



ANALYSIS

# Design and development of a measuring method for environmental sustainability in food production systems

P.W. Gerbens-Leenes\*, H.C. Moll, A.J.M. Schoot Uiterkamp

*Center for Energy and Environmental Studies (IVEM), University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

Received 22 July 2002; received in revised form 24 April 2003; accepted 24 April 2003

## Abstract

These days, sustainability is a key issue for many private companies that address their sustainable corporate performance (SCP). The perspective is essential for their license to operate and forms the basis for business principles and practices. The lack of internationally accepted reporting standards on what, when and where to report makes it difficult to assess sustainability, however. Moreover, measuring tools providing information on SCP are only the first step towards sustainability. To prevent negative effects of operations being transferred from one company to another, the second step is the development of a system-based approach for all companies that contribute to an end product. This paper presents the findings of a study about the use of environmental indicators for food production and proposes a measuring method for environmental sustainability in food production systems. The study shows that environmental SCP often focuses on events at a local level. The enormous number of indicators found in the literature generates too much data that often provide no additional knowledge on the environmental sustainability of a system. Moreover, although environmental research has addressed many aspects of sustainability, it has often ignored interactions. Overall environmental implications of food production are therefore poorly understood. The proposed measuring method uses three indicators that address global environmental issues: the use of energy (from both fossil and renewable sources), land and water. The systemic approach can calculate trade-offs along supply chains that make up a production system. The use of the method implies an extension of environmental SCP towards the overall performance of a production system. The final outcome is expressed in three performance indicators: the total land, energy and water requirement per kilogram of available food. For companies, the data generated can be used to compare trends over time, to compare results with targets and to benchmark a company against others. For consumers, data can be used to compare the environmental effects of various foods. The method is also applicable to other business sectors. The study is part of a multidisciplinary project on the scientific modeling and measuring of SCP involving economic, social and

*Abbreviations:* EMAS, European Union's Eco-Management and Audit scheme; EMS, environmental management systems; ERE, energy required for energy; EU, European Union; FAO, Food and Agricultural Organisation of the United Nations; GRI, global reporting initiative; HEI, high environmental impact; IPCC, International Panel on Climate Change; ISO, International Standards Organisation; LCA, life cycle assessment; LCSP, Lowell Center for Sustainable Production; OECD, Organisation for Economic Co-operation and Development; SCP, sustainable corporate performance.

\* Corresponding author. Tel.: +31-50-363-4611; fax: +31-50-363-7168.

E-mail address: [w.gerbens@fwn.rug.nl](mailto:w.gerbens@fwn.rug.nl) (P.W. Gerbens-Leenes).

environmental dimensions. Acceptance of the measuring methods developed may be a powerful contribution towards creating sustainable business practices.

© 2003 Elsevier B.V. All rights reserved.

*Keywords:* Corporate responsibility; Corporate performance; Environment; Food; Indicators for sustainable development; Production systems; Sustainability

---

## 1. Introduction

During the last decades, environmental issues have evolved from pollution and depletion of natural resources towards global issues, such as climate change. Three important milestones have been: the identification of chlorinated pesticides as major pollutants in ‘*Silent spring*’ (Carson, 1962), the notion that non-renewable natural resources can become depleted (Meadows, 1972) and the introduction of the sustainability concept in the ‘*Brundtland report*’ (World Commission on Environment and Development, 1987).

Private companies have attempted to respond to environmental issues. Nowadays, the economic performance of business is often seen in conjunction with its social and environmental performances (Steg et al., 2001). Environmental sustainable corporate performance (SCP), defined as ‘Good housekeeping’ through prevention of pollution and waste and efficient use of scarce resources, is considered important for every company. For many companies, this new perspective is essential for their license to operate and forms the basis for business principles and practices. The perspective meets societal demands for responsible business behavior and it fits into a modern culture requesting accountability and transparency from powerful institutions. The increasing influence of companies on societies all over the world should go along with their own increasing responsibility and accountability (SER, 2001). In some countries, however, regulations are sometimes less developed than the standards of companies. Therefore, proactive management is sometimes needed because regulatory compliance is not always sufficient to manage the negative environmental or social impacts of business operations effectively. Failure to manage these impacts raises three serious risks: the threat of increased regula-

tory control by national governments and international organizations, financial risks caused by pollution and large resource use, and damage to the corporate image (Rondinelli and Berry, 2000). Important developments for the issue of sustainability were the foundation of the World Business Council for Sustainable Development (1997), the foundation of the GRI (Global Reporting Initiative, 2000) and the development of standards for environmental management systems, such as the ISO and EMAS standards (Organisation for Economic Co-operation and Development; OECD, 2001). However, the lack of internationally accepted reporting standards on what, when and where to report makes it difficult to assess sustainability.

For the manufacture of a final consumption item, many processes take place in several companies that form a production system. These processes generate a large variety of impacts. Existing sustainable business practices tend to focus on company performance rather than on the performance of the production system as a whole. This has two important disadvantages. First, if companies center on impacts generated by their own activities, large company efforts may still result in small improvements in the production system. Second, the focus on company performance often implies that impacts on a local level of scale, for which the company is responsible, are addressed. Impacts on a global level of scale, for which all companies in a production system are responsible, require a systems approach resulting in a shared responsibility. An important step towards sustainable business practices is the design and development of a system-based measuring tool providing information on the sustainability of all companies that contribute to an end product. A technique for assessing the potential environmental impacts associated with the manufacture of a product is

life cycle assessment (LCA) (Heijungs et al., 1992). The systems approach considers all the companies involved, follows products, materials and substances from cradle to grave, and assesses relevant physical flows (Moll, 1993). The approach prevents that the negative effects of operations being transferred from one company to another or to consumers. A systems approach implies that companies not only focus on their own performance, but also state what they expect of business partners. For example, some companies demand that their suppliers refrain from child labor or create good working conditions (OECD, 2001). While companies have often focused on their own performance, sustainability related scientific research has mainly addressed isolated issues such as, for example, climate change and related fossil energy use. Scientific research should also address sustainability issues in an integrated way, identify interplay and avoid ‘problem shifting’. At present, it is not possible to measure sustainability from a system perspective because an integrated measuring method addressing the three aspects of sustainability—economic, social and environmental—has not yet been designed and developed.

There are many different and often rather complex production systems manufacturing an enormous variety of consumer items. This study focuses on one complex system: the production of food. Food production requires the input of natural capital, such as land and water, but also of energy provided by the natural capital. A doubling of global food demand is expected in the next 50 years. This poses huge challenges for the sustainability of food production (Tilman et al., 2002). Environmental impacts of agriculture often remain unquantified and therefore do not influence farmer or societal decision-making about production methods. This paper presents the findings of a study about the use of environmental indicators for food production. It proposes a measuring method based on a small set of system-based indicators for the assessment of sustainable, environmental performance in food production systems.

The study is part of a multidisciplinary research project on the definition and measuring of SCP.

The project defines sustainability in three dimensions: economic, social and environmental. It focuses on the definition of SCP and on the development of a practical measuring system. SCP is defined in relation to the potential addition of economic, social and environmental value to the society through corporate activities. These three ‘added values’ are the components of the ‘sustainability value added’ of a company. SCP develops activities that increase the economic and social capital in society without affecting its natural capital. The general findings of the SCP project are reported elsewhere (e.g. Steg et al., 2001). The specific aims of this paper are:

- to identify and analyze the methods used so far to describe and improve environmentally sustainable business practices for food production;
- to identify the key global issues relevant for food production from the perspective of the main functions of the natural capital needed for the proper function of society;
- to design and develop a measuring method based on a small set of system indicators that address the main environmental impacts of food production.

The measuring method proposed here considers the entire production system and addresses global environmental issues. It calculates the use of resources for food production, but it is also applicable to other production systems. Acceptance of the measuring methods developed in the SCP project may make a powerful contribution towards creating sustainable business practices.

## 2. System description

Food constitutes an important and indispensable group of consumer items. In the Netherlands in 2002, for example, households spent 17% of their budgets in this category (CBS, 2002). Food items are produced in a complex system made up of many processes in several supply chains. To manufacture a cake, for example, various commodities from agriculture are needed, including wheat, sugar beet, milk and eggs. The food

industry processes some commodities to produce basic ingredients for cakes: sugar, flour and butter. Finally, using ingredients from different supply chains, bakeries make cakes. Transportation by airplane, boat, train or truck provides the global availability of commodities and foods. The food system encompasses production, consumption and final waste handling. Fig. 1 shows a raw materials production chain of the system, the system boundary of this study and the network of supporting business sectors. The purpose of this paper was to design and develop a measuring method for environmental sustainability in food production systems. Consumption, waste handling

and the supporting network, therefore, fall beyond the scope of the study because the application of the method is targeted to company performance.

The food production system consists of a huge number of processes. A process is defined here as an activity with an identifiable beginning and end that takes place at a certain location, with a fixed ratio of input and output flows. The output of one process is the input of the next one. Processes can sometimes be broken down into discrete sub-processes or unit operations as defined in the chemical process industry. The baking of a cake, for example, consists of several sub-processes, such as mixing the ingredients and putting the cakes

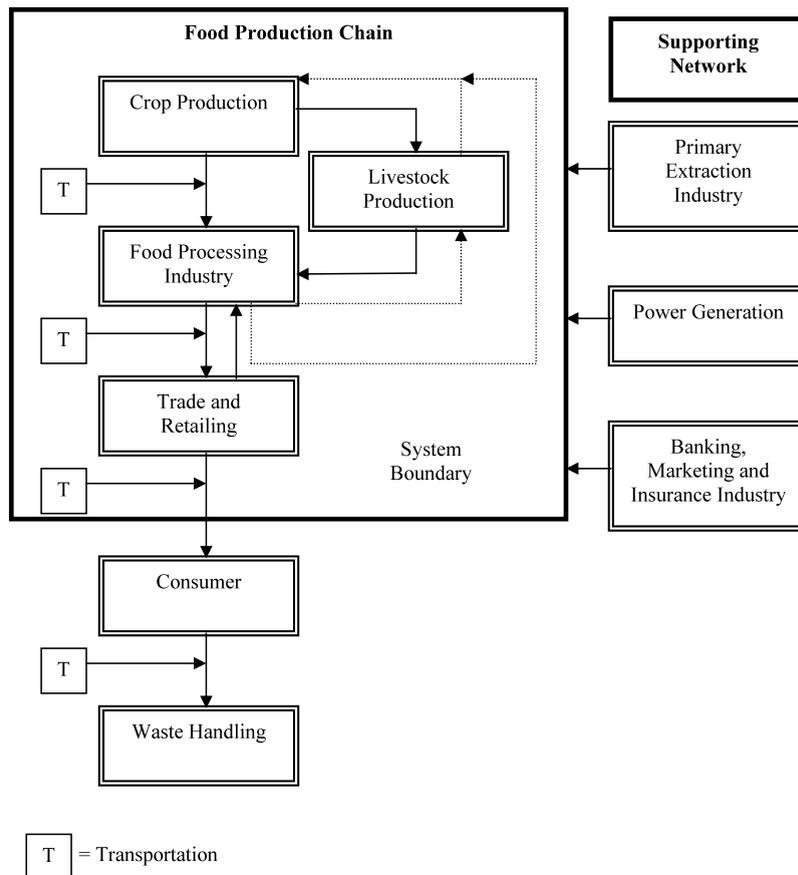


Fig. 1. Overview of the food production system, the system boundary, the output to consumers and the network of supporting business sectors that also provide their services to other production systems. Production processes take place in several business sectors represented by the boxes. A series of processes forms a production chain. The arrows show transportation of physical streams between the links of the chain. Closed arrows represent transportation in one direction at level 2, open arrows represent physical streams in the opposite direction at level 3.

into an oven. This study distinguished three scale levels for the food production system: the first level is the raw materials process level, the second level is the raw materials chain and the third level is the food production web. At level one, processes for the manufacture of raw materials take place. At level two, a series of processes form a linear production chain and provide raw materials. In contrast to processes, production chains have variable input and output flows. At level three, raw materials originating from several chains join and form a complex production web. Physical streams sometimes flow in the opposite direction. At this level, the process of the manufacture of a final food item requiring input from more than one chain takes place. Fig. 1 shows a raw materials production chain at level two and two return flows at level three. Private companies are defined here as business units in which production and transportation processes take place that contribute to the manufacture and availability of a final food item. Some companies are responsible for only one process while others control complete production webs.

The complexity of the food system is demonstrated by an example, the manufacture of a Dutch cake. Processes take place in several companies in various sectors: a French farm grows wheat, a Dutch flour manufacturing company processes the wheat, a bakery manufactures the cakes and several transportation companies bring raw materials from supplier to producer. At level one, processes and sub-processes contributing to the manufacture of raw materials, like sowing wheat and processing sugar beet, take place. At level two, the production of flour is an example of a raw materials production chain. First, the wheat is grown. Second, the wheat is transported to the Netherlands. Third, the wheat is processed to make flour. At level three, the web level, the chains necessary for the raw materials for cakes are joined, such as production chains for eggs, sugar, milk and butter. At this level, the process of baking the cake, the final food item, takes place. Sometimes physical flows in the opposite direction occur; for example, waste streams from the sugar industry can be reused for livestock fodder. Fed to

cows, these waste streams contribute to butter manufacture for cakes.

In a production web, all chain links and transportation activities between links contribute to the overall environmental impact of a food item. For the production of a package of frozen French beans at level two, for example, vegetables are grown, processed, packed, transported and stored. These processes require the input of scarce natural resources, such as land, energy carriers and water, and contribute to pollution (Tilman et al., 2002). The environmental impacts of processes in chain links or of transportation between links often differ considerably. This is illustrated by an example taken from energy studies (Kok et al., 2001). Table 1 shows the energy requirements for processes and transportation in production chains of Dutch vegetables.

Table 1 reveals large differences among the specific energy requirements for production processes and for transportation modes (MJ per kg, or MJ per 1000 kg per km). The final energy requirement of 1 kg of vegetables varies by a factor of 15. Fresh vegetables produced in Africa and transported by airplane to the Netherlands require 88 MJ per kg, whereas locally produced

Table 1  
Overview of energy requirements in production chains of vegetables available in the Netherlands (source: Kok et al., 2001)

Process	Energy requirement (MJ per kg vegetables)
<i>Agriculture</i>	
Open air production	0.7
Greenhouse production	26.2
	Energy requirement (MJ per 1000 kg/km)
<i>Transportation</i>	
Ship (inland shipping)	0.6
Ship (sea, bulk)	0.1
Lorry	1.7
Train	0.6
Airplane	9.0

open air vegetables require only 6 MJ per kg (Kramer et al., 1994). In 1990, an average Dutch household consumed 162 kg of vegetables with a related energy requirement of 2500 MJ (Gerbens-Leenes, 1999). The example shows the necessity of a system-based approach for the assessment of sustainability related to food production. Not only the performance of an individual company or business sector is important, but also the overall performance of all companies in a production chain or web. Differences among production methods, transportation modes and distances heavily influence the environmental pressure of a final food.

### 3. Methods

#### 3.1. Analysis of existing measuring methods and scientific research issues

Business mainly addresses sustainability issues using a bottom-up approach and focuses on the performance of individual companies. Scientific research, on the other hand, often focuses on sustainability issues on a global level using a top-down approach. This study inventoried and analyzed these two approaches. It performed a literature search of scientific publications on items concerning sustainability from the perspective of sectors involved in food production. These sectors were agriculture, transportation, manufacturing and retailing. Environmental status reports of individual companies fell beyond the scope of this study. A recent OECD report (2001) provided additional information. The results give an impression of the efforts made so far to measure and report on sustainability issues for food production. This study identified existing environmental sustainability indicators and clustered them according to their level of scale. These levels were the local, regional and global level. The analysis of the top-down approaches focused on the identification of global issues relevant for food production identified by environmental researchers. Section 4 presents the results of the literature search.

#### 3.2. Design and development of an environmental measuring method

To design and develop a system-based measuring method for food production, this study used a combination of top-down and bottom-up approaches. The starting point was the selection of a small set of environmental sustainability indicators addressing issues on a global level relevant for food production. The bottom-up approach implies that actual measurements take place in companies. The measuring method provides information on three system levels: the process level, the raw materials production chain level and the production web level. For a company, information about environmental performance becomes available for benchmarking or for the improvement of performance over time. At the production chain level, information about the environmental pressure of suppliers becomes available. At the web level, the combination of the performances of all companies reveals the total environmental pressure related to the production of a final food. Section 5 presents a detailed description of the method.

### 4. Results

#### 4.1. Environmentally sustainable business practices

The literature search revealed a large number of publications on the relationship between sustainability and business. The following presents the main results that apply to all company types. Some studies have identified consumer demand for quality products that includes environmental requirements (Stauffer, 1997; Boudouropoulos and Arvanitoyannis, 1999). Societal demand has led companies to recognize that proactive environmental management leads to profitable results (Stauffer, 1997). A study on environmental supply chain dynamics (Hall, 2000) has shown that environmental change within a supply chain can be stimulated by a so-called 'channel leader' with sufficient power over suppliers. These 'channel leaders' must be under specific environmental pressure themselves. A number of studies have found that one of the most significant pressures

forcing firms into addressing environmental concerns was the emergence of the ‘green consumer’ (Williams et al., 1993; Steger, 1993; Drumwright, 1994; Elkington, 1994). Consumer pressure, however, is almost entirely focused on recognizable consumer goods, often associated with large multinationals (Hall, 2000). Firms that operate far from the end consumer and are hidden within a supply chain are under little environmental pressure. For example, it is unlikely that airline passengers fully understand the environmental impacts of aircraft manufacturing and would therefore exert little pressure on airlines to purchase ‘green aircraft’.

Other studies have demonstrated that the economic, social and environmental impacts of multinationals cause concern (OECD, 2001). Many firms have responded to these concerns with managerial innovations, including codes of conduct. This study found three important steps towards the measuring and reporting of sustainability. The first step was in the 1970s. Companies started to issue policy statements or *principles* (OECD, 2001). These principles are codes of conduct, stating commitments on business ethics and legal compliance. The first corporate code of conduct was the 1977 ‘Issuance of guidelines on conducting business in South Africa’ by an automobile manufacturer. Later, many other companies adopted these ‘Sullivan Principles’ or began to issue corporate codes dealing with business ethics. The second step was the development of management systems or *practices* that refer to action strategies and programs. More recently, the third step formulated the *outcomes*, standards providing guidance for business reporting on non-financial performance. The literature search showed, however, that many companies mainly focus on their own performance and that only some firms feel responsible for their suppliers’ activities (Hall, 2000).

At the end of the 20th century, many multinationals certified their environmental management systems (EMS) under ISO 14000 standards and many others were in the process of doing so (Rondinelli and Vastag, 2000). Nowadays, an increasing number of companies publish information on environmental impacts of their activities, the outcomes. According to the OECD study

(2001), however, the absence of internationally agreed reporting standards on sustainability results in a range from rudimentary reporting to full-scale reporting. For example, only 17% of European companies and 41% of European high environment impact (HEI) companies reported in some way on their environmental performance. Moreover, companies made their own choices regarding the scope and depth of reporting. Of all the companies that reported on environmental performance, 62% provided some quantitative data while only 15% of these companies reported on all key issues.

#### 4.2. Sustainability indicators from the perspective of companies

The study found many attempts to develop tools to measure sustainable business performance. This is in line with the OECD report (2001). For example, the International Standards Organisation (ISO) (Boudouropoulos and Arvanitoyannis, 1999; ISO World, 2000), the EU’s Eco-Auditing Management System (EMAS) (Kolk, 2000; OECD, 2001) and the Lowell Center for Sustainable Production (LCSP) (Veleva and Ellenbecker, 2001) have developed indicators for sustainable production. The LCSP has presented 22 indicators on five levels of scale that can be calculated as totals or per unit of a product. To operationalize business principles and to measure performance, business sectors and scientists have developed many environmental indicators. Table 2 is an overview of frequently used indicators for environmental sustainability in food production. First, Table 2 shows indicators according to the business sector they apply to. Second, it ranges indicators according to three levels of scale: the local level, the regional level and the global level.

For the agricultural sector, Table 2 shows indicators proposed by agricultural researchers, the Dutch government, and the EU. Many of these indicators address issues at a local or regional level, such as pollution and the quality of resources. This results in a large number of indicators. At a global level, indicators address the use of phosphorus, land, energy and emission of greenhouse gasses. Although sustainability concepts

Table 2  
Overview of frequently used indicators for environmental sustainability in food production

Local level	Regional level	Global level
<b>Agriculture</b>		
<i>Pollution:</i> emission of NH <sub>3</sub> , NO <sub>x</sub> (I: a, b, II, III); SO <sub>2</sub> (II); pesticides (I: a, b, c, II); N, P (I: a, b, c, II); heavy metals (a, c)	<i>Depletion of resources:</i> ecological structures (I: b); % unsprayed area (I: c); % uncultivated area (I: c); land use (I: e, f); water use (II); crop diversity (I: b)	<i>Depletion of resources:</i> phosphorus use (I: b); land use (I: e, f); energy use (I: b, c, II)
<i>Efficiency:</i> N efficiency (I: c)		<i>Climate change:</i> emission of methane (I: d, III); N <sub>2</sub> O (I: d); CO <sub>2</sub> (I: b, d, II, III)
<i>Depletion of resources:</i> concentration soil organic matter (I: b); alteration of ion balance (I: a); salinization (I: a); alteration of biological cycles (I: a); soil cover (I: b); % weeds in grain crops (c)		
<b>Transportation</b>		
<i>Quality of urban environment:</i> congestion, deterioration of streets, public places and architectural heritage (a, b); noise (a, b, c, d); malodor (c)	<i>Depletion of resources:</i> land use (a, b, c)	<i>Depletion of resources:</i> material use (c); natural resource degradation (d)
<i>Pollution:</i> emission of: lead (a); NO <sub>x</sub> ; volatile organic compounds (VOC), particulates (a, b, c, d); CO (a, c, d); hydrocarbons (HC) (a, b, d); SO <sub>2</sub> (a, c, d); mean values of ozone (a, d); soil pollution by petroleum product disposal, sulphuric acid leaks, heavy metal sludges (d)	<i>Pollution:</i> oil spills, loss of cargo, operational pollution from shipping activities (a)	<i>Climate change:</i> burning of fossil fuels and related emission of CO <sub>2</sub> (a, b, c, d); emission of N <sub>2</sub> O, CH <sub>4</sub> , HFK's, PFK's, SF <sub>6</sub> (c)
<b>Manufacturing industry</b>		
<i>Waste treatment:</i> reuse, recycling, incineration, deposition (I, a)	<i>Procurement planning:</i> supplier selection, surveillance of supplier's performance (I)	<i>Energy planning:</i> total energy consumption, energy mix, consumption of non-renewable energy sources, energy efficiency (I)
<i>Environmental management system performance:</i> performance total system, organization of product development/design	<i>Transport planning:</i> transport media selection, environmental performance of transport media in use (I)	
<i>Production planning:</i> rejects and material waste performance (I)	<i>Pollution:</i> emission of SO <sub>2</sub> , water quality (a)	
<i>Production:</i> environmental performance of processes, number and consequences of environmental incidents (I, a)	<i>Depletion of resources:</i> protection of habitats, corridors, and endangered species; water use (a)	
<i>Pollution:</i> emission of VOC's, dioxins, heavy metals, SO <sub>2</sub> , NO <sub>2</sub> , particulates, O <sub>3</sub> , CO, development of cleaner technologies (a)	<i>Other issues:</i> reduction of animal experimentation (a)	
<b>Retailing</b>		
<i>Pollution:</i> pesticide and herbicide emissions, water quality (a, b, c, d)	<i>Depletion of resources:</i> reduction of biodiversity, water depletion (a); forest depletion (a, b, c, d)	<i>Pollution:</i> ozone depletion (a)
<i>Quality of urban environment:</i> noise and traffic congestion, aesthetics (a)	<i>Other issues:</i> animal welfare, biotechnology (a, b, c, d); inefficient agriculture (a)	<i>Depletion of resources and climate change:</i> oil and gas depletion, use of fossil fuels (a)

The table shows indicators according to the business sector they apply to: agriculture, transportation, manufacturing industry and retailing. Indicators are ranged according to three levels of scale: the local level, regional level and global level. **Agriculture:** I. Scientists, e.g. a: Giupponi (1998); b: Bockstaller et al. (1997); c: Halberg (1999); d: Kramer et al. (1999); e: Gerbens-Leenes (1999) Wackernagel et al. (1997). II. The Netherlands government (Source: Nationaal Milieubeleidsplan 3, (Boer et al., (1998)). III. The EU (Source: EUR-Lex, 1993). **Transportation:** a: EU (Source: European Community (1993)); b: the Netherlands government (Source: Netelenbos et al. (1999)); c: environmental scientists (Source: (Bouwman (2000))); d: business scientists (Source: Rondinelli and Berry (2000)). **Manufacturing industry:** I Source: Thoresen (1999); a: EU (Source: European Community (1993)). **Retailing:** a: Bansal and Kilbourne (2001); b: Drumwright (1994); c: Steger (1993); d: Williams et al. (1993).

exist for agriculture, they do not necessarily imply a measurable set of indicators for their characterization. Some concepts are philosophical by their very nature (Hansen, 1996) and therefore difficult to measure. In his overview article, Hansen (1996) described these philosophical approaches to sustainable agriculture. Approaches are often contrasted with conventional agriculture that is characterized as capital-intensive, large-scale, with the extensive use of artificial fertilizers, herbicides and pesticides, and intensive animal husbandry. Environmental values associated with sustainability include mimicry of nature and an ecocentric ethic. That overview has also shown that some other concepts interpret sustainability as a set of strategies providing useful, measurable indicators.

For the transportation sector, indicators have not only been proposed by the EU, governments and environmental researchers, but also by business researchers. Table 1 shows that most indicators address pollution and the related quality of the urban environment on a local level, whereas relatively few indicators address issues at regional or global levels. For the manufacturing industry, business researchers, among others, have described the relationship between companies and the environment. Here, indicators mainly address emissions by the company on a local level. Furthermore, energy use and climate change have been recognized as environmental problems. In order to control performance, some companies developed environmental performance indicators and recognized the importance of the environmental performance of suppliers (Thoresen, 1999). The EU in particular recognizes many environmental issues related to the manufacturing industry. For the retailing sector, environmental issues in preceding links in the food chain are very important (Bansal and Kilbourne, 2001). Retailers pay less attention to environmental impacts related to their own activities, such as distribution, choice of location and merchandising and pay more attention to environmental effects in preceding links in the supply chains, such as agriculture.

Table 2 shows that further down a production chain, the environmental performance of the whole chain becomes more important than the

performance of an individual company. In the first chain link, agriculture is mainly concerned with the environmental effects of their own performance. Transportation also focuses on own performance. Although the manufacturing industry mainly focuses on own performance, suppliers' performance is also important. In the last chain link, retailing is mainly concerned with the environmental effects of upstream activities.

#### *4.3. Sustainability issues from the perspective of environmental research*

Environmental research recognizes the importance of chain management for the sustainability of food production. Life cycle assessment (LCA), for example, is a technique for assessing the potential impacts associated with a product, by compiling an inventory of relevant environmental exchanges of the product throughout its life cycle ('cradle to grave') and evaluating the potential environmental impacts associated with those exchanges (Heijungs et al., 1992; Weidema, 1999; Weidema and Meeusen, 2000). It is argued that in order to make food systems more sustainable, it is important to avoid trade-offs between chain links. Many studies have addressed energy and some have developed concepts like indirect energy use (e.g. Wilting, 1996; Wilting et al., 1999; Carlsson-Kanyama and Faist, 2000; Kok et al., 2001). In these concepts, all energy use in and between chain links contributes to the final energy intensity (MJ per financial unit), or the final energy requirement (MJ per physical unit) of a product. These studies formed the basis for a large number of studies addressing energy reduction strategies in food chains (e.g. Kok and Kramer, 1995; Carlsson-Kanyama, 1997, 1998; Gerbens-Leenes, 1999; Andersson, 2000; Dutilh and Kramer, 2000; Gerbens-Leenes, 2000).

Several studies have recognized the importance of land use for food production. For example, Wackernagel et al. (1997) developed the concept of the ecological footprint that evaluates human land use. Some authors have shown the importance of food consumption patterns on land requirements (Gerbens-Leenes, 1999; Van Vuuren and Smeets, 2000; Gerbens-Leenes et al., 2002), while agricul-

tural studies have demonstrated the relationship between food security and land use (Penning de Vries et al., 1995; Bouma et al., 1998; Groot et al., 1998). Andersson (2000) has proposed the application of LCA to food production systems, and has recognized the importance of energy, land, water, and nutrients for the sustainability of these systems.

## 5. Design and development of a measuring method

The measuring method proposed here is part of a multidisciplinary project on the scientific modeling and measuring of SCP aimed at the development of a three-dimensional model involving economic, social and environmental dimensions. Some environmental effects of individual companies become manifest at local and regional scales. Examples are noise, malodor and emissions of locally polluting substances. The overall project considered these effects to be indicators of social SCP and addressed them in the social part of the SCP project. This study focused on the integral environmental effects of operations of all companies that contribute to the manufacturing of a final food on a global scale leading to the concept of shared responsibility. It designed and developed a measuring method in three steps. First, this study integrated bottom-up and top-down approaches, second it selected relevant indicators and third it designed a flow chart of calculations and inputs thereby adopting the life cycle approach and allocation methodology from LCA.

### 5.1. *Integration of bottom-up and top-down approaches*

Table 2 demonstrates that environmental corporate performance mainly focuses on local events, such as pollution by emissions. This leads to an enormous variety of indicators that are often not in line with general constraints for indicators, that focus on company rather than production system performance and that generate too much data. As a result, too much information is generated that in many cases provides no additional knowledge on the environmental sustain-

ability of the production system as a whole. Therefore, the environmental effects on the web level, to which all companies contribute, as well as global issues, are paid too little attention.

Environmental research has addressed many aspects of sustainability, such as energy use and global warming. It has calculated the trade-offs between chain links for the environmental effects of production, but has often ignored the interactions between aspects of sustainability. When calculating the energy reductions for food, for example, environmental studies have not considered the effects of these strategies on other resources (e.g. Kramer, 2000). Overall environmental implications of food production, therefore, are poorly understood. A measuring method for environmental sustainability in food production systems should also address these interactions.

LCA has already developed methods to evaluate the environmental impacts related to the manufacturing of products. The basis for the calculations is the life cycle approach. Environmental effects caused by processes that generate more than one output are assessed by the method of allocation (Heijungs et al., 1992). In general, LCA is independent of the location of a production system and assumes a linear relationship between the amount of product manufactured and the environmental impacts (Wegener Sleeswijk et al., 1996). This study proposes a measuring method that integrates top-down and bottom-up approaches, using the strengths of both. It adopts the methodology of the life cycle approach and allocation from LCA. First, it identifies main environmental issues on a global level. Second, it proposes a small set of indicators to measure these issues. Third, it upscales measurements in companies for individual processes to the total production system.

### 5.2. *Selection of indicators*

Natural capital is a key concept in ecological economics (Costanza and Daly, 1992) and refers to the possibility of the natural environment to provide products and to perform functions essential for human existence (Ekins et al., 2003). There are four types of natural capital, air, water, land

and habitats (Ekins and Simon, 2003) that perform four important functions for society. These are the ‘source function’, the ‘sink function’ (Daly, 1990), the ‘life support function’ (Van Dieren, 1995; Ekins and Simon, 2003) and the ‘human health and welfare function’ (Ekins and Simon, 2003). The ‘source function’ refers to the delivery of natural resources to the economy, such as energy carriers, agricultural land or biological resources. The ‘sink function’ implies the possibility to dispose of waste. The ‘life support function’ addresses a set of functions performed by land, water and air essential to sustain life. The ‘human health and welfare function’ refers to services that maintain health and contribute to human well-being. According to Daly (1990), the sustainable use of natural resources has three implications: (i) renewable resources should not be exploited at a greater rate than their regeneration level; (ii) non-renewable resources should not be depleted at a greater rate than the development rate of renewable substitutes; and (iii) the absorption and regeneration capacity of the natural environment should not be exceeded. The four types of natural capital are all essential for the production of food, while the four functions are all important for food production and consumption.

For the selection of sustainability indicators for the food production system, this study used three criteria: general functions and constraints of indicators, essential natural resources for food production and the functions of the natural capital to society. For the selection of indicators, the study used four constraints: (i) indicators provide relevant information about the sustainability of the system; (ii) reliable and accurate measurement is possible; (iii) data are available; (iv) information can change management choices and optimize production. For the selection of essential resources, the study addressed three important requirements for food production: agricultural land, fresh water and energy input. For land and water input, the human use of these resources is mainly dominated by food production; for energy input, the use for food production is substantial. Globally, 38% of the total land area is used for food production (FAO, 2002). Due to industrialization, urbanization, infrastructural development, land degrada-

tion and desertification, however, arable land is becoming an increasingly scarce resource. It is estimated that the global agricultural land area is decreasing at a rate of 7% per decade (Oldeman et al., 1991). Land is needed for food, but in the near future, probably also for the generation of renewable energy. The area to be set aside for renewable energy, such as energy generated by wind, biomass, photovoltaic cells and water, is substantial. The study therefore proposes the quantity of land use as an indicator for the use of scarce natural resources of the ‘source function’, as an indicator for the ‘life support function’ and as an indicator for the potential competition among agricultural interests, energy production capacity and the requirement of natural areas for biodiversity.

The second essential requirement for food production is the availability of sufficient fresh water of adequate quality. In large parts of the world, interaction among plants, land and water sometimes causes irreversible environmental effects that threaten food production (Falkenmark, 1989). In some parts of the world, water is a scarce resource in a highly competitive context. Water for urban supply or for industrial activities then competes with the large quantities needed for agriculture. In many countries, there is already a scramble for land (Falkenmark, 1989). If a ‘water scramble’ is not to follow, extremely wise consideration of technical, financial, economic, political, legal and administrative issues is needed. This study therefore proposes the quantity of fresh water use as an indicator for the use of scarce, high quality, fresh water resources of the ‘source function’ and of the ‘life support function’.

The third essential requirement for food production is energy, generated either by fossil energy carriers or by renewables, such as biomass. The consumption of food has a considerable impact on household energy use (Kramer, 2000). An average EU household, for example, requires 19% of its energy use for food (Nonhebel and Moll, 2001). This study therefore proposes the quantity of fossil energy use as an indicator for the depletion of non-renewable resources of the ‘source function’ (IPCC, 1996) and for possibilities of the ‘sink function’ to neutralize climate change and acidification. The quantity of renewable energy use is

also an indicator for the 'life support function' and for the potential competition among agricultural interests, energy production capacity and the requirement of natural areas for biodiversity.

An important criterion for the selection of the indicators land, energy and water for the measuring method for environmental sustainability in food production systems is the interaction among these indicators. For example, 'high external input farming' (HEI) requires large energy input in the form of fertilizer and pesticides to reach high production levels. As a result, land use is relatively low. On the one hand, irrigation in agriculture results in higher yields and thus lower land use, but on the other hand, in larger energy and water requirements. The use of the three indicators proposed in this study also addresses interactions among aspects of environmental sustainability.

### 5.3. Flow chart of calculations and input

For the assessment of the environmental sustainability of food production, a step-by-step approach, in which the output of one step forms the input of the next one, calculates total environmental system performance. Fig. 2 shows an overview of the three levels of scale, three calculation steps, and the required input. At level one, processes take place in companies; at level two, processes for the manufacture of one raw material take place in chains; at level three, production chains join and form a web in which a final food item is produced. The outcome of the combination of direct company input with indirect chain and web input is the total land, energy and water requirement per kilogram of available food.

The total energy, land, and water requirements for a specific food item are calculated in three steps as follows:

Step one:

$$DR_x = \sum_{s=1}^n I_{x,s} * ERE_{x,s} \quad (x = \text{energy}) \quad \text{or}$$

$$DR_x = \sum_{s=1}^n I_{x,s} \quad (x = \text{land or water})$$

where  $DR_x$  is the total direct input per indicator  $x$  per company ( $\text{MJ}, \text{m}^2, \text{m}^3$ ) per year;  $I_{x,s}$ , the direct input per indicator  $x$  per process  $s$  ( $\text{MJ}, \text{m}^2, \text{m}^3$ ) per year;  $ERE$ , the energy required for energy = amount of primary energy per process  $s$  needed for the production of the energy used ( $\text{MJ per MJ}$ ).

Step two:

$$TR_x = \sum_{i=1}^n R_{x,i} * A_i + DR_x$$

where  $TR_x$  is the total input per indicator  $x$  per company ( $\text{MJ}, \text{m}^2, \text{m}^3$ ) per year;  $R_{x,i}$ , the specific, indirect requirement for indicator  $x$  per kg of physical input  $i$  ( $\text{MJ}, \text{m}^2, \text{m}^3$ ) per kg per year;  $A_i$  is the total amount of input  $i$  needed for the production ( $\text{kg per year}$ ).

Step three:

$$R_o = \frac{E_o / t_o * TR_x}{O_o}$$

where  $R_o$  is the specific requirement for indicator  $x$  per kilogram of physical output  $o$  ( $\text{MJ}, \text{m}^2, \text{m}^3$ ) per kg;  $E_o$ , the economic value of output  $o$ ;  $E_t$ , the economic value of the total output; and  $O_o$  is the amount of output  $o$  ( $\text{kg per year}$ ).

Step one calculates direct energy, water, and land use for a specific company per year. Energy use is converted into primary energy use, or in the case of renewable energy, into land and water use. Data on basic materials used and on energy and water inputs are taken from the economic data of the companies concerned. A method to assess land requirements is presented in Gerbens-Leenes et al., (2002). Step two combines direct resource use per company per year with resource use in the preceding chain links. Information on indirect requirements must be obtained from the suppliers in the preceding links. Step three adopts an allocation methodology from LCA. It assesses resource use per kilogram of a specific food by dividing total direct and indirect resource use over end products according to their economic value. The quantity of land use, water use, and energy use can be calculated for any company along a food production chain. In this

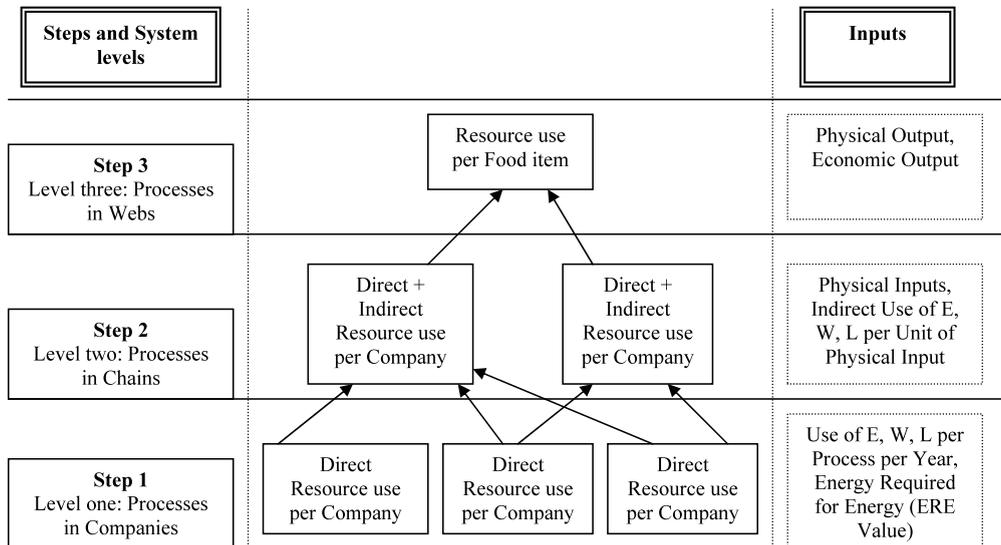


Fig. 2. Overview of the three levels of scale, three calculation steps and required input for the calculation of the environmental sustainability of a food item. Level one is the raw materials process level; level two is the raw materials chain level; and level three is the food production web level. Step one calculates direct resource use per company, step two calculates resource use per production chain and step three calculates resource use for the final food item. Required inputs are: energy (E), water (W) and land use (L) per company, per chain, and per combination of chains contributing to a final food. The allocation of resource use to food items is carried out according to economic value.

respect, attention must be paid to the energy use indicator. A shift in energy use from fossil sources to energy from renewable sources brings with it a requirement for more land, or, in the case of the use of biomass, a need for agricultural land and water. These requirements should also be included in the calculations.

Box 1 shows an example of the calculation method taken from the energy studies assessing the energy requirement of 1 kg of French beans in a jar (Kramer et al., 1994). It shows how the calculation method works. The example demonstrates that differences in resource use in links of a production chain may have important impacts on the final resource use of a specific food.

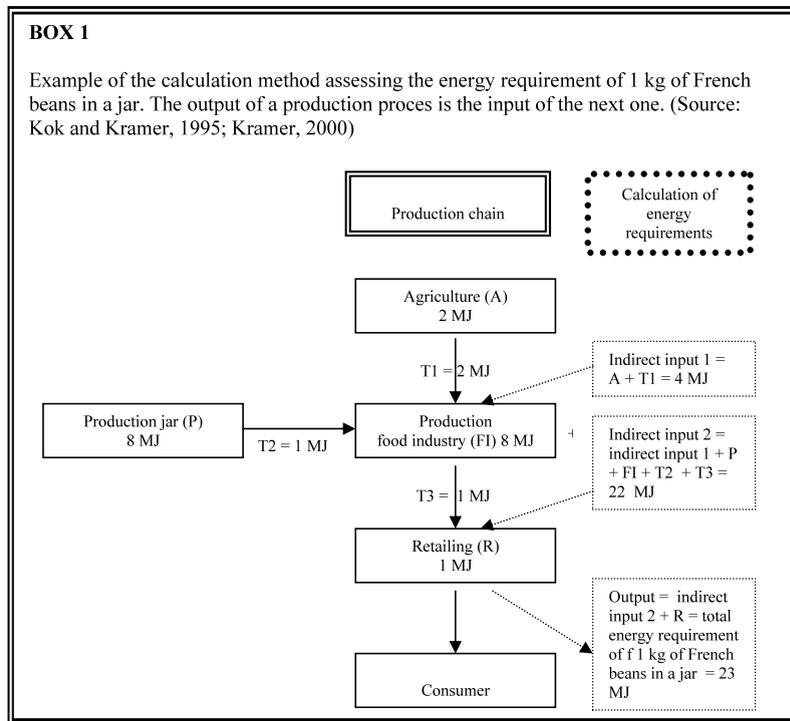
## 6. Discussion

### 6.1. Present situation: type of information generated and utility

Our contacts with business (e.g. Royal Ahold), our studies in the economic, social and environ-

mental fields, and a presentation of our work held at an international workshop in Groningen in 2001 (Steg et al., 2001) confirmed the general idea that there are large numbers of conceptual frameworks for SCP, but that a generally accepted measuring and reporting system is lacking. Many companies address the sustainability issue, but use an enormous variety of indicators to assess environmental SCP. For three reasons, this generation of large information streams provides hardly any additional knowledge on SCP or on the environmental sustainability of a production system. First, indicators differ among companies and therefore generate incompatible information. Second, companies differ, sometimes even in the same business sector. Outsourcing of specific processes to other companies, for example, is very common. Sustainability, therefore, cannot be assessed at a company level because the type and number of processes performed differ per company. Third, interactions among aspects of sustainability are very important but are often ignored.

LCA has developed methods to assess the impacts associated with the manufacture of agri-



cultural products (Weidema, 1999; Weidema and Meeusen, 2000). It uses large indicator sets and provides information on differences of agricultural production systems. LCA assumes a linear relationship between the amount of product manufactured and environmental impacts, and neglects spatial and temporal variation. If only few products are compared, LCA is the appropriate tool. For the assessment of environmental sustainability of complex food production systems, however, it is important to select only few indicators and take non-linear relationships and natural variation into account. The measuring method proposed here can assess sustainability from a systems perspective because it addresses all the processes in a system in an integrated way and can calculate trade-offs.

### 6.2. The measuring method: type of new information and utility

The method presented here is, as far as we know, the first attempt to measure the environ-

mental sustainability issue in food chains and systems in an integrated way from a global perspective. It is part of a three-dimensional model of SCP involving the social, economic, and environmental dimensions of sustainability. It is stressed that the SCP project considered local environmental effects as indicators of social sustainability and addressed these effects elsewhere. There are three important constraints for a measuring method: it must be simple, it must be easy to use and it must lead to relevant information on sustainability. The small set of core indicators, land, water and energy use, is in line with these requirements and can be calculated for all companies in the food system. The final outcome is the total land, energy and water requirement per kilogram of available food.

Bottom-up approaches have already developed methods to assess environmental SCP on a local level of scale. In our opinion, the proposed indicator set should complement the indicator sets used so far. In this way, companies can also

address sustainability issues on a global level of scale. For companies, the utility of generated information is to compare trends over time, compare results with targets, benchmark a company against others and assess the relative contribution of the company to a final product. Time trends, for example, provide information on the effects of changes in production methods or the effects of financial investments. On the one hand, environmental pressure is determined by production systems, for example efficiency in the food industry, but on the other hand by food consumption patterns. The influence of consumption on resource use is large. Land requirements for existing European food patterns, for example, differ by a factor of two (Gerbens-Leenes and Nonhebel, 2002). For consumers, the utility of the information is to enable them to compare the environmental effects of various foods and to make well-founded choices.

An individual process in a chain link shows little variation over time. For the manufacture of an end product, however, the collective behavior of several processes combined in a production chain can show large variation because very often there are several ways to make a final food item. An important advantage of the systems perspective is that these differences among production chains become visible. The consequence of the use of system indicators is that the sustainability issue is no longer restricted to the performance of a single company, but is extended towards the performance of others. This implies a difference between corporate performance and shared corporate responsibility. The former focuses on the relationship between the company and its stakeholders. These stakeholders are often well known, while methods to assess corporate performance have already been developed. Shared responsibility is related to the place of the company in the production system and the responsibility of a company for the performance of other companies contributing to that system. For the sustainability of production systems, there are relatively few stakeholders. Moreover, the sustainability of these systems is difficult to assess and requires other measuring methods.

### *6.3. Future research: type of additional information required*

At the moment, it is important to start measurements in companies willing to cooperate and bridge the existing gap between theoretical scientific knowledge and practical company knowledge. This will take great effort from both sides. In addressing the sustainability issue, research emphasizes the need for accuracy and completeness; business, on the other hand, wants to have an easy to handle, practical and cheap tool to assess their SCP. The development of such a tool will therefore take some time and adjustments from both sides. At present, there is a relatively small group of companies that are innovative and willing to take the lead in sustainable entrepreneurship (Vollenbroek, 2002). Food companies should realize that proactive, environmental management leads to profitable results. This will become possible when companies start reporting on the set of indicators proposed so that data become available. These data will provide insight on the use of natural capital in specific chain links and will form the basis for optimization strategies.

The information generated might lead to differences in reduction strategies because the availability of natural capital shows temporal and spatial variation. This implies that sustainability indicators should not be minimized but rather optimized within environmental constraints. For example, energy reduction strategies in agriculture require larger land inputs. Environmental pressure also differs strongly among business sectors. The emission of wastes, for example, can be a useful indicator for the food processing industry, but is less appropriate for the retailing sector. Future research should further elaborate the core indicators proposed in this paper into sets of supplemental indicators that are only used for relevant business sectors.

Conventionally, the three central objectives of sustainable development are environmental, social and economic in nature (World Commission on Environment and Development, 1987). In terms of the contribution of private sector companies to sustainable development, the use of the sustainability concept implies that environmental, social

and economic indicators have to be optimized within existing constraints. Future studies should develop methods that address the trade-offs and interplay between the three aspects of sustainability. However, what is considered important and what is not is a political choice that can be addressed using weighing factors that differ both in time and among regions. Wide acceptance of the environmental measuring method together with methods to measure economic and social dimensions, as proposed in the SCP project, will make a powerful contribution towards creating sustainable business practices. It can drive towards the decoupling of economic growth and environmental and social degradation.

## 7. Conclusions

- The environmental reporting of companies is still poorly developed. Widely accepted standards for sustainability reports are not available. So far, companies have usually addressed the environmental effects caused by their operations on a local level using a large number of indicators. As a result, the information generated is incompatible and does not address the sustainability issue as a whole.
- To fully understand the environmental implications of food production, this paper proposes a measuring method for environmental sustainability using a systems approach. First, it assesses the environmental sustainability of processes in companies. Second, it calculates sustainability for a production system. It reveals the overall environmental effects related to food production, and it expands the SCP of an individual company towards the SCP of all companies contributing to a production system. In this way, companies have a direct responsibility for effects related to their own operations and a shared responsibility for chain-related effects.
- Three indicators address the sustainability issue: (i) land use, (ii) water use and (iii) energy use. When data become available, future studies can establish the interaction between these indicators leading to optimization within environmental

constraints varying among regions and in time rather than reduction strategies addressing only one sustainability characteristic.

- Future research should develop supplemental indicators derived from the core indicators proposed here. This additional set can be used for relevant business sectors.
- Although the method to assess environmental sustainability was developed for food production, the concept has a much wider applicability.

## Acknowledgements

The study reported here is part of a multidisciplinary project on the scientific modeling and measuring of SCP aimed at the development of a three-dimensional model of SCP involving economic, social and environmental dimensions. The project is supported by the University of Groningen Ubbo Emmius Fund and partly financed by the Royal Ahold Corporation in Zaandam, the Netherlands.

## References

- Andersson, K., 2000. LCA of food products and production systems. *International Journal of LCA* 5 (4), 239–248.
- Bansal, P., Kilbourne, W.E., 2001. The ecologically sustainable retailer. *Retailing and Consumer Services* 8, 139–146.
- Bockstaller, C., Girardin, P., Van der Werf, H.M.G., 1997. Use of agro-ecological indicators for the evaluation of farming systems. *European Journal of Agronomy* 7, 261–270.
- Boer, M. de, Wijers, G.J., Aartsen, J.J.v., Jorritsma-Lebbink, A., Vermeend, W.A.F.G., Pronk, J.P., 1988. *Nationaal Milieubeleidsplan 3*. Gravenhage, The Netherlands.
- Boudouropoulos, I.D., Arvanitoyannis, I.S., 1999. Current state and advances in the implementation of ISO 14000 by the food industry. Comparison of ISO 14000 to ISO 9000 to other environmental programs. *Trends in Food Science and Technology* 9, 395–408.
- Bouma, J., Batjes, N.H., Groot, J.J.R., 1998. Exploring land quality effects on world food supply. *Geoderma* 86, 43–59.
- Bouwman, M., 2000. *Tracking Transport Systems*, an environmental perspective on passenger transport modes. Centre for Energy and Environmental Studies of the University of Groningen.

- Carlsson-Kanyama, A., 1997. Weighted average source points and distances for consumption origin-tools for environmental impact analysis? *Ecological Economics* 23, 15–23.
- Carlsson-Kanyama, A., 1998. Climate change and dietary choices—how can emissions of greenhouse gases from food consumption be reduced? *Food Policy* 23 (3/4), 277–293.
- Carlsson-Kanyama, A., Faist, M., 2000. Energy use in the food sector: a date survey. 291. Stockholm, Sweden, Forschungsgruppen för Miljöstrategiska Studier. AFR-report.
- Carson, R., 1962. *Silent spring*.
- Statistisch Jaarboek, 2002. Voorburg, the Netherlands, Centraal Bureau voor de Statistiek (CBS).
- Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. *Conservation Biology* 6, 37–46.
- Daly, H.E., 1990. Toward some operational principles of sustainable development. *Ecological Economics* 2, 1–6.
- Drumwright, M., 1994. Socially responsible organizational buying: environmental concerns as a non-economic buying criteria. *Journal of Marketing* 58, 1–19.
- Dutilh, C.E., Kramer, K.J., 2000. Energy consumption in the food chain. Comparing alternative options in food production and consumption. *Ambio* 29 (2), 98–101.
- Ekins, P., Simon, S., 2003. An illustrative application of the CRITINC framework to the UK. *Ecological Economics* 00, 1–21.
- Ekins, P., Folke, C., De Groot, R., 2003. Identifying critical natural capital. *Ecological Economics* 00, 1–5.
- Elkington, J., 1994. Towards the sustainable corporation: win-win-win business strategies for sustainable development. *California Management Review* 36 (2), 90–100.
- European Community, 1993. EUR-Lex: community legislation in force. Official Journal NO.C 138 493Y0517(01).
- Falkenmark, M., 1989. Comparative hydrology—a new concept. In: Falkenmark, M., Chapman, T. (Eds.), *Comparative Hydrology. An Ecological Approach to Land and Water Resources*. Unesco, Paris, France, pp. 10–42.
- FAO, 2002. Food and Agricultural Organisation of the United Nations (FAO). <http://www.fao.org>.
- Gerbens-Leenes, P.W., 1999. Indirect ruimte- en energiebeslag van de Nederlandse voedselconsumptie. 102. Groningen, the Netherlands, Centre for Energy and Environmental Studies (IVEM). IVEM-onderzoeksrapport.
- Gerbens-Leenes, P.W., 2000. Groen Kookboek. Milieubewust koken met een laag energie- en landgebruik. 103. Groningen, the Netherlands, Centre for Energy and Environmental Studies (IVEM). IVEM-onderzoeksrapport.
- Gerbens-Leenes, P.W., Nonhebel, S., 2002. Consumption patterns and their effects on land required for food. *Ecological Economics* 42, 185–199.
- Gerbens-Leenes, P.W., Nonhebel, S., Ivens, W.P.M.F., 2002. A method to determine land requirements relating to food consumption patterns. *Agriculture Ecosystems and Environment* 90, 47–58.
- Global Reporting Initiative, 2000. Sustainability Reporting Guidelines on Economic, Environmental and Social Performance. Interim Secretariat Global Reporting Initiative, Boston, USA.
- Groot, J.J.R., Penning de Vries, F.W.T., Uithol, P.W.J., 1998. Food supply capacity study at global scale. *Nutrient Cycling in Agroecosystems* 50, 181–189.
- Giupponi, C., 1998. Environmental evaluation of alternative cropping systems with impact indices of pollution. *European Journal of Agronomy* 8, 71–82.
- Halberg, N., 1999. Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farmers. *Agriculture Ecosystems and Environment* 76, 17–30.
- Hall, J., 2000. Environmental supply chain dynamics. *Journal of Cleaner Production* 8 (6), 455–471.
- Hansen, J.W., 1996. Is agricultural sustainability a useful concept? *Agricultural Systems* 50, 117–143.
- Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener, A., Ansems, A.M.M., Eggels, P.G., Van Duin, R., De Goede, H.P., 1992. Milieugerichte levenscyclusanalyses van produkten-Handleiding. The Netherlands, Centrum voor Milieukunde Leiden (CML), Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO), Apeldoorn en Bureau Brand- en Grondstoffen (B&G).
- IPCC, 1996. Climate change 1995. The science of climate change. Contribution of working group I to the second assessment. Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Australia.
- ISO World, 2000. The number of ISO 14001/EMAS certification registration of the world. <http://www.ecology.or.jp/>
- Kok, R., Kramer, K.J., 1995. Hoeveel energie kost onze voeding? *Voeding* 56 (6), 12–15.
- Kok, R., Benders, R.M.J., Moll, H.C., 2001. Energie-intensiteiten van de Nederlandse consumptieve bestedingen anno 1996. 105. Groningen, the Netherlands, Center for Energy and Environmental Studies (IVEM). IVEM-onderzoeksrapport.
- Kolk, A., 2000. *Economics of Environmental Management*. Financial Times/Prentice Hall.
- Kramer, K.J., 2000. *Food Matters*. Centre for Energy and Environmental Studies (IVEM).
- Kramer, K.J., Biesiot, W., Kok, R., Wilting, H.C., Schoot Uiterkamp, A.J.M., 1994. Energie geld(t). 71. Groningen, The Netherlands, Interfacultaire Vakgroep Energie en Milieukunde (IVEM). IVEM-onderzoeksrapport.
- Meadows, D.L., 1972. *The Limits to Growth. A Report for the Club of Rome Project on the Predicament of Mankind*. Universe Books, New York.
- Moll, H.C., 1993. Energy counts and materials matter in models for sustainable development. Dynamic lifecycle modelling as a tool for design and evaluation of long-term environmental strategies. Rijksuniversiteit Groningen.
- Netelenbos, T., Van Kemenade, J.A., Van der Ham, W.B., Tchernoff, A., 1999. *Perspectievennota Verkeer en Vervoer*. Ministeries van V & W, VROM, EZ, LNV.
- Nonhebel, S., Moll, H.C., 2001. Evaluation of Options for Reduction of Greenhouse Gas Emissions by Changes in

- Household Consumption Patterns. 410 200 059, 94. Bilthoven, RIVM, National Institute of Public Health and the Environment.
- Oldeman, L.R., Hakkeling, R.T.A., Sombroek, W.G., 1991. World map of the status of human-induced soil degradation: global assessment of soil degradation. Wageningen, International Soil Reference and Information Centre.
- Organisation for Economic Co-operation and Development (OECD), 2001. Corporate Responsibility, Private Initiatives and Public Goals. Paris, France, OECD Publications.
- Penning de Vries, F.W.T., Van Keulen, H., Rabbinge, R., 1995. Natural resources and limits of food production in 2040. In: Bouma, J. (Ed.), *Eco-Regional Approaches for Sustainable Land use and Food Production*. Kluwer Academic, The Netherlands.
- Rondinelli, D., Vastag, G., 2000. Panacea, common sense, or just a label? The value of ISO 14001 environmental management systems. *European Management Journal* 18 (5), 499–510.
- Rondinelli, D.A., Berry, M.A., 2000. Environmental citizenship in multinational corporations: social responsibility and sustainable development. *European Management Journal* 18 (1), 70–84.
- SER, 2001. Corporate social responsibility. Assen, the Netherlands, Royal van Gorcum.
- Stauffer, J.E., 1997. ISO 14000 Standards. In: *Cereals–Foods–World*, pp. 228–230.
- Steg, L., Vlek, C., Feenstra, D., Gerbens, W., Karsten, L., Kok, R., Lindenberg, S., Maignan, I., Moll, H., Nonhebel, S., Schoot Uiterkamp, T., Sijtsma, F., Witteloostuijn, A., 2001. Towards a comprehensive model of sustainable corporate performance, three-dimensional modelling and practical measurement. Departments of Economics, Environmental Sciences, Management Science, Psychology and Sociology, University of Groningen, Groningen.
- Steger, U., 1993. The greening of the board room: how German companies are dealing with environmental issues. In: Fischer, K., Schot, J. (Eds.), *Environmental Strategies for Industry*. Island Press, Washington, DC.
- Thoresen, J., 1999. Environmental performance evaluation—a tool for industrial improvement. *Journal of Cleaner Production* 7, 365–370.
- Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature* 418, 671–677.
- Van Dieren, W., 1995. *Taking Nature into Account: a Report to the Club of Rome*. Springer-Verlag, New York.
- Van Vuuren, D.P., Smeets, E.M.W., 2000. Ecological footprints of Benin, Bhutan, Costa Rica and the Netherlands. *Ecological Economics* 34 (234), 115–130.
- Veleva, V., Ellenbecker, M., 2001. Indicators of sustainable production: framework and methodology. *Journal of Cleaner Production* 9, 519–549.
- Vollenbroek, F.A., 2002. Sustainable development and the challenge of innovation. *Journal of Cleaner Production* 10, 215–223.
- Wackernagel, M., Onisto, L., Callejas Linares, A., Lopez Falfan, I.S., Mendez Garia, J., Suarez Guerrero, A.I., Suarez Guerrero, M.G., 1997. *Ecological Footprints of Nations: How Much Nature Do They Use? How Much Nature Do They Have?* International Council for Local Environmental Initiatives, Toronto, Canada.
- Wegener Sleswijk, A., Meeusen-van Onna, M.J.G., Sengers, H.H.W.J.M., Van Zeijts, H., Reus, J.A.W.A., 1996. *Toe-passing van LCA voor agrarische producten*. Centrum voor Milieukunde Leiden, Centrum voor Landbouw en Milieu, Landbouw-Economisch Instituut (LEI-DLO), Den Haag, the Netherlands.
- Weidema, B.P., 1999. Data, databases and software for LCAs on food. Theme report for the LCA-NET-Food.
- Weidema, B.P., Meeusen, M.J.G., 2000. *Agricultural data for Life Cycle Assessments*. 2.00.01. Agricultural Economics Research Institute (LEI), The Hague, the Netherlands.
- Williams, H., Medhurst, J., Drew, K., 1993. Corporate strategies for a sustainable future. In: Fischer, K., Schot, J. (Eds.), *Environmental Strategies for Industry*. Island Press, Washington, DC.
- Wilting, H.C., 1996. An energy perspective on economic activities. Center for Energy and Environmental Studies, University of Groningen, the Netherlands.
- Wilting, H.C., Benders, R.M.J., Biesiot, W., Louwes, M., Moll, H.C., 1999. *Energy analysis program, manual version 3.0*. 98. Center for Energy and Environmental Studies (IVEM). IVEM-onderzoeksrapport, Groningen, the Netherlands.
- World Commission on Environment and Development, 1987. *Our Common Future*. Oxford University Press, Oxford, UK.
- World Business Council for Sustainable Development (WBCSD), 1997. *Signals of Change: Business Progress Toward sustainable Development*. Geneva, Switzerland.