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Progress in working towards a more sustainable agri-food industry

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ABSTRACT

The human health and environmental issues related to food, feed, and bio-based systems, range widely from greenhouse gas emissions and energy use to land use, water availability, soil quality, water quality and quantity, biodiversity losses, and chemical exposure. Threats that stem from other issues, including food quality and food security, the development of genetically modified organisms, desertification, pesticide exposure, antibiotic-resistant strains of microorganisms, growth hormone residues in food, etc., are of concern. Life Cycle Assessment (LCA) methodology provides the organizing framework to holistically evaluate the environmental impacts of products and production systems, whether it's to make a durable, disposable or edible good. The use of LCA in environmental management and sustainability has grown rapidly in recent years as demonstrated by the increasing number of published papers on LCA methodology and case studies, which totaled over 4,500 by 2010. Recognizing the need to focus on the impacts of the agri-food industry, this special issue was developed by selecting sixteen papers from the 85 presented at the Bari LCA Food 2010 conference, and publishing them with eight papers submitted as part of the normal flow to the Journal of Cleaner Production on food-related subjects. The papers in this special issue include case studies from LCAs on relevant dimensions of production of a wide array of types of food, discussions on methodological issues, especially water and land use, the application of product certification schemes, and food preservation. The editors of this special issue acknowledge that progress has been made in strengthening the LCA tools but challenge all LCA practitioners and researchers to push the envelope on LCA methodology and encourage them to develop tools that dynamically address the diverse, rapidly evolving issues related to agricultural products that are not currently addressed. It is hoped the challenges that are outlined in this Special Issue will stimulate many to make progress on improving the food LCA tools prior to the next food LCA conference in this series, which will be held in Saint-Malo, France, on 2–4 October 2012. For more information, visit: https://colloque.inra.fr/lcafood2012.

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1. Introduction

The number of research articles that address the holistic human health and environmental impacts related to food, feed, and bio-based systems, including biofuels production and usage, has increased in recent years. Studies on agricultural systems have identified environmental issues ranging from global climate change and energy use to land use, water use, water scarcity, water quality, soil quality, biodiversity losses, spreading of 'super weeds', human health and food scarcity. However, threats that stem from other issues, including the development of genetically modified organisms (GMOs), desertification, pesticides, antibiotic-resistant strains of microorganisms, growth hormone residues in food, etc., are not adequately addressed. In addition, the increased production of bio-based materials and biofuels potentially increases the risk of famine as valuable agricultural lands are diverted to produce biofuels.

As one approach to address some of these challenges, the ISO 14040 standard for Life Cycle Assessment (LCA) provides the basic template, which can be used to holistically address the environmental and human health risks associated with food production and consumption. However, LCA practitioners and researchers should develop new life cycle tools that can be used effectively and efficiently in addressing the diverse environmental, economic, and social impacts related specifically to food/feed and to other bio-

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based products. Research is needed to develop systematic approaches to integrate the entire suite of potential trade-offs into decision-making processes as well as to elevate consideration of food systems to the forefront of the current scientific and popular literature. Better understanding is needed of the life cycle impacts related to food supply chains extending from production to consumer use, to develop and implement strategies that help societies ensure a sustainable agri-food industry.

2. Identifying environmental threats with increasing demand

The human population passed seven billion, in October 2011, and continues to increase. These increases in human population and the concomitant expanding demands upon our ecosphere is one of the dominant societal challenges. As human impacts expand, scientists and all members of society must increasingly work in an integrated manner to reduce the negative biophysical and socio-economic impacts upon the biosphere, atmosphere, hydrosphere, cryosphere, geosphere, and technosphere in spatial and temporal scales. The impacts determine the environmental health of the earth and affect the ecosystem's capacity to provide essential nature's services that are required to sustain human societies for the short and long-term future. (Rockström et al., 2009).

The increasingly severe threats from human activities upon our ecosystems and upon our global food security need to be given serious consideration. Some of the threats arise from impacts from global climate change, desertification, pesticide exposure, antibiotic-resistant strains of microorganisms, animal growth hormone residues in human food, the development and widespread dissemination of GMOs, the increase in extent and severity of invasive 'super weeds' and other challenges. In addition, the increased production of bio-based materials and biofuels is increasing the risk of widespread famine as valuable agricultural lands are diverted from production of human food and animal feed to produce bio-feedstocks, such as corn, to make biofuels. Additionally, these actions must be cast against the sea level rising and spreading deserts and the fact the human population continues to increase at a rate of 75,000,000 people per year.

With terrestrial and aquatic-based food and feed production and consumption as one of the major driving forces behind increasing negative environmental impacts and surging resource consumption, it is essential to look holistically at the production, transportation, packaging, use, and end-of-life of products to return to the cyclic flows upon which the ecosystem gas evolved for billions of years. In addition, the increasing demands for biofuels and other bio-based materials have catapulted the issues related to bio-feedstock acquisition to the forefront. This is particularly important since agriculture is expected to comply with the principles of sustainability.

The movement to sustainable agricultural systems is gaining increasing support and acceptance within the agri-food industry along with the acknowledgment that a 'systems' perspective is essential to fully understand and to make progress toward the development of more sustainable societies. The systems are envisioned in the broadest sense, from the individual farm, to the local ecosystem, and to communities affected by the agricultural system, locally and globally. The integration of a systems approach can help us learn how to work with the dynamic interconnections among farming, human health, environmental health, and societal sustainability. A systems approach implies interdisciplinary efforts in research, education, and governance. This will require input of researchers from many scientific disciplines, and from farmers, farm workers, processors, wholesalers, retailers, consumers, policymakers, and others.

3. Life cycle assessments of food and agriculture

The LCA methodology provides a framework that is needed to evaluate the environmental impacts of products and production systems, whether it's to make a durable good, a disposable good, or an edible good (ISO, 2006a; ISO, 2006b). Fig. 1

The use of LCA in environmental management and sustainability has grown in recent years as seen in the steadily increasing number of published papers on LCA methodology and on case studies that have been performed to use LCA. A search in SCOPUS, an abstract and citation database, on the term "life cycle assessment" resulted in documenting the publication of over 4,500 scientific papers on diverse facets of LCA between 1999 and 2010 (Fig. 2).

A similar SCOPUS search that was focused upon food-related LCAs has revealed approximately 40 papers over the same timeframe with a similar rise in publication in recent years. Although food-based LCA's were outnumbered by studies on other consumer products such as building materials, packaging, and energy sources (especially biofuels), it is increasingly important that we do more integrated LCA studies with regard to our entire food production and consumption system.

LCAs on food crops as well as on industrial products such as biofuels have identified common environmental issues such as greenhouse gas emissions and energy use, which have been extensively studied and reported on (von Blottnitz and Curran, 2007). The categories addressed most frequently in food-related LCAs included energy use, global warming, eutrophication, acidification, tropospheric ozone formation, and land use. Other, less often-studied impacts, included biodiversity, water use, toxicity impacts, erosion, and landscape. However, unfortunately there is currently no commonly applied methodology to assess and to communicate environmental information along the entire food chain from the seed producers, the farmers, the processors, wholesalers, retailers and the consumers, in a practical and reliable way (Peacock et al., 2011). Additional research is needed, especially in the areas of land use, soil quality, biodiversity losses, and human health to bring the entire suite of potential impacts and trade-offs to the forefront to assist in decision-making to help reduce risks of implementing unsustainable societal patterns.

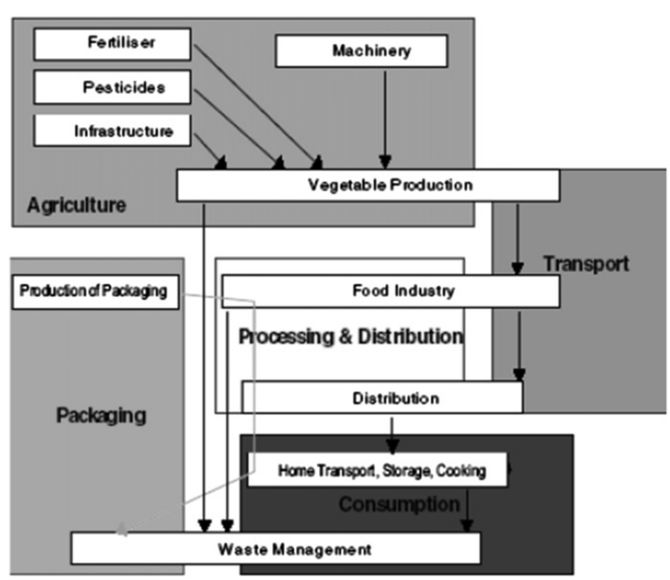

Fig. 1. Life cycle assessment provides the basic template to capture the holistic environmental impacts related to food production and consumption (Jungbluth and Tietje et al. 2000).

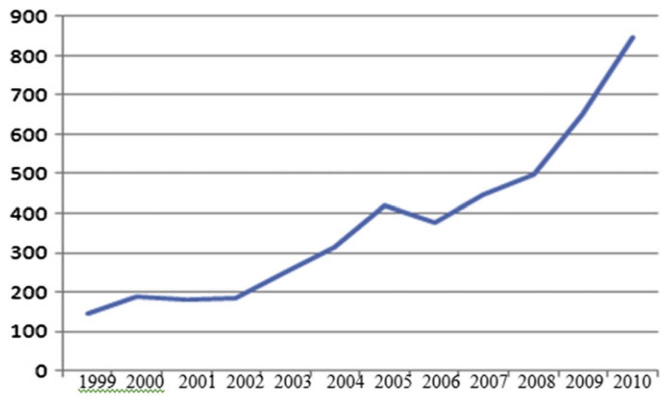

Fig. 2. A search via SCOPUS using the term "life cycle assessment" resulted in identifying approximately 4,500 scientific papers between 1999 and 2010. The number of LCA-based papers published per year is presented in the graph.

3.1. Land use changes

Only a few integrated, longitudinal studies of land use impacts of current crop production schemes have been done. Much of the research was driven by the growing interest in studying the production of biofuels. Land use changes due to biofuel production occur (1) directly, when uncultivated land, pasture, etc., is converted to produce new crops (e.g., grassland converted to grow cereal crops) or (2) indirectly, through displacement of food and feed crop production to new land areas previously not used for cultivation (Börjesson Pål and Tufvesson, 2011). Although land use impacts are widely acknowledged to have profound consequences for biodiversity, water quality, and climate, there is no consensus regarding the modeling of land use via any of the current LCA tools. This is partly due to the emphasis the LCA methodology gives to quantifying material flows rather than characterizing consequential changes in resource stock quality and quantity. Most models focus on certain aspects of land use systems and their dynamics, such as agriculture, forestry, urbanization, or economic trade phenomena, while representing other sectors as external drivers or treating them in a simplified manner. These models are not capable of representing the social, economic, and environmental effects of biofuels on global land use with certainty (CBES, 2009).

Oil palm, for example, is the most productive oil seed crop in the world making it the world's number one fruit crop. A single hectare of oil palm may yield 5,000 kg of crude oil, or nearly 6,000 L of crude, annually (FOE, 2004). In the last five years, demand for palm oil, a common ingredient used in making half of all consumer goods, from soaps and detergents to breakfast cereals and biofuels, has tripled, resulting in the clearing and burning of huge tracts of rainforests to open land for palm oil plantations. This has put indigenous and forest-dependent people in jeopardy, as well as it has endangered species such as the orangutans, Sumatran tigers and elephants Approximately 85 percent of palm oil is grown in the tropical countries of Indonesia, Malaysia and Papua New Guinea on industrial plantations that have severe impacts on the environment, forest peoples and the climate (RAN, 2011).

3.2. Soil quality

Forms of soil degradation include soil erosion, soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinization, soil acidity, or alkalinity problems and accumulation of pesticide residues. Typical tillage and cropping practices lower soil organic matter levels, cause poor soil structure, and result in compaction, which increases soil erosion and decreases productivity. Carbon compounds in waste biomass left on the ground are consumed by microorganisms and are degraded to produce valuable nutrients for future crops. When cellulosic ethanol is produced from feedstocks like switchgrass and sawgrass, the nutrients that are required to produce the lignocellulose are removed and cannot be processed by microorganisms to replenish the soil nutrients and soil organic matter, which helps the soil hold water and provide the proper micro-climate for healthy root growth. The soil quality becomes poorer if widespread human use of biomass removes all or most of the organic material, which would normally be returned to the soil as humus as the hundreds of species of soil organisms decompose the plant and animal tissues. Such regular removal of all or most of the biomass from the fields for biofuel production will result in decreased soil fertility and ultimately to unsustainable production systems, because the normal ecological systems that help to maintain healthy and fertile soils are not integrated into that type of management system (ETC, 2008). Better LCA tools, models, and systems are needed to more adequately assess and guide the transformation of such short-term and long-term unsustainable practices into sustainable ones.

3.3. Biodiversity losses

It has long been recognized that changing agricultural land use is a major cause of declines of biodiversity. Although intensively farmed land supports a certain level of biodiversity, it generally lacks significant areas of 'high nature values', which are essential for preserving biodiversity. Europe's more traditional, low-intensity farming systems with 'high nature values' are gradually disappearing, even when abandoned, agricultural land is replaced by less diverse vegetation or forests (EEA, 2010).

3.4. Pesticide exposure

While consumers worry about the chemical residues on or within their food, farm workers are currently often unnecessarily exposed to pesticides, leading to harmful health effects (Ridley, 2010). Although regulations exist to reduce the risk of pesticide poisonings and injuries among agricultural workers and pesticide handlers, such as the US Environmental Protection Agency's Worker Protection Standard for Agricultural Pesticides (EPA, 1992), more research is needed regarding exposure patterns among all types of farm workers. Furthermore, uniform and consistent enforcement of the safety precautions have been or should be developed as a result of better LCA tools to properly address the human and ecosystem health risks of many of the current and potential practices.

3.5. Genetically modified foods

Genetically modified (GM) foods are derived from genetically modified organisms (GMOs) which have had specific changes introduced into their DNA by genetic engineering techniques. The use of GM foods is highly controversial. While GM foods can help farmers produce greater quantities of food or fiber per year, reduce pesticide use, and operate more economically, the short and long-term human health and ecosystem effects from producing with GMOs are not adequately understood. Examples of the more prominent concerns are illustrated in the following paragraphs.

- A recent study from Mexico documented extensive contamination of numerous wild forms of corn (maize) that were hundreds to thousands of kilometers from plots of pollen producing GM corn. However, scientists found DNA from GM

crops in wild corn growing on remote mountains in Mexico. The wild corn was growing around 100 km (62 miles) from the nearest GM crops (Noble, 2001).
- A coalition of environmental and agricultural technology groups sued the US Department of Agriculture (USDA) for permitting open-air testing of genetically engineered eucalyptus trees across states, according to the Environmental News Service. The plaintiffs fear the GM eucalyptus could become invasive. They claim the USDA had not conducted a thorough environmental impact analysis of the project. The USDA issued the permit to allow the international biotech company, Aborgen to continue experimenting with cold-tolerant eucalyptus for producing pulp products and biomass (Ludwig, 2010).
- A senior soil scientist discovered a new microscopic pathogen in high concentrations of GM corn and soy that researchers believe could be causing infertility in livestock and diseases in crops that can threaten the entire domestic food supply (Ludwig, 2011). The LCA researchers must develop tools to analyze these risks and help society to chart an ecologically and ethically sound path forward with this and other risks for which the 'Precautionary Principle', has not been properly applied.

4. Strategies for sustainable food and fiber production and consumption

Impacts such as climate change, water use, land use, and pollution can be addressed through reduction strategies that are applied across the food and fiber production and consumption systems. In addition, more innovative strategies for creating sustainable systems should be utilized including creating access to local food outlets, increasing local food production, promoting closed-loop resource recovery systems, and other innovative approaches. A few of these approaches are listed in the following paragraphs:

4.1. Establish sustainable agricultural systems

Establishment of sustainable agricultural systems is an important strategy to improve many issues (indicators) that were already discussed (NAP, 2010). For example, environmental impacts caused by land use and land use changes are closely related to how sustainable agriculture is implemented (Perfecto and Vandermeer, 2010; Foley et al., 2011). Soil quality measures an ecosystem service provided by agriculture, in addition to the degree of mitigation of global warming through carbon sequestration. The relationship between agricultural intensification and biodiversity is a central topic in establishing sustainable agricultural systems (Kleijn et al., 2009; Clough et al., 2011). Although many concepts related to sustainable agriculture have been proposed (Table 1), life cycle thinking may be able to play an important role in assessing and establishing and supporting societal sustainability.

4.2. Implement sustainable agricultural practices

More specifically, the strategies to establish sustainable agricultural systems can be divided into the following four detailed strategies, each of which provides valuable perspectives on the application of LCA tools (Foley et al., 2011).

a. The first strategy is to stop agricultural land expansion. We have already highlighted the problems associated with clearing and burning of rainforests for palm oil plantations. Land use impact assessment is an emerging theme in LCA.

Table 1
Key concepts related to sustainable agriculture that must be addressed on our journey to ensuring sustainable societies.

Search words by key concept[a]	Number of articles in SCOPUS
Sustainable agriculture	3745
Organic agriculture	991
Conservation agriculture	269
Ecological agriculture	217
Multifunctional agriculture	125
Low-input agriculture	117
Permanent agriculture	49
Permaculture	39
Environmentally-friendly agriculture	20
Eco-agriculture	14
Regenerative agriculture	8
Natural agriculture	8

[a] Searches were based on TITLE-ABS-KEY, as of November 30, 2011.

b. The second strategy is to increase food production without expanding agricultural land by maximizing crop yields in a sustainable manner. To accomplish this, reconciling food production and environmental conservation, which is a fundamental objective in applying LCA to agriculture, must be addressed.
c. The third strategy is to minimize resource use without reducing food quality and quantity. Agricultural inputs such as fertilizers, pesticides, and water have to be utilized efficiently. In addition, material cycles, including agricultural residues have to be optimized to ensure sustainable productivity of our soils.
d. The fourth strategy is to change our diets and non-food applications. Recent discussions about whether to consume less meat and less energy/water/pesticide intensive crops are important topics that should be increasingly addressed via life cycle management of food and bioenergy production and consumption.

4.3. Establish local food networks

There are many references that address the economic and enhanced local and regional resilience that can be achieved from redeveloping local food networks.[2]According to the Neighboring Food Co-Op Association (NFCA), rural and urban communities nation-wide have started food co-ops to provide crucial retail markets for many food-related social movements, including natural foods, organic agriculture, and Fair Trade. In the U.S., one in four Americans are members of about 29,000 co-ops (NFCA, 2011). A unique opportunity exists to map the process and networks formed to create an LCA case study of "real world" performance as groups of "locals" begin to compete with large corporations in a fight for consumer food dollars (Levidow and Psarikidou, 2011).

4.4. Increase utilization of currently wasted materials

Roughly one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tons per year (Gustavsson et al., 2011). However, food waste is one of the least utilized materials. Waste food converted to bioenergy can replace conventional diesel oil, methane, or ethanol, thereby, reducing the use of nonrenewable resources as well as decreasing global warming impacts. Additionally, the residues from production of these biofuels from food wastes can be utilized as soil fertility sustaining amendments.

[2] The United Nations (UN) declared 2012 the International Year of Co-Operatives.

To illustrate this point, researchers tested if they could use surplus, spoiled, or nonfood-grade butter to make biodiesel at competitive prices. They found they could convert a quarter of a ton of butter into the fatty acid esters that constitute biodiesel. They found the resulting material met all but one of the official test standards for biodiesel. The researchers concluded that with further purification or by blending their biodiesel with biodiesel from other feedstocks, spoiled butter-based biodiesel could be integrated into the supply of bio-based fuel for diesel engines (Haas et al., 2010).

5. Focusing on agri-food LCAs

To find, evaluate and promote alternative paths to more sustainable food and fiber production and consumption, LCAs have been conducted for more than 15 years on agricultural and food systems, identifying their environmental impacts throughout their life cycle and supporting environmental decision-making. A variety of databases and methodological approaches have been developed and tested to support the application of LCA to food systems.

The "International Conference on Life Cycle Assessment in the Agri-Food Sector" (http://www.lcafood2010.uniba.it), which was held during September 22–24, 2010, in Bari, Italy– called "LCA Food 2010", for short – was the seventh in a series of events that includes previous conferences held in: Brussels (1996, 1998), Göteborg (2001, 2007), Horsens (2003), and Zurich (2008). More than 270 participants from four continents joined the event in Bari; this was the largest number of participants for any of the LCA Food conference series (Notarnicola et al. 2011).

In planning the Bari conference, the objective was to keep the high scientific quality of the conference brand, while providing an occasion to involve diverse, relevant stakeholders, including key players from the agricultural, industrial, and distribution sectors; academic researchers, and from households. This objective was achieved and the conference received extremely positive feedback from important economic actors, at national and international levels, as evidenced by their providing sponsorship and/or patronage support.

The objectives of the conference were:

- To show recent developments in methodology, approaches, databases and tools of LCA;
- To present applications of the LCA methodology to food production systems and to food consumption patterns;
- To increase the use of LCA and other industrial ecology tools in agricultural and industrial food production processes; and
- To support information sharing and exchange of experiences regarding environmentally conscious decision making in the agri-food chains.

More than 200 presentations were delivered at the conference, after having been selected via a peer-review process by the 21 members of the International Scientific Committee. All the papers were published and made available online at the conference website: http://www.lcafood2010.uniba.it/conference-proceedings (Notarnicola et al. 2010).

Progress was documented in this conference on the following topics:

- Increasing relevance of carbon and water foot printing;
- Stronger integration of food LCAs with economic analyses, social performance, and optimization techniques;
- Active involvement of the agri-food sector via providing evidence and practical experiences from important industrial players;
- More holistic aspects of packaging of food products, trade, ecodesign, and alternative uses of land;
- Expanded emphasis on the specific impacts of the primary sector, such as water use, land use, soil erosion, biodiversity losses, ecotoxicity;
- Increasing inputs from non-European countries (Ghana, Cameroon, Thailand, New Zealand, etc.); and
- Latest trends in databases and tools.

6. Developing this special agri-food LCA issue of the *Journal of Cleaner Production*

Recognizing the need to focus on the agri-food industry, this special issue of the Journal of Cleaner Production (JCLP) was developed with the objective to highlight presentations that were selected from the Bari LCA Food 2010 conference. Sixteen were chosen from the 85 abstracts accepted as platform presentations for inclusion in the special issue. To these papers, eight additional manuscripts submitted as part of the normal flow to the JCLP on food-related subjects were added. Selection and processing of the papers included in this issue was performed by Drs. Bruno Notarnicola, Kiyotada Hayashi, Mary Ann Curran, and Bo Weidema.

The 24 papers selected for this special issue deal with the following main macro-aspects regarding the application of LCA to the agri-food sector:

- Applicability - Addressing the need for the application of LCA from a global point of view, to various regions of the world with growing economies
- Intensity - The assessment via LCA of the ever-growing intensive production systems needed to sustain current levels of agri-food production
- Organic production - Addressing aspects of alternative, less intensive organic production systems via LCA
- Land and water use - New methods for dealing with the impacts of these categories that are still open issues in LCA
- Methodological issues and interpretation of results - Focusing on the variability and relative interpretation of LCA results due to typical agri-food methodological issues
- Mathematical programming **-** Novel mathematical approaches coupled with LCA
- Consumer - Using LCA as a tool or a guide for the consumer
- Food technology - Evaluation of the sustainability of some interesting novel food technologies
- Environmental costing - Taking into account the costs of environmental impacts of some agri-food product systems.

6.1. Applicability

Although the use of LCA tools, in some nations, is standard practice, as pointed out in some of the articles included in this special issue, there is compelling urgency to introduce and tailor LCA tools for use in other nations or regions of the world to promote more sustainable product systems at the global level. For example, **Ruviaro** et al. state, in their article, that considering the status of Brazilian agriculture, it would be necessary to adapt the LCA tools to the peculiarities of Brazil's environmental and technological context, regarding the ability to follow the trends in application of LCA as a tool for analysis of environmental impacts. Specifically, an overall effort to develop appropriate methodologies for both Life Cycle Inventory and Life Cycle Impact Assessment are urgently needed for Brazil to remain among the leaders of food and feed exporters, which would be appreciated by consumers worldwide.

In the paper by **de Alvarenga** et al., consideration was provided of methodological appropriateness through the comparison of Ecological Footprint (EF) and CML 2001, using a case study of four scenarios of feed production for broiler chickens in Brazil. They concluded the use of EF is not suitable for the agricultural sector, because it neglects important impact categories such as eutrophication and acidification.

As **Zhang** et al. documented the current Chinese promotion of rural development via the introduction of novel production systems, when analyzed via an emergy synthesis method and compared to traditional production systems, may help to produce better performance in economic terms but they are by no means environmentally sustainable. The authors, therefore, concluded the current Chinese agricultural diversification practices should not be encouraged and that other solutions must be developed. New LCA tools may be needed to help make progress in guiding the development and testing of the needed improvements.

6.2. Intensity

Other authors of this special issue highlighted the fact the new intensive approaches used to maintain production levels of agri-food products, implemented in some countries, do not always have lower impacts than the approaches they are replacing. In that line of research, **Torrellas** et al. analyzed the environmental and economic profile of current agricultural practices for greenhouse crops, in cold and warm climates in Europe. They documented that such practices are very energy intensive and generate substantial impacts due to the structure of the greenhouses and the use of fertilisers. The authors emphasized that such practices could be made to be more sustainable via co-generation or by using geothermally heated water together with the use of recycled materials for the construction of the greenhouses and via a more accurately calibrated use of fertilisers.

Similarly, **Cellura** et al. assessed the energy and environmental performance of peppers, melons, tomatoes, cherry tomatoes, and zucchini in different typologies of greenhouses (tunnel and pavilion). The results revealed that tunnel and pavilion greenhouses have comparable eco-profiles and, as with the previous study, the structure of the greenhouses has a large impact on the effectivity and efficiency of the food production system. Furthermore, they underscored the importance of the packaging step, which is seldom adequately addressed.

Romero-Gámez et al. analyzed green-bean cropping systems including a screenhouse, a screenhouse equipped with a misting system, and a control (open-field). The results illustrated the open-field treatment showed the greatest environmental impact in most categories due to its lower yields and the misting system was justified for enhancing the net productivity increases. They documented the importance of achieving good yields and reductions of environmental impacts of different treatments.

Tassielli et al. analyzed two innovative, intensive olive growing models based on high density (HDO) and super high density orchards (SHDO) in Italy. The LCA of these two models documented a better performance of the HDO system for all the impact categories, due to a lower use of energy and chemical inputs and to higher olive yields/hectare/year. From an economic point of view, the HDO method was more profitable than the SHDO. In fact, despite the lower operating costs of the latter due to the complete mechanization of pruning and harvesting operations, these costs were counterbalanced by higher initial investment costs, consequently, the company had to charge three times more for their produce that was produced with the SHDO system than with the produce that was produced with the HDO system.

Biswas et al.'s work, relative to vegetables and fruit grown and transported to retail outlets in Western Australia, emphasised the high environmental impact of the production of strawberries and lettuce compared to the impact of producing mushrooms due to intensive agricultural machinery operations and the higher greenhouse gas emissions of mushrooms during the pre-farm stage due to transport of peat, spawn and compost.

6.3. Organic production

Some of the work considered in this special issue addressed aspects of alternative, less intensive, organic production systems. These, supposedly environmentally more sustainable systems, however, are not always more sustainable. For example, **Salomone** et al. studied nine different olive oil production scenarios. They found higher environmental loads for some of the organic scenarios compared to the conventional ones, which they explained to be due to increased land areas being used as a consequence of lower yields. The significant positive contribution, in terms of environmental credits for avoided production, associated with the use of by-products as fuels or fertilizers was highlighted, based upon various uses and treatments of olive mill wastes. The study outlined how useful the LCA methodology can be in the decision-making process connected to the definition of an environmental chain strategy.

Hokazono and Hayashi focused on the conversion process to organic farming. They compared three rice production systems in Japan: organic, environmentally friendly, and conventional systems, based upon field trial data. The results illustrated that environmental impacts of organic farming fluctuated widely during the conversion phase due mainly to yield variations, although the five-year average performance of organic farming was lower than that of conventional farming. The environmental impacts of these farming systems were almost the same by the time of the last phase of conversion.

Schaefer and Blanke analyzed four pumpkin farming and marketing systems including an organic farm by using carbon footprint. They concluded that for cleaner production, carbon reduction potential is a significant way to reduce environmental impacts in all farming systems, except for the large farm and consumer behavior regarding the means of transport for shopping.

6.4. Land and water use

Ponsioen and Blonk developed a simple impact model based on statistical trends in land use changes within countries. Within the context of agricultural land expansion, they estimated differences between the global warming potential (GWP) due to burning and decay of natural, above ground biomass, agricultural and timber harvesting systems. They estimated the GWP of soil organic carbon decay due to land use changes due to transition of land uses from forested systems to agricultural production systems.

Ridoutt et al. used a recently developed life cycle assessment-based methodology that takes into account local water stress. Their results demonstrated the production and consumption of meat does not necessarily impose a heavy burden on freshwater resource usage.

6.5. Methodological issues and interpretation of results

The importance of the analysis and interpretation of the results deriving from an LCA is outlined in several of papers. This is especially true when considering agri-food products since there are many unresolved methodological approaches and issues that can give varying results. For example, as shown in **Flysjö** et al.'s work, when considering the carbon footprint of milk production, there appear to be contradictory results for organic/non-organic farming when using allocation as opposed to system expansion to account for corresponding beef by-products. The results are similar when considering land use changes, which continue to be an open issue in LCA with various methodological approaches that may produce contradictory results when comparing organic versus conventional high-yielding milk producing systems.

Similarly **Eady** et al. when considering mixed activity farming made use of different kinds of allocation to account for co-production derived from sheep activity, which resulted in very variable global warming impact measurements. Specifically using an economic allocation resulted in different estimates of global warming impacts for sheep co-products, with figures varying by 7–107%. When compared to biophysical allocation, economic allocation shifted the environmental burden to the higher value co-products and away from the high resource use products.

Fantin et al. also performed an LCA regarding milk that followed an iterative approach that was comprised of very detailed primary data collection that was done in compliance with the PCR (product category rules) for milk of the International Environmental Product Declaration (EPD)® System. The comparison with the results of a published EPD of another brand of high quality milk highlighted critical aspects that affect the comparability of LCA studies and EPDs of the food sector. The most relevant source of differences between the two studies is the choice of different system models, mainly due to lack of detailed instructions in PCR, especially for fertilizers, field emissions and choice of the models for their estimation. Additional sources of analytical challenges pertained to the complementary fodder production & waste management.

Based upon these papers, it is clear that there is urgency for LCA developers/users to improve on methodological harmonization in order to more effectively support future developments and applications of LCA in the agri-food sector.

6.6. Mathematical programming

A recent trend in the modeling of agri-food issues is the combination of LCA and mathematical programming. **Acosta-Alba** et al. presented trade-off analysis using LCA and multi-objective mathematical programming. The trade-offs predicted consequences of applying environmental constraints on agricultural production and revealed some of the challenges that agricultural policy makers must address. They summarized the major benefits of coupling LCA and multi-objective programming. **Nguyen** et al. used an approach using LCA and linear programming for least cost feeding formulations. They analyzed a feed production plant in Bretagne, France, in which they found the environmental impacts of poultry feed increased with the energy and protein content of the formula and were affected by the relative costs of the feed components.

6.7. Consumer

Saarinen et al. made an original and interesting use of LCA for an unusual audience, school children, with the intent of increasing the awareness of the young generations of what needs to be done to progress towards a more sustainable future. Specifically, they developed a food-related communication tool for sustainable education in the upper levels of Finnish elementary schools. The comparative environmental impacts were assessed for complete lunches, based upon: a. home-made portions, b. ready-to-eat portions and c. school prepared lunches. In particular, comparisons between mixed, vegetarian and vegan home-made lunches were carried out as well as between home-made and ready-to-eat lunches. In general, the home-made lunches resulted in 2–5 times more potential impact than vegetarian and vegan lunches. In addition to protein source, the choice of contents of salads made a substantial difference, especially regarding impact on climate. Ready-to-eat lunches caused less potential impact than the equivalent home-made lunches, due more to the raw material choices than to the energy consumption. The school lunches were found to be the least impacting type of lunch.

Jungbluth et al. discussed the main challenges facing the provision of meaningful information to support consumer decisions. They concluded that carbon footprint is insufficient for life cycle thinking, that starting with higher levels of decision-making is efficient, and the environmental information should be shown for the product as it is bought in the shop.

6.8. Food technology

Pardo et al. used LCA methodology to evaluate the environmental impacts of traditional and novel food preservation technologies to provide environmental criteria for selecting food preservation methods to develop more efficient and sustainable food products throughout their life cycles. Four thermal and non-thermal techniques were assessed: autoclave pasteurisation, microwaves, high hydrostatic pressure (HHP) and modified atmosphere packaging (MAP). The latter two technologies had reduced environmental impacts in terms of energy demand and CO_2 emissions in relation to conventional pasteurisation. Additionally, lower water requirements were observed for non-thermal technologies, such as MAP and HPP, in comparison to equivalent thermal processes. The MAP was found to be the more sustainable option. The significant impact sources of the life cycle of the technologies were analyzed and several potential improvements were identified, based upon technical and environmental perspectives.

Ewoukem applied LCA to four farms that integrated fish farming with other agricultural production in two regions of the western highlands of Cameroon. The results showed that eutrophication impacts were higher than literature reporting information of other aquaculture systems, mainly because the Cameroon fish production systems used pig manure and wheat bran as fish food sources. This shows that fish farming systems can/must address all facets of the process to reduce the environmental burden as they seek to improve fish quality and production efficiency.

6.9. Environmental costing

Monetization techniques were used by some authors. **Nguyen** et al. applied the Stepwise2006 method to monetize environmental costs of pig meat. The results showed the environmental costs of producing conventional pig meat are larger than the private costs and the three improvement measures are feed use, manure management, and manure utilization. **Silalertruksa** et al. evaluated the influence of externalities on the cost performance of various palm oil biodiesel blends through measuring willingness to pay (WTP). A case study of palm oil biodiesel was assessed and compared to conventional diesel. The results indicated that environmental costs contribute to 34% of the total costs of conventional diesel. In comparison to diesel and for the same performance, the total environmental cost of biodiesel based palm methyl ester (PME) is about 3%–76% lower depending on the blending levels.

The papers described above deal with a series of macro-aspects of food LCA. These are by no means exhaustive and represent only a small part of what still needs to be studied further and applied to achieve a sustainable agri-food industry.

The following items were highlighted during the closing session of the LCA Food 2010 conference as recommendations from the participants for the next conference in this series:

- Move the LCA debate beyond the methodological issues to include ethical aspects;
- Involve people from different sectors and countries, to address problems that are not currently known within the food LCA community;
- Place more emphasis on prevention and management of food wastes;
- Improve the use of LCA as a supporting decision tool for public and private food sector decision makers.
- Acknowledge the role of consumers and consumer organizations in providing independent evidence for product; testing
- Involve industrial organizations and other stakeholders.
- Improve the development of public food databases.

Much work needs to be done in the field of food LCA prior to the next meeting that will be held in France, St. Malo, on 2-4 October 2012.

7. Conclusions

The ISO 2006 standard for LCA provides the basic template for helping producers capture the human health and environmental impacts related to food production & consumption in a holistic and long-term manner. Unfortunately, the current life cycle impact models and supporting databases are not capable of adequately assessing the comparative short and long-term risks and benefits of food, feed, and biofuel production systems. LCA practitioners and researchers need to further develop LCA tools so they can address the rapidly evolving issues related to agricultural products, such as exposures to pesticides, soil function impairment, biodiversity losses, and invasive GM crops. Agri-medicines, animal growth hormones, antibiotics and other toxins that may enter the food supply chain must also be investigated. Furthermore, LCA researchers must investigate how to model species diversity challenges caused by GM crops and other 'selective pesticides' as well as the short and long-term consequences of usage of 'terminator genes'.

We need to push the envelope on the methodology and develop new and improved methods and models, as well as to develop the necessary supporting databases to achieve significant advances in the use of LCA concepts and life cycle-based tools, especially with regard to the numerous and wide ranging health and nutritional dimensions that are urgent problems that confront society. Continued research is needed, and researchers are encouraged to build upon the topics that are presented here and share their findings at the LCA Food 2012 conference.

Notice

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