculations

Second stage calculations can be performed upon the adoption and release of first stage calculations by the majority of manufacturers. The equations are transformed as follows:

$$\mathrm{PEF}^2 = \frac{EF_M^2 + EF_A^2 + EF_L^2}{\text{Product Units}}\left(\frac{\text{ha}}{\text{unit}}\right) \quad (6)$$

Where:

$$EF_M^2 = \sum_M PEF_M^i, \quad (7)$$

where $i = 1$ or 2 depending on market information availability

$$EF_A^2 = \sum_{\text{Area type}} \left[\text{Area(ha)} \cdot \text{Dist factor}(-) \cdot \text{Yield factor}(-) \cdot \text{Equiv factor}\left(\frac{\text{gha}}{\text{ha}}\right) \right] \quad (8)$$

$$EF_L^2 = \sum_{\text{Employees}} PEF_L^i, \quad (9)$$

where $i = 1$ or 2 depending on market information availability

With PEF^1 adopted and accompanying the majority of products (as a form of ecolabelling), the calculation of material and energy inputs (EF_M^2) becomes a simple aggregation of readily available information, the respective PEF^i for each material and energy input (PEF_M^i) (Eq. (7)). Similarly the labor embedded EI component will be computed as the aggregate PEF^i due to work related employee (labour) activities (PEF_L^i) (Eq. (9)). The exponent i refers to first stage or second stage PEF information available for each material and energy input and is used to account for the transitional period between first and second stage calculations. Initially only PEF^1 values will be available, whereas the adoption of second stage calculations within a few cycles will fully replace them by the respective PEF^2 values.

Electronic scanning technology can automate PEF input accounting in the production chain. This can also be applied to the end-product outlet level, allowing consumers to track the aggregate PEF of the products they consume. The accuracy of second stage PEF calculations will increase with every (annual) cycle, as the proportion of first stage PEF estimations based on national and global averages will be replaced with producer provided PEF. Pollutants and wastes will still be reported separately to PEF, however they can now be aggregated to also account for all previous stages of the production chain, utilizing first stage reported information on activity inputs.

2.3.3. 3rd stage calculations

In the initial two stages we chose not to include waste and pollution absorption as part of the PEF value, and suggested separate reporting in primary values instead. This was done primarily because such information is currently available only for a minority of pollutants (i.e. CO_2 emissions), in which case it is also highly controversial. In the case of waste and pollution absorption rates becoming available for the majority of wastes and pollutants and land types, PEF equations can be adjusted to include waste and pollution absorption as follows.

$$\mathrm{PEF}^3 = \frac{EF_M^3 + EF_A^3 + EF_L^3 + EF_W^3}{\text{Product Units}}\left(\frac{\text{ha}}{\text{unit}}\right) \tag{10}$$

Where:

$$EF_M^3 = \sum_M \mathrm{PEF}_M^i, \tag{11}$$

where $i = 2$ or 3 depending on market information availability

$$EF_A^3 = \sum_{\text{Area type}} \left[\begin{array}{l}\text{Area(ha)} \cdot \text{Dist factor}'(-) \cdot \text{Yield factor}(-) \\ \cdot \text{Equiv factor}\left(\frac{\text{gha}}{\text{ha}}\right)\end{array}\right] \tag{12}$$

$$EF_L^3 = \sum_{\text{Employees}} PEF_L^i, \tag{13}$$

where $i = 2$ or 3 depending on market information availability

$$EF_W^3 = \sum_W \left[\frac{W\left(\frac{\text{tn}}{\text{yr}}\right)}{\text{W absorption yield}\left(\frac{\text{tn}}{\text{ha}\cdot\text{yr}}\right)} \cdot \text{Equiv factor}\left(\frac{\text{gha}}{\text{ha}}\right)\right] \tag{14}$$

It should be noted that in the case of adopting stage 3 calculations, the Disturbance factors used in the EF_A^3 component will need to be reviewed (*Dist factor'*). As pollution and waste are the main drivers of soil and ecosystem disturbance, one should be careful not to double count their influence. Therefore the Potential Disturbance Factor component will need to become adjusted or even redundant, excluding the impact of any elements that are now taken into consideration as part of EF_W^3.

3. Comparing three apple production systems

The importance and need for the PEF measure is dependent upon the significance of differences in PEF values between product categories and production methods. In order to investigate potential differences we conducted a small scale comparative calculation utilizing data from a research experiment conducted by Reganold et al. (2001), who applied organic, conventional and integrated apple production systems on replicate plots from 1994 until 1999. In addition to the secondary production data we used data available in international databases and literature to calculate the required parameters. PEF first stage calculations were conducted for the years 1998 and 1999, as soil quality ratings were only provided for those two years. EF_M has not been taken into consideration, as analytical material input accounts were not available. As this is a primary production industry and EF_M is a measure of indirect ecological impacts, it is estimated that this will not greatly impact the results. In the case of pesticides and fertilizers, for example, EF_M captures the ecological impacts that occurred during the production of these materials and not during their application. Direct ecological impacts due to the use of pesticides and fertilizers are embedded within EF_A, and more specifically within the Current and Potential Disturbance Factors.

3.1. Calculating EF_A

Four rows of trees were used for each production system. Each row was planted with 80 trees, at a density of 2240 trees per ha. Therefore the total area per production system was 1/7 ha.

In order to calculate EF_A the Yield, Equivalence and Disturbance factors will need to be defined. Based on the definition of the Yield Factor it is a single value for each land category (in this case land for apple production) in each world region. It expresses the ratio between the country's and world average land yields for a specific land/area type and is used to account for differences in biological productivity of the same land category in different world regions. Therefore a single Yield factor was calculated for each year, dividing the average US apple yield by the world average apple yield (Table 1, Annual Yield in Section 1). Apple yields for the United States and world yields were based on UN statistics (http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567). Productivity differences between the three systems are captured as noted further down in the calculations where each systems annual production units are used when applying Eq. (1).

Table 1
PEF of three apple production systems.

1. Annual yield	Area harvested (ha)	Product quantity (t)	Yield (ha/t)	Annual yield
USA				
1998	189,230	5,282,509	27,915.81	
1999	186,486	4,822,078	25,857.59	
World				
1998	5,772,689	56,668,215	9816.61	
1999	5,600,710	57,912,083	10,340.13	
1998				2.844
1999				2.501

2. Disturbance factors	Organic	Conventional	Integrated
Soil quality			
1998	0.88	0.78	0.92
1999	0.83	0.70	0.81
Current Disturbance factor			
1998	0.624	0.644	0.616
1999	0.634	0.660	0.638
Potential Disturbance factor			
1998	1.0	6.2	4.7
1999	1.0	6.2	4.7
Disturbance factor			
1998	0.624	3.993	2.895
1999	0.634	4.092	2.999

3. EF_A	Organic	Conventional	Integrated
1998 (global ha)	0.532	3.406	2.470
1999 (global ha)	0.476	3.070	2.250

4. EF_L	Organic	Conventional	Integrated
Labor (h/ha)	2921	2008	2147
Labor h	417.3	286.9	306.8
Employee number	0.178	0.123	0.131
EF_L (global ha)	0.161	0.111	0.118

5. Total production units	Organic	Conventional	Integrated
1998 (tn)	10.71	9.71	10.00
1999 (tn)	7.14	10.14	10.00

6. Product Ecological Footprint	Organic	Conventional	Integrated
1998 (ha/tn)	0.06	0.36	0.26
1999 (ha/tn)	0.09	0.31	0.24
Average (ha/tn)	0.08	0.34	0.25
Average (m^2/kg)	0.8	3.4	2.5

Recent Equivalence factors can be sourced from the Global Footprint Network. The case study however refers to the period 1998–1999 and we therefore applied the Monfreda et al. (2004) equivalence value for cropland of 2.1, which refers to the year 1999. It should be noted that energy land from fossil fuel was taken into account in Monfreda et al. (2004) calculations. We have not adjusted these values as it will not affect the comparability of our results, as only one land area is used. In order to apply this method across industries and land types, Equivalence factors computed without the inclusion of fossil fuel and nuclear power should be used.

Current Disturbance factors were calculated based on Reganold et al. (2001) soil quality ratings (Table 1, Section 2). These were based on an assessment of the following four soil quality functions: accommodate water entry; facilitate water movement and availability; resist surface structure degradation; sustain fruit quality and productivity. Each quality function was given a maximum of 25% and values were aggregated to determine total soil quality rating, where the value of 1 would represent soil conditions optimal for both fruit production and environmental quality (Reganold et al., 2001). Without altering the soil quality rating itself we have conducted a rescaling to transform it to Current Disturbance factor, so the values are made commensurable to the other parameters. The Current Disturbance factor is a measure of land disturbance and by definition ranges from 0 for slightly disturbed land to 1 for consumed land (built). For any crop land it will fluctuate from 0.6 (optimum value for replaced land) to 0.8 for degraded land (values according to Lenzen and Murray, 2001).

Potential Disturbance factors were calculated based on Reganold et al. (2001) environmental impact ratings (Table 1, Section 2). They applied an index developed by Stemilt Growers Inc of Wenatchee, Washington as part of their 'Responsible Choice' program. The assessment considered the active ingredient of each pesticide, dose and frequency of application, leaching potential, soil sorption index, chemical half-life, effects of chemicals on beneficial organisms, and others, all based on toxicological studies and chemical characteristics of each product input. (For more information see Reganold et al., 2001). The impact rating of the organic system was very low and was used as a reference point to conduct the rescaling. The Potential Disturbance factor expresses the potential future impact of the production method on the occupied and adjacent land and ecosystem and by definition fluctuates from 1 (none or slight potential disturbance) and over. We divided all impact ratings by 100 in order to transform them into Potential Disturbance factors while maintaining their relative importance, thus attributing to the organic system a Potential Disturbance factor of 1 and resulting in the values of 6.2 and 4.7 for the conventional and integrated systems respectively. The overall Disturbance factors were then calculated applying Eq. (5) (Table 1, Section 2). EF_A values were then derived by applying Eq. (3) (Table 1, Section 3).

3.2. Calculating EF_L

National EF figures are computed by the Global Footprint Network. US historical values for 1998 and 1999 were not available and therefore 2003 values were used as an approximation. Excluding carbon and nuclear footprint, the US EF was 3.37 ha/capita. Reganold et al. (2001) report annual labor hours per ha (Table 1, Section 4). Values were not provided for each year separately; therefore a single EF_L factor will be calculated for both years. From the annual labor hours per ha we derive the number of fulltime employees for each production system by multiplying with the area (in ha) and dividing with the annual labor hours for a full time employee assuming 52 weeks in a year and an average of 45 working hours per week. EF_L values were then derived applying the Eq. (4) (Table 1, Section 4).

3.3. Aggregation

The values of annual production for each production system were extracted from Reganold et al. (2001) (Table 1, Section 5). PEF was then calculated by applying Eq. (1). The conventional production method was found to cause an environmental impact four times greater than the organic method (Table 1, Section 6). These results stand in contrast to previous literature conclusions that the usefulness of the EF as a standalone environmental indicator is limited for product life cycles with relatively high mineral consumption and process-specific metal and dust emissions, as only in these groups can product EF substantially deviate from the group average (Huijbregts et al., 2008). It illustrates that taking into consideration current and potential land degradation, as well as excluding the carbon component which dominated previous calculations, allows significant differences in PEF values to surface even from first stage approximations and within a single product category in a primary industry.

4. Discussion

In an effort to assess significant costs that are not reflected in market prices, we are proposing a return to the use of a land measure, after having completed what seems to be a full historical circle (Fig. 2). The physiocrats believed that wealth is derived solely from the value or development of agricultural land, giving way to the labor theory of value, according to which the values of commodities are related to the labor needed to produce them, and later to the use of embodied energy as a measure of commodities value.

Financial valuation today takes into account all the above types of capital (land, labor, energy and others), however it fails to account for certain social or environmental costs, called negative externalities. Aggregation effects can lead to the affected resource (i.e., water or air quality) becoming scarce. Ecological footprinting has been suggested as a consistent way of measuring ecological externalities across industries.

Product ecological footprint (PEF) as an ecolabel provides otherwise unavailable information to consumers and allows them to realize and compare the environmental impact of a variety of products, raising awareness in categories of seemingly benign, conventional products, eliminating misconception and underestimation of ecological impacts. Following De Boer's (2003) classification of ecolabels as either benchmarks to achieve ideals (e.g., EU eco-label, Energy consumption label) or as bottom lines to avoid ills (e.g., Organic label, fair trade label), PEF would be a multi-sector label that would fall in the first category as a driver of environmental improvements. Labels of this form have been criticized firstly for the lack of a methodology that can clearly distinguish products within an entire category and secondly for the identification of an 'ideal' based on the existing products, thus discouraging innovation (De Boer, 2003). PEF addresses both these concerns, firstly due to its widely applicable methodological basis that can be applied within and across product categories, allowing direct comparisons to take place. Secondly, the rating is not related to an optimum, or to the product's relative position in the market, in contrast to EU eco-labelling that is awarded

Period	Concept	Scholars
2000's	EF Value	Wackernagel, Rees
1970's	Energy Value	Odum, Scienceman
1860's	Labor Value	Smith, Ricardo, Marx
1760-80's	Agricultural Land Value	Turgot, Quesnay

Fig. 2. Historical concepts of value.

to a percentage of the higher performers in each category. PEF is therefore a widely applicable, quantitative measure, dependent only upon the supply, manufacturing and distribution processes of the particular product.

We are not advocating the replacement of current labels, and especially sector-specific labels by PEF. Sector-specific labels are required for very complex products or when they act as indicators for the avoidance of sector-specific ills (e.g., Dolphin Safe label for tuna, No Sweat label, Green electricity label) (De Boer, 2003). PEF could only replace generic, multi-sector labels that work as benchmarks (such as the EU eco-label) and it could certainly have a complementary use to the majority of other ecolabels. PEF could act as a holistic value of product ecological impacts, providing a level of consistency across product categories that would reduce consumer confusion and mistrust to ecolabels in general. As a widely applicable, quantitative ecolabel, PEF could drive market adjustments of demand, supply and pricing, as comparisons and preference shifts would occur both within same product categories (e.g., farmed salmon vs free-range salmon, fresh vegetables vs frozen vegetables) and across product categories and product substitutes (e.g., fish vs meat, fruits vs vegetables). Fig. 3 provides a conceptual illustration of PEF market values upon a widespread adoption of the measure.

Such wide application can contribute to a top-down sharing of environmental responsibility, by allowing consumers to make informed and therefore responsible purchasing decisions. Consecutively, bottom-up influence of industry environmental performance increases in scope and sophistication. The main argument of the paper is that PEF adoption and disclosure will allow expression of consumer preference, reflecting on product demand and thus driving multiple firm behaviors towards reducing their products' ecological footprint. We envisage that as a result the variation of PEF values within product categories (Fig. 3) would decrease over time, shifting the category averages downwards. PEF data aggregation further allows monitoring single industry and aggregate industries PEF, and therefore collective environmental impact changes over time. Certain countries or areas may prove to generate lower PEF for specific industries or products available in certain markets. Similarly, certain products may result in being much more ecologically competitive compared to close substitutes. Long-term market shifts may be generated; however the methodology does not inherently generate bias towards any area, country, industry or product.

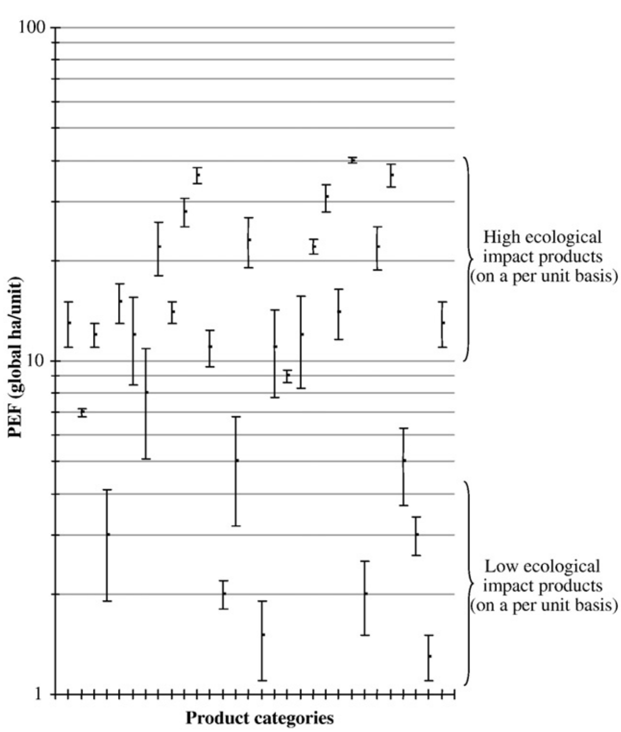

Fig. 3. Conceptual PEF market values.

In addition to providing the consumer the ability to choose products that have reduced environmental impact, such information is necessary to drive a cultural change away from ecologically disruptive consumption models. Private industry may achieve efficiency improvements (i.e., energy and material efficiency), however efficiency increases can lower the cost of production and eventually lead to increased consumption, and thus increased aggregate environmental impact (York and Rosa, 2003). This “efficiency paradox” has led to US energy consumption rising the fastest where efficiency improved the most (Rubin and Tal, 2007). Products may become more environmentally friendly, but if there is no mechanism preventing the consumer from reaping the financial benefits of efficiency improvements, and while social status is linked with increased levels of materialistic consumption, consumption per capita and aggregate environmental impacts will continue to increase. By applying the notion that one cannot manage what one cannot measure, a measure of product environmental impact that can be aggregated with each purchase can be used to measure and thus motivate individuals to manage their aggregate environmental impact. This aggregate Consumer Ecological Footprint (CEF) will be a personal measure for each individual or family. Supported by swipe card and electronic transaction technologies, CEF monitoring and management can become an automated and highly accurate process. If such a tool is marketed correctly by policymakers or integrated in tax and other policy measures it could assist in detaching economic and social status growth from consumption. Conspicuous consumption could gradually be replaced by a new culture of responsible consumption, whereby consumers “show off” their low-impact (but still high-comfort) consumption style.

Similar benefits can be achieved at the corporate level. As Figge and Hahn (2004) stress, increasing eco-efficiency can result in decreased eco-effectiveness due to the rebound effect of increased growth and use of environmental resources. Furthermore, investments in eco-efficiency can result in decreased economic effectiveness if opportunity costs of other investment opportunities are not taken into consideration (Figge and Hahn, 2004). PEF is a measure of eco-efficiency as it expresses the ecological impact per kg of product (or other applicable production unit). PEF decreases do not necessarily result in a decrease of the total corporate ecological impact, as the company may have increased its production (total number of units) and thus its total environmental impact. However, the aggregate PEF for all the products (units) that an organization produces, the Business Ecological Footprint (BEF), is a measure of company eco-effectiveness, in that it captures total ecological impact. BEF therefore becomes a critical measure for management when assessing alternative business scenarios or investment opportunities (i.e. investing in new technology), in which case it provides the ability to compare aggregate environmental savings to aggregate economic costs (ecological return on investment). A Pareto set for the two-objective minimization problem is illustrated in Fig. 4. Pareto optimality is a concept that formalizes the trade-off between a given set of mutually offsetting objectives, in this case cost of investment and the aggregate PEF (lower investment costs result in smaller reductions of ecological footprint, thus higher PEF values). A solution is Pareto optimal when it is not possible to improve one objective without deteriorating the other. A set of Pareto optimal solutions constitute the Pareto frontier. Decision makers can then select among scenarios that lie on the Pareto frontier.

PEF can further be used in multicriteria optimization methods to enhance decision making, integrating ecological considerations with other targets or concerns. One should be careful when using PEF for decision making not to attach one's own value system to the method. In

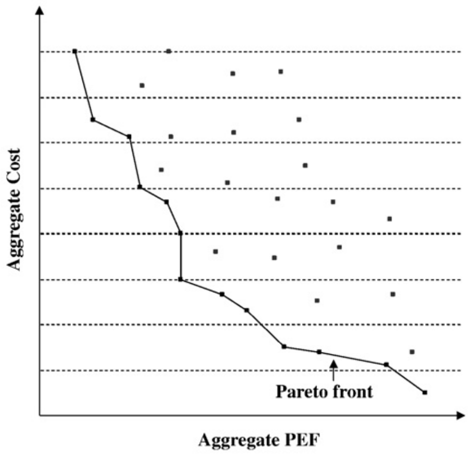

Fig. 4. Pareto front.

theory if we accept the aggregation methodology it is the final value (PEF) that assesses how optimal each production system is. However in reality one catchments' EF_A will be more important for the local stakeholders compared to the overall value that takes into consideration ecological impacts that have taken place elsewhere. Similarly if say two production systems have the same PEF, however one has a higher EF_A and the other a higher EF_M component, the production system with the lower EF_A impact will be preferred by local stakeholders. In other words if we don't differentiate geographically and all land has the same utility value then production systems with lower PEF would be considered "better". However, political and social preferences, as well as the commercial value of land (i.e. built land closer to city centers or areas with commercial activity and high residential density having higher economic value to rural areas), result in a complex utility function which differs for each stakeholder, attributing higher or lower values to individual PEF components (EF_A, EF_M, EF_L) and to PEF in general.

An example of attaching a specific value system to EF assessments is the association with the ecological deficit concept, assuming that "trade should only be allowed to the point where the sum of land use domestically and abroad equals the available productive land in the region" (Van den Bergh and Verbruggen, 1999). Based on such interpretations, the Ecological Footprint methodology has been criticized for introducing an anti-trade bias, supporting regional self-sufficiency (ecological autarky) as the most desirable scenario (Ayres, 2000; Van den Bergh and Verbruggen, 1999). This is however not a generic characteristic of the EF methodology; it is rather a subject of interpretation and use of the measure. As Wackernagel et al. (2004b) note, some may "claim that regions need to live within their ecological capacity", yet others may "celebrate trade for alleviating local economies from local constraints" and the EF analysis can provide an empirical base for examining these issues. PEF applications, for instance, would allow for the achievement of global environmental gains through trade and specialization, something that has not and cannot be achieved through national and international EF applications in the form of time series analysis.

4.1. Data availability

An important concern with any proposed measure and market application is the availability of data. When examining data availability one needs to differentiate between direct and indirect ecological impacts. Data for calculating direct ecological impacts will be available for first stage calculations for the majority of producers and manufacturers through primary data collection.

Indirect ecological impacts (embedded in activity inputs of materials, labor and energy) may not be readily available to the producer or manufacturer in first stage calculations. In order to calculate those values, global material yields would need to become readily available. Such information is currently available online in a variety of databases, such as OECD Statistics (see Agricultural Outlook under Agriculture and Fisheries, and Production under Industry and Services Statistics), The World Factbook by CIA and Eurostat. More detailed information at lower levels of aggregation is commonly available at the national level. However, all the necessary information will need to be extracted from these sources and made available in a consistent format to the industry to allow for first stage calculations to be completed. This could potentially be conducted at the national level, following a set of international guidelines.

It is important to stress that upon second stage calculations global material yields will gradually be eliminated from the system, as the respective ecological impact information will be sourced directly from the supply chain (in the form of PEF_M^1 values). International databases will therefore only need to maintain national Yield and Equivalence factors for each land type, values that are already available by the Global Footprint Network.

4.2. Limitations

Despite our efforts, there are some inherent limitations in the Ecological Footprint methodology. Firstly, the Ecological Footprint measure is based on the calculation of Yield and Equivalence factors. Although the proposed methodology gradually eliminates the use of global yields in materials EI estimates (substituting them with producer provided PEF), Yield and Equivalence factors averages is used in the area component in order to make adjustments due to bioproductivity differences of the same land type between various regions and of different land types globally. EF values are not measures of physical land, rather an equivalent of land area assumed to have world average bioproductivity. This idea is the backbone of the methodology, which allows for aggregation between a variety of land areas and therefore industrial functions. It limits the accuracy of the measure, as it is dependent upon the accuracy of national accounts of yields for each land type. In order to address this concern, an extended application of the measure will need to be supported by the formation of testing and accreditation bodies, not only for corporate supplied PEF measures, but also for international Yield and Equivalence factor databases.

Furthermore, the inherent complexity of the Ecological Footprint methodology is expected to limit end-user understanding of the process that leads to the formation of the aggregate PEF value. Users however are not required to understand the computational process. It is only necessary that they develop a level of trust in the process and the end values. Ongoing marketing and educational programs integrated both in schools and in the workplace, could assist in this direction. In the case of early adoption and first stage calculations, the limited accuracy of the end values should be stressed.

Lastly, we recognize that ecological impact is not easily identified and measured due to non-linear effects, time delays, threshold effects, etc. PEF is an effort to make headway in this direction and integrate both current and potential ecological disturbance, as well as direct and indirect ecological impacts of production, utilizing the ecological footprinting methodology to translate these impacts into comparable land measures of world average bioproductivity. In order to improve the accuracy of calculations further research is required within each industry to categorize production methods in terms of their Current and Potential Disturbance factors, assessing their ecological impact on biodiversity and soil degradation in a consistent way. Furthermore, the accuracy of calculations can be improved if land type bioproductivity yields are differentiated not on a national basis, but taking into consideration natural ecosystem boundaries and climatic differences to define regional boundaries instead. Other directions for further research include the definition of environmental policy options that could facilitate the implementation of Product Ecological Footprint, such as incentives for producers, link to carbon trading, incentives for consumers, usage for taxation by applying "the polluter pays" principle, subsidies for low PEF production or consumption, etc. The development of such instruments should be complemented with education initiatives, not on changing preferences, but on helping consumers understand the economic–ecological instruments that are in place (Wagner, 2006).

5. Conclusion

We have developed a market-driven, self-improving, consumer information process based on wide scale calculation and disclosure of Product Ecological Footprints. The proposed method gradually reduces dependence on international databases and increases accuracy of end values. In this process we have addressed some of the major criticisms of the generic EF methodology, such as the inability to account for unsustainable production methods and the dependence on the controversial carbon component.

PEF provides a practical way to link individuals' consumption with their ecological impact, thus developing a market-driven approach to internalizing ecological externalities. This shift in market information dynamics allows consumers to conduct comparisons and express their ecological preferences, directly impacting demand. The quantitative nature of the measure increases comprehension and comparability, as there is no need for classification (like EU energy levels) or use of positive and negative expressions in labelling. Furthermore, the indicator is a single aggregate number, but can also provide more analytical information by outlining impacts per land or EI category. In addition to the above, when aggregated it becomes an eco-efficiency measure that can be used to monitor the ecological performance of individuals (Consumer Ecological Footprint) and businesses (Business Ecological Footprint), becoming a useful managerial tool.

PEF's real strength lies in its level of adoption. Like the majority of information technology innovations, we estimate increasing returns to scale. The wider the adoption of the label, the greater the usefulness for the consumer, as it allows for wider comparability of products. Also, wider applicability would result in reduced implementation costs, as PEF for processed material inputs becomes available and does not need to be estimated. A transition to second stage calculations will then result in increasing accuracy and thus increased usefulness both for business and individual users. When higher accuracy is achieved, e-ABC can be applied to further break down PEF contributions of each activity, resulting in identification of ecological impact drivers and improvement opportunities within business processes. As traditional activity based costing and modelling encouraged more cost-conscious design (Tornberg et al., 2002), e-ABC is expected to drive eco-technological innovations.

Finally, one should be very cautious not to attach one's value system to the method, like some proponents of the ecological footprinting methodology may be prone to doing. One should take PEF for what it is; a measure of biological productivity, the amount of land of world average biological productivity that would be needed to sustain the production of the respective product and accumulate the wastes generated in the process. By making this measure available to decision makers (may they be consumers, business managers or politicians), one allows for the ecological component to be included and evaluated along with other social, economic and political factors.

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