LIFE CYCLE ASSESSMENT OF AGRICULTURAL PRODUCTION SYSTEMS: CURRENT ISSUES AND FUTURE PERSPECTIVES

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ABSTRACT

The applications of and recent issues on life cycle assessment (LCA) for agriculture are reviewed in order to provide an integrated perspective on environmental and food safety issues. First, the relationship between the good agricultural practice (GAP) approach and LCA of agricultural production systems is discussed. Second, applications of LCA to agricultural production systems are surveyed mainly on the basis of literature information. Third, future research challenges that are related to the characteristics specific to agriculture are outlined. Finally, a summary of the review and practical implications of this study are presented.

Key words: life cycle assessment, cradle-to-gate, agricultural production systems, environmental impacts, food safety, functional units, agricultural intensity

INTRODUCTION

Life cycle assessment (LCA) and risk assessment (RA) are considered to be tools that can be applied to evaluate agricultural production systems. The similarities and differences between LCA and RA have already been pointed out; they are related to the purposes of the assessments and to the analytical structures (Society for Risk Analysis 2002). For example, human health, natural resources and natural environment are classified as areas of protection in life cycle impact assessment (LCIA) in ISO 14042. Both protection of human health and protection of the environment can be considered as goals of laws and regulations that use risk assessment to inform decision making (The Presidential/ Congressional Commission on Risk Assessment and Risk Management 1997). Public attention to the areas of protection can be considered as a reason for the recent increase in the number of applications of LCA to agricultural production systems and of comparative risk assessment (CRA) to many agricultural and food products.

This paper focuses on the LCA of agricultural production systems. LCA studies in the specific area have the following methodological characteristics: (1) they are LCA studies for production processes and thus, their system boundaries are defined as the cradle-to-gate type (Baumann and Tillman 2004); (2) they compare several agricultural production systems and thus they can be classified as comparative LCA (Baumann and Tillman 2004). Agricultural production systems – decision alternatives in decision analytic terminology – include organic production systems, integrated production systems, and conventional production systems. Such production systems are the results of long developments of agronomic research under consideration of overall principles regarding the relationship between mankind and nature: for example, integrated pest management refuses the idea of preventive treatments without evidence of damage and organic farming prohibits the use of chemical inputs per se. The production system based on the codes of good agricultural practices (GAPs) is rather an example of the application of standards and certification procedures with the goal of reducing the risks in agriculture and to reassure consumers (see, for example, EurepGAP n.d. a). GAPs concern a priori all farming systems, provided that they respect the normative documents. Comparisons among agricultural production systems with and without the codes of GAPs may be useful in the introduction phase of such codes into production processes compared with other sets of standards like for example, the organic farming rules or cross compliance criteria.

However, several issues have to be clarified. (1) Because each methodology has its own terminology, people may find some confusion in problem definitions. Furthermore, people may have difficulty in understanding the reason why the specific methodology has to be applied. (2) Because LCA is still under development and each country (region) has its own agricultural problems as well as own agricultural research and extension systems, there are remarkable differences in the development and applications of LCA even within European countries. (3) Because LCA is originally developed for assessing the environmental impact of industrial products, people easily encounter the problems specific to agriculture.

Therefore, in this paper, Section 2 discusses the relationship between the GAP approach and LCA. In Section 3, a survey of applications of LCA to agricultural production systems is presented. Issues specific to agriculture and research challenges are discussed in Section 4.

WHY LCA HAS TO BE DISCUSSED

This section discusses the differences in the purposes between the introduction of GAPs and the application of LCA to agricultural production systems. Then, this section discusses the differences in the concepts of production systems between GAPs and LCA. If we use the terminology of LCA, the first point is related to the goal definition and the second point is related to the definition of system boundaries in defining the scope of an LCA study (Fig. 1).

Environmental Issues or Food Safety Issues?

The area of protection in life cycle impact assessment (LCIA) contains human health in addition to natural environment. This is equivalent to the fact that main risks in RA are health risks and environmental (ecological) risks. However, there are differences in perceptions among various kinds of GAPs: that is, environmental issues and food safety issues

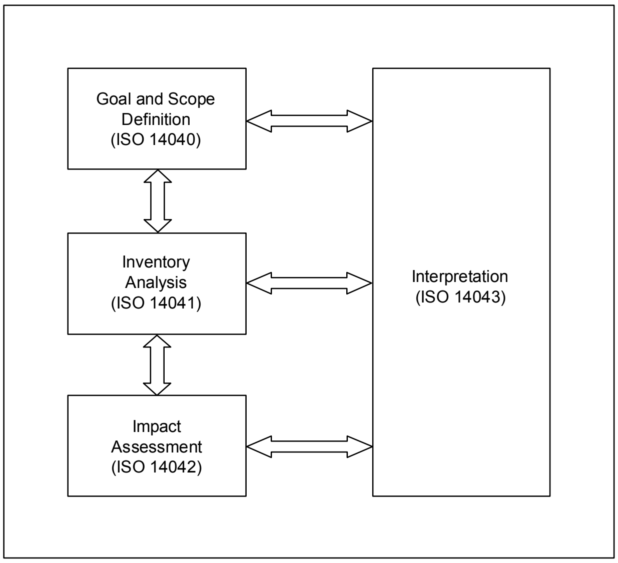

Fig. 1. ISO framework of life cycle assessment.

are separated, although in essence, environmental issues and food safety issues are interrelated and thus, GAPs by the Food and Agriculture Organization (FAO) refers to "food production and security, food safety and quality, and the environmental sustainability of agriculture" (FAO n.d.) and EurepGAP is a certification standard for "safe food that is produced respecting worker health, safety and welfare, environmental and animal welfare issues" (EurepGAP n.d. b).

The most definitions of GAPs in Europe are related to environmental issues. A series of the Code of Good Agricultural Practice for the Protection of Water, of Air, and of Soil by MAFF UK are the examples of this. Furthermore, EU uses another term, good farming practices (GFPs), which is a requirement under EU Commission Regulation 1750/1999 and is an integral part of the Less Favored Area Compensatory Allowance Scheme (LFACA) and Agri-environment schemes. GFPs can be regarded as an equivalent of GAPs for environmental protection (European Commission n.d.). As a result, both GAPs and GFPs are used in the documents in OECD.

In contrast, GAPs in the United States are only related to food safety issues and thus, their main focus is the reduction of the microbial risks to fruits and vegetables (see, for example, Rangarajan *et al.* 2000; University of Maryland 2002). This is also applicable to the case of Japan; the code of GAPs for food safety is related to the Food Sanitation Law and is under the jurisdiction of Food Safety and Consumer Affairs Bureau, MAFF of Japan, although the code of GAPs for environmental protection (the code of good agri-environmental practices, the direct translation) is under Agricultural Production Bureau.

Of course, the actual situation is not so simple. For example, the concerns of Agroscope in Switzerland include topics such as mycotoxins, acrylamide, and GMOs (genetically modified organisms), in addition to environmental issues. The discussions on GAPs are focused now more on minimum ecological requirements, which correspond to a kind of an integrated production system.

These discussions illustrate that integration of environmental issues and food safety issues is necessary. LCA is a method to make the integration possible. In order to use LCA for analyzing agricultural production systems, we have to clarify the scope of the analysis (the system boundary).

Production Systems in the GAP Approach and in LCA

The code of GAPs concerns the direct production and related processes of agricultural products. For example, we find the following description in a manual: "The use of Good Agricultural Practices (GAPs) during growing, harvesting, sorting, packaging, and storage operations for fresh fruits and vegetables is key to preventing pathogen contamination. Key areas of concern when implementing a GAP program are prior land use, adjacent land use, water quality and use practices, soil fertility management, wildlife, pest, and vermin control, worker hygiene and sanitary facilities and harvesting and cooling practices" (University of Maryland 2002).

An important fact from the perspective of LCA is that the GAP approach is equivalent to the gate-to-gate type of LCA. Although there might be objections against calling the latter "LCA" because such LCA studies do not fully respect the idea to consider the whole life cycle, it may be correct to perform gate-to-gate type LCA studies under some assumptions. In this case, the attention is paid to the foreground system in the system boundary (Fig. 2). This is confirmed by the fact that there are many codes or guidelines of good practices for each background system: good manufacturing practices, good distribution practices, and so on.

REVIEW OF APPLICATIONS TO AGRICULTURAL PRODUCTION SYSTEMS

Having clarified the reason why LCA has to be discussed to obtain an integrated perspective for evaluating agricultural production systems, our next task will be the survey of earlier applications of LCA. The production systems based on the code of GAPs are defined as the conventional production systems in some case studies.

Survey of Journal Papers

Selected applications of LCA to agricultural production systems are summarized in Table 1. Since the attention in this paper is paid to

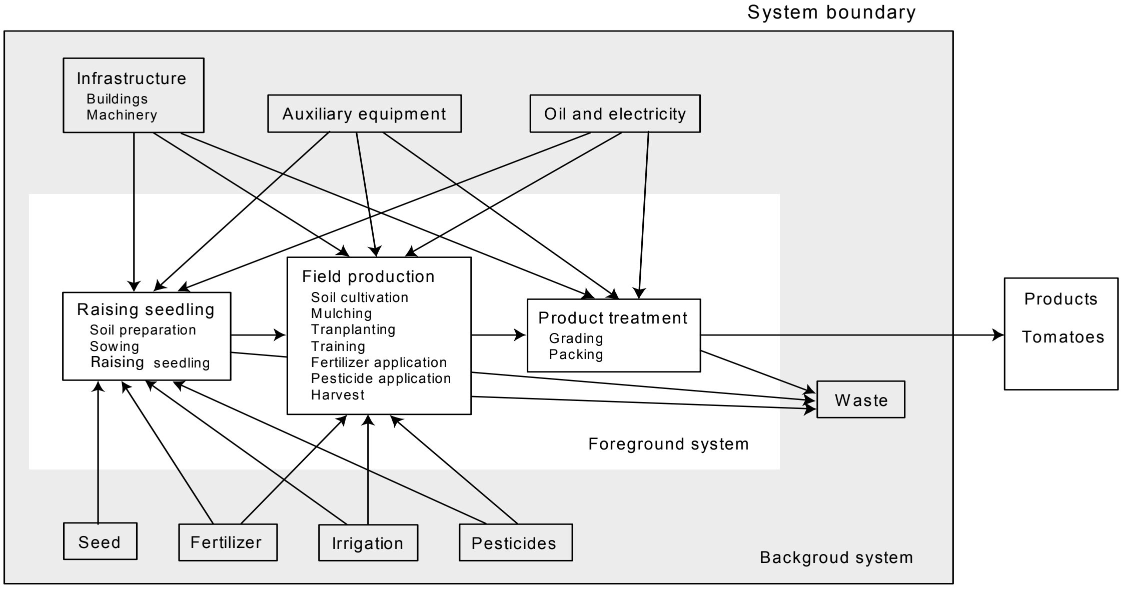

Fig. 2. Schematic representation of the processes in LCA of agricultural production systems. An example of greenhouse tomato production is presented.

LCA studies for comparing (discrete) alternatives, the studies that try to find the environmental hotspots are not included.

This table shows the following points: (1) all studies were conducted in Europe; (2) the purpose of the analysis is to quantify the impacts of environmental measures such as fertilizer application methods and organic agricultural practices; (3) most applications can be classified as cradle-to-gate types; (4) midpoint (environmental themes) approaches to LCIA are used in all the examples.

LCA Studies in Europe

Although the survey of the journal papers reveals the general tendency of the applications, it is necessary to study the research systems for agricultural LCA in Europe in order to understand the circumstances behind the table and to draw the whole picture of the study of LCA for agricultural production systems. Thus, this subsection describes the research systems in Europe up to now and the present situation.

Short history of LCA studies in Europe. This short history begins with presenting the past conferences on LCA in agriculture and the food sector.

- 1996: Application of LCA in Agriculture, Food and Non-Food Agro-Industry and Forestry. Brussels, Belgium
- 1998: LCA in Agriculture, Agro-Industry and Forestry. Brussels, Belgium
- 2001: LCA in Foods. Gothenburg, Sweden
- 2003: LCA in the Agri-Food Sector. Horsens, Denmark

In 2005, the 2nd International Conference on Life Cycle Management was held in Barcelona, Spain, in which agriculture was one of the four scientific topics. Some of the conference papers in the proceedings above will be mentioned in this section.

1. Renewable energies

As estimated from Hanegraaf, Biewinga and van der Bijl (1998), most of the first studies dealt with biofuels (and renewable raw materials). This is especially applicable to Switzerland and Germany (see Wolfensberger *et al.* (1997) and Heinzer *et al.* (2000) for

Table 1. Applications of LCA for evaluating agricultural production systems

Author(s)	Issues	Alternatives	Functional units	Cradle-to-gate	Midpoint
Hanegraaf, Biewinga and van der Bijl (1998)	Energy crop production in the Nertherlands	Route + Crop(GAP)	1 GJ and 1 ha	Cradle-to-gate	Midpoint
Cederberg and Mattsson (2000)	Milk production in Germany	Conventional and organic farming	1000 kg ECM (energy corrected milk)	Cradle-to-gate	Midpoint
Haas, Wetterich and Kopke (2001)	Grassland farming in Germany	Intensive, extensive, and organic farming	1 ha and 1 t milk	Gate-to-gate	Midpoint
Frick *et al.* (2001)	Arable crop rotations with clover-grass	Integrated intensive, integrated extensive, and organic farming	1 ha and 1 kg dry matted	Cradle-to-gate	Midpoint
Brentrup *et al.* (2001)	Sugar beet production in Germany	Sugar beet production with calcium ammonium nitrate (solid fertilizer), urea (solid fertilizer), and urea ammonium nitrate solution (liquid fertilizer)	1 t of extractable sugar	Cradle-to-gate	Midpoint
Eide (2002)	Industrial milk production in Norway	Small, middle-sized, and large dairy	1000 L of drinking milk brought to the consumers	Cradle-to-gave	Midpoint
Gaillard and Nemecek (2002)	Cereal and rape seed production in Switzerland	Conventional, integrated intensive, integrated extensive, and organic production	1 ha and 1 kg	Cradle-to-gate	Midpoint
Bennet *et al.* (2004)	GM sugar beet production in the UK and Germany	Conventional and GM-herbicide tolerant sugar beet	50000 kg fresh weight of surgar beet	Cradle-to-gate	Midpoint
Brentrup *et al.* (2004)	Winter wheat production in the UK	(Nitrogen fertilizer rate)	1 t of grain	Cradle-to-gate	Midpoint
Basset-Mens and van der Werf (2005)	Pig production in France	Conventional GAP, a French quality label (red label), and organic agriculture	1 ha and 1 kg of pig	Cradle-to-gate	Midpoint
Anton, Montero and Munoz (2005)	Greenhouse tomato production in Spain	Soil cultivation, open, and closed hydroponic systems (+3 waste management scenarios)	1 kg of tomatoes	Cradle-to-gate	Midpoint

Note: Web of Science was used to search the papers. Frick *et al.* (2001) and Gaillard and Nemecek (2002) are listed in the table because of the importance in this context, although they are not included in that database.

Switzerland and Kaltschmitt and Reinhardt (1997) for Germany). This contributed to the establishment of LCA research at Swiss Federal Research Station for Agricultural Economics and Engineering (Agroscope FAT Tänikon), which was transferred to the Swiss Federal Research Station for Agroecology and Agriculture (Agroscope FAL Reckenholz) at the end of 1999, in Switzerland and at Institute for Energy and Environmental Research (IFEU) Heidelberg in Germany.

2. Wheat

There were a lot of studies, which dealt with the LCA of single crops. At the very beginning, it was almost always wheat. Büchel (1993), Charles *et al.* (1998) and Gaillard and Hausheer (1999) are examples in Switzerland (at or in collaboration with FAT Tänikon). A special case that should be mentioned here is the European concerted action (Audsley *et al.* 1997), which was the first attempt of exchange in Europe on the basis of the case study of wheat. Some of the participating institutes became leaders in LCA of agricultural processes, although others left this field. The following are the institutes in alphabetical order of the countries, in which the current situation is also supplemented:

- Austria: Institute for Technology Assessment and International Cooperation.
- Denmark: Technical University of Denmark. Although LCA studies on agriculture are not so active, they transferred the know-how to their new private company.
- France: Ecobilan: Ecobilan performs LCA studies for the food industry. The agricultural part is supported by INRA Grignon (without known publications).
- The Netherlands. Center for Environmental Science (CML), Leiden University and Center for Agricultural and Environment (CLM) (See also Sleeswijk *et al.* 1996). CML worked for some time on agricultural LCAs, although CLM no longer plays any role.
- Switzerland: FAT (now transferred to FAL) (in which the second author of this paper was a member.) and EPFL. The major contribution of the latter institute in the field of agricultural LCA was the impact assessment of pesticides.
- The U.K.: University of Surrey and Silsoe Research Institute. At the University of Surrey, a new project has begun on the field of food chains and the questions of importations, although few activities were in the field of agricultural LCA in the last years.

3. Animal production

As the publication of a journal paper (Cederberg and Mattsson 2000) implies, the most important place is the Swedish Institute for Food and Biotechnology (SIK) and connecting institutes. This may be the only place where the PhDs (for example, Andersson 1998; Mattsson 1999) are parts of a whole research strategy. See also LCAnet Food Project (Olsson 1999). Recently, the INRA Rennes in France conducted research on the basis of an overall research strategy (Basset-Mens 2005).

4. Horticulture

The LCA research on greenhouse tomato production was conducted in the Netherlands (Nienhuis and de Vreede 1996; van Woerden 2001) and recently in Spain (Antón, Montero and Muñoz 2005).

5. Organic farming

The comparison between organic and conventional farming is one of the important themes in the LCA studies of agricultural production systems as shown in Table 1. An important institute is the Institute for Organic Agriculture, University of Bonn in Germany (Geier and Köpke 1998; Haas *et al.* 2001), although the institute is now less active than before. Nemecek *et al.* (2005b) performs a systematic analysis of organic farming compared with integrated production for Swiss conditions. Most of the other researchers studied only the energy question.

Present situation in Europe. By trying to describe the research field in Europe, we have to distinguish between institutions with agricultural specificity performing LCAs and those with LCA specificity with some punctual activities in agriculture of high level.

In the first group, leading research groups in the field of agricultural LCAs are as follows (in alphabetical order):

- Agroscope FAL Reckenholz: They are establishing an LCA method to agriculture (the SALCA method) which requires specific developments (emission factors for nitrate leaching, heavy metals, etc. and characterization categories specific to agriculture such as soil quality and biodiversity) and also expanding and updating LCA database for agriculture (the SALCA database). The latter is the base for the agricultural part of ecoinvent (a joint Swiss LCI database) (Nemecek *et al.* 2004; Nemecek and Erzinger 2005), which is now on being translated into Japanese by a Japanese company (Yamatake).

- INRA in Rennes: They decided to develop the LCA activities in the future. It is part of INRA's global strategy. In the future, more closed coordination with other INRA institutes, which are active in the field of environmental assessment (Grignon, Colmar, Dijon and Toulouse) may be secured.
- Nordic countries: This includes SIK (which is strong for food LCAs), Chalmers University of Technology, Agrifood Research Finland (MTT), SINTEF Fisheries and Aquaculture and diverse private offices such as 2.-0 LCA consultants. A large part of the work is outsourced to private offices with former people from academic institutions. The Danish Institute for Agricultural Sciences (DIAS) is developing the LCA Food Database, which is an LCA database on basic food products produced and consumed in Denmark.

In the second group, major institutes in the field of LCA and are also active for agricultural LCAs are the University of Surrey, IFEU Heidelberg and Ecobilan in France. The major difference is that, as compared with the above three research groups, they do not develop a methodology and define only a few data specific to agriculture. Major universities such as the Swiss Federal Institute of Technology (ETH) Zurich and Leiden University will always be present in the forms of PhDs (Jungbluth 2000; Mouron 2005). There are isolated places in south Europe (Spain and Italy), including the Institute for Food and Agricultural Research and Technology (IRTA) in Spain.

LCIA methodologies. As shown in Table 1, the LCA of agricultural production systems utilizes midpoint approaches to LCIA; CML or EDIP is used depending on the geographic circumstances and on the impact assessment. Endpoint approaches such as Eco-indicator99 (Goedkoop & Spriensma 2001) are also used in the applications (See Hayashi and Kawashima [2004] on the difference between midpoint approaches and endpoint approaches to agricultural production systems). Their tendencies are as follows:

- If the results have to be supported by agricultural stakeholders, people work with methods like CML or EDIP. If the stakeholders come rather from industries and non-agricultural policy fields, they prefer endpoint approaches;
- If the results are part of a project with practical relevance, people work with methods like CML or EDIP. When academic questions such as allocation procedures, error propagation models and sustainability concepts are studied, it is simpler to work with endpoint approaches.

As to computer software, almost all use SimaPro and some work with Umberto, especially in Switzerland and Germany as a complement to SimaPro for detailed sensitivity analysis. Agroscope FAL Reckenholz and IRTA use TEAM.

Japanese Perspectives

There was a five-year project in Japan and a manual (National Institute for Agro-Environmental Sciences 2003) was prepared. The method used for the impact assessment can be classified as a midpoint approach, although the multimedia models for estimating the environmental fate and effect, for example, were not utilized. Instead, the manual recommends the users to use LC50s (3 hours) for water fleas for the characterization of pesticides. As to the impact assessment of pesticides, we have to recognize the fact that the database developed by the METI project does not contain the damage or categorization factors for pesticides. This Japanese situation will make a striking contrast with the European case mentioned earlier. Currently, the other kinds of LCA research activities are conducted in, for example, animal production and horticulture.

ISSUES SPECIFIC TO AGRICULTURE AND RESEARCH CHALLENGES

We have conducted the state-of-the-art surveys of LCA studies applied to agricultural production systems. Our next task will be to indicate the research challenges that are related to the characteristics specific to agriculture.

Discussions on Functional Units

One of the important characteristics in the applications of LCA to agriculture is the use of plural functional units as shown in Table 2. A farm, an area, a livestock unit and a product such as milk are the examples of plural functional units (Haas *et al.* 2000). Recent discussions on multifunctionality of agriculture give an interpretation on plurality of functional units. That is, both environmental impacts per kg of products and per unit of land area are applicable; the former corresponds to the essential function of production and the latter to the occupation of the countryside (Nemecek *et al.* 2001, 2005b; Payraudeau and van der Werf 2005). Gross profit is also used as a functional unit for expressing the financial function (Mouron *et al.* 2005). It is possible to use two functional units at the same time and discuss the differences. A system extension may be necessary for the secondary function in the case of renewable raw materials.

Table 2. LCA case studies using multiple functional units

Author(s) (Year)	Issue	Functional Units	System Boundary	LCIA
Nienhuis and de Vreede (1996)	Greenhouse tomato production	1 ha and 1 kg tomatoes	Gate-to-gate	Midpoint
Hanegraaf *et al.* (1998)	Energy crops	1 GJ and 1 ha	Cradle-to-gate	Midpoint
Charles *et al.* (1998)	Optimum fertilization levels for wheat	1ha, 1 t grain, and 1t-eq.grain	Cradle-to-gate	Midpoint
Geier and Koepke (1998)	Agricultural region	1 livestock unit, 1 ha, and 1 product unit	Cradle-to-gate	Midpoint
Haas *et al.* (2001)	Grassland farming	1 ha and 1 t milk	Gate-to-gate	Midpoint
Nemecek *et al.* (2001)	Arable crop production	1 ha and 1 kg DM	Cradle-to-gate	Midpoint
van Woerden (2001)	Greenhouse tomato production	1 m^2 and 1kg of tomatoes	Cradle-to-gate	Midpoint
Huguenin & Nemecek (2004)	Roughage production	1 ha and 1 mJ netto energy lactation (NEL)	Cradle-to-gate	Midpoint
Basset-Mens and van der Werf (2005)	Pig production	1 ha and 1 kg of pig	Cradle-to-gate	Midpoint
Hayashi (2005a)	Greenhouse tomato production	1 ha and 1 kg of tomatoes	Cradle-to-gate	Midpoint Endpoint
Rossier & Gaillard (2005)	Farms	1 ha, 1 MJ digestible energy and 1 franc gross product	Cradle-to-gate	Midpoint
Mouron *et al.* (2005)	Apple production	1 ha and total receipts	Cradle-to-gate	Midpoint

Note: Papers in scientific journals and conference proceedings are included.

Since the results (the orders of alternative production systems) are dependant on the choice of functional units, the interpretation should be based on agricultural intensity as shown in the next section.

Intensity and Environmental Impact

The research result on the relationship between agricultural intensity and the environmental impact in greenhouse tomato cultivation illustrates that the degree of the environmental impact per hectare correlates with the intensity (intensive cultivation has a greater impact on the environment) and that the degree of environmental impact per kilogram of fruits inversely correlates with the intensity (extensive cultivation has a greater impact) (Hayashi 2005b). In this case, the intensity is measured by applied nitrogen (kg/ha) and the environmental impact is measured by global warming potential expressed as kg CO_2 equivalence.

This discussion is related to the concept of eco-efficiency, and the recent research on eco-efficiency in arable and grassland systems illustrates that neither extensive nor intensive farming systems per se are sustainable and that the ecological optimum depends on the specific situation (Nemecek *et al.* 2005a). In order to clarify the discussion related to efficiency, the recent discussion on the appropriateness between nature-friendly conservative farming (which may decrease crop yields) and intensive farming (which may spare agricultural land) will be useful (Green *et al.* 2005). In fact, by constructing impact-yield functions, we can get a clear perspective on the relationships among intensity, efficiency and environmental impact (Hayashi 2005c).

In order to deeply understand the discussion, the following studies concerning the inevitability of land use in agricultural production are also helpful. The first is the study using a reference system within LCA (Wolfensberger *et al.* 1997; Gärtner *et al.* 2001). A reference system can be recognized as a method to take into account alternative land use. For example, organic farming should be compared with conventional agriculture, together with the right share of natural fallow because organic farming has a lower yield than conventional agriculture. Alternatively, several functional units (area, product) may be used (see Table 2). The second is the research on opportunity cost principles within LCA (Berlin and Uhlin 2004), which is another method to cope with the possibility of alternative land use. The recent debate on "ecology of scale" (Schlich and Fleissner 2005; Jungbluth and Demmeler 2005) might also be useful for the discussion.

Other Important Topics

Although the number of institutes is limited, there are research projects to complement and correct the LCA methodologies for agriculture.

The regionalization of indicators. Originally LCA is not considered as a site-specific assessment. However, because agriculture has to be considered as site-specific, some institutes in Europe (Denmark, Finland, Sweden and France) try to regionalize the emission and characterization factors for eutrophication and acidification caused by N and P fertilizer (including manure) application.

Development of missing indicators. One of the most significant problems in the current LCIA methodology for evaluating environmental impacts of agricultural practices is that all of the important environmental impacts cannot be assessed by the methodology. An example are the indicators for soil quality and biodiversity, which are currently investigated by Agroscope FAL Reckenholz. Another example are the indicators related to pesticides. Although EDIP and USES-LCA are applied and modified in applications, there are still many problems to be resolved.

From the perspective of the GAP approach, integration with microbial risk assessment is necessary. Furthermore, paying attention to working conditions (workers' health and safety) is also necessary, although EDIP contains the working environment as a criterion in the environmental assessment of products.

CONCLUDING REMARKS

The result of the review in this paper can be summarized as follows: (1) the GAP approach focuses on the foreground system in the system boundary and LCA can be used for integrating environmental and food safety issues; (2) the characteristics of the agricultural

LCA that clearly defines alternative production systems (decision alternatives) are that they analyze environmental impacts of environmental measures such as fertilizer application methods and organic agricultural practices, that they are the cradle-to-gate type, that they utilize midpoint approaches to LCIA and that they are now being refined by some research groups in Europe; (3) further research challenges are needed especially in clarifying the relationship between agricultural intensity and environmental impact, in regionalizing characterization factors and in constructing indicators related to, for example, biodiversity and pesticide risks.

LCA is an evolving quantitative tool that has the potential to be used in various areas. For example, it can be used to improve the quality of extension services, improve the profitability of farms by green marketing and support the regional transition to sustainable agricultural systems. Further research for developing methodologies and databases will broaden areas of practical applications.

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