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In quest of reducing the environmental impacts of food production and consumption

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ABSTRACT

Food supply chains are increasingly associated with environmental and socio-economic impacts. An increasing global population, an evolution in consumers' needs, and changes in consumption models pose serious challenges to the overall sustainability of food production and consumption. Life cycle thinking (LCT) and assessment (LCA) are key elements in identifying more sustainable solutions for global food challenges. In defining solutions to major global challenges, it is fundamentally important to avoid burden shifting amongst supply chain stages and amongst typologies of impacts, and LCA should, therefore, be regarded as a reference method for the assessment of agri-food supply chains. Hence, this special volume has been prepared to present the role of life cycle thinking and life cycle assessment in: i) the identification of hotspots of impacts along food supply chains with a focus on major global challenges; ii) food supply chain optimisation (e.g. productivity increase, food loss reduction, etc.) that delivers sustainable solutions; and iii) assessment of future scenarios arising from both technological improvements and behavioural changes, and under different environmental conditions (e.g. climate change). This special volume consists of a collection of papers from a conference organized within the last Universal Exposition (EXPO2015) "LCA for Feeding the planet and energy for life" in Milan (Italy) in 2015 as well as other contributions that were submitted in the year after the conference that addressed the same key challenges presented at the conference. The papers in the special volume address some of the key challenges for optimizing food-related supply chains by using LCA as a reference method for environmental impact assessment. Beyond specific methodological improvements to better tailor LCA studies to food systems, there is a clear need for the LCA community to "think outside the box", exploring complementarity with other methods and domains. The concepts and the case studies presented in this special volume demonstrate how cross-fertilization among difference science domains (such as environmental, technological, social and economic ones) may be key elements of a sustainable "today and tomorrow" for feeding the planet.

1. Introduction

Food systems are at the heart of the 2030 Agenda for Sustainable Development (UN, 2015), a global commitment to eradicate poverty and hunger while ensuring reduction of environmental and socio-economic impacts. Amongst the United Nations Sustainable Development Goals, Goal 2 ("end hunger, achieve food security and improved nutrition and promote sustainable agriculture") and Goal 12 ("ensure sustainable consumption and production patterns") are the focus of this special volume.

Ensuring sustainable human development means being able to feed a planet with increasing population, decoupling the socio-economic development from environmental impact, and addressing the evolving food and energy demand (UN, 2015). Food and energy supply chains are associated with complex and intertwined

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environmental and socio-economic impacts (Ericksen, 2008), as an evolution in consumers' needs and the changes in consumption models pose serious threats to the overall sustainability of food production and consumption.

The identification of sustainable solutions in the food and energy sectors needs to rely on integrated appraisal methods for comparing possible alternatives, and avoiding burden shifting geographically, temporally and along supply chains (FAO, 2012). Due to the variety of challenges and perspectives related to food systems, several methods are needed to answer different sustainability questions. This requires a transition towards systemic thinking, where impacts of global production and consumption patterns remain within the carrying capacity of the planet, namely the sustainability thresholds identified as planetary boundaries (recently updated by Steffen et al., 2015). This systemic thinking entails the identification of complementarity amongst methods and the critical analysis of their pros and cons for supporting decision making (Sala et al., 2013a,b).

Food systems entail the overall supply chain from agriculture to production, trade, distribution, consumption and the waste production. With an increasing global population, the need of 'resource-smart' food systems is of uppermost importance (UNEP, 2016). Life Cycle Thinking (LCT) and the different life cycle-based methods, such as Life Cycle Assessment (LCA) (ISO, 2006a, b), Life Cycle Costing (LCC), Social Life Cycle Assessment (sLCA) and the overall Life Cycle Sustainability Assessment (LCSA) may support a transition toward increasing the sustainability of current patterns of production and consumption. Specifically, Life cycle assessment (LCA) represents a reference method that helps in analysing supply chains with the aim of achieving environmental sustainability objectives, including improved agriculture, food production and consumption as well as more efficient energy conversion and use, supporting the identification of sustainable solutions for global food challenges (Notarnicola et al. 2016a). However, the complexity of food systems and supply chains requires food systems-tailored approaches in LCA, and the aim of this volume is, therefore, to gather together studies on LCA, and on the integration of LCA and other domains and disciplines, in order to assess agricultural supply chains.

In defining solutions to major global challenges, life cycle thinking and life cycle assessment are applied for: i) the identification of hotspots of impacts along food supply chain with a focus on major global challenges; ii) the comparison of options related to food supply chain optimizations (such as increase of productivity, and reduction of food losses) towards sustainable solutions; and iii) assessment of future scenarios both related to technological improvement, behavioural changes and under different environmental conditions (e.g. climate change); iv) assessment of social impacts associated to consumption patterns.

Analyzing these challenges from a global/continental perspective, major improvements are needed in all step of the LCA method. For example, life cycle inventories should cope with data availability, data quality and representativeness, whereas life cycle impact assessment needs the enhancement of impact modelling of water, land use, resource and toxicity for robust assessment of alternatives.

These topics were discussed during a conference organized by the European Commission- Joint Research Centre jointly with the Italian Association of Life Cycle Assessment. The conference "LCA for Feeding the Planet and Energy for Life" (6–8 October 2015) was held during the Universal exposition EXPO 2015 in Milan. The volume includes selected papers from the conference (proceedings available ENEA, 2015) as well as other contributions submitted to the journal that addressed the key challenges presented at the conference.

This special volume builds specifically on the theme proposed by (EXPO 2015) held in Italy in 2015, entitled "Feeding the Planet, Energy for Life". The key topics were related to the issue of the sustainability of agricultural intensification for answering the food needs of a growing population, the competition between land use for energy and for food, and the maximization of societal benefits whilst reducing environmental and socio-economics burdens (Fig. 1).

The special volume welcomed submission of papers focusing on: 1) analysing these challenges from a global/continental perspectives and proposing potential solutions; 2) case studies presenting comparison of results adopting different approaches leading to environmental improvements and optimizations; 3) reviewing methods and tools for sustainability assessment of food supply chains, focusing on food waste and resource recovery; and 4) Thinking outside the box: LCA and its complementarity with other methods and domains.

Contributions to this special volume were selected in order to cover these topics which are major challenges, proposing methodological improvements and specific case studies towards better assessment of agri-food supply chains. To set the context and the need for the improvement of life cycle based assessment of food supply chains, the volume opens with an overview of challenges for improving the robustness of current LCA method, identifying the research needs at the modelling, inventory and impact assessment level (Notarnicola et al., 2016a). The volume is then structured in four main parts: i) improving the current LCA methodologies for responding to Food LCA challenges; ii) how to better assess intensive, extensive and organic farming with LCA; iii) resource-smart food systems: LCA supporting the assessment of food waste and nutrient recovery; and iv) LCA supporting consumers and stakeholder's choices.

2. Improving current LCA methods for responding to food system challenges

Current Life Cycle Assessment applied to single food products and to food systems faces a number of methodological challenges. A review of them has been recently performed and opens the special volume (Notarnicola et al., 2016a). These challenges affect all steps of the method: from goal and scope definition, to life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of LCA results.

2.1. System boundaries and functional unit

When dealing with the assessment of the impacts/benefits due to agricultural intensification, one of the fundamental elements to be taken into account is the functional unit selected for the assessment. In the majority of LCA studies, mass is the only functional unit used to report LCA results of food product.

Recently, the number of LCA studies of whole diets has increased and Pernollet et al. (2016) investigated a number of studies on choices of systems boundaries and impact categories and how that affected the results. The results showed that many studies still include the agricultural phase only and most often included one or a few impact categories (e.g. climate change and land use), which significantly reduced the potential to make general conclusions. Similarly, Baldini et al. (2016) performed a review and analysed 44 studies on dairy production. The main conclusion was that there is a need for harmonization of approaches. Some areas for further development include broader range of impact categories, functional units, transparency, system boundaries, and sensitivity analysis.

Figueiredo et al. (2016) assess the production of sunflower in

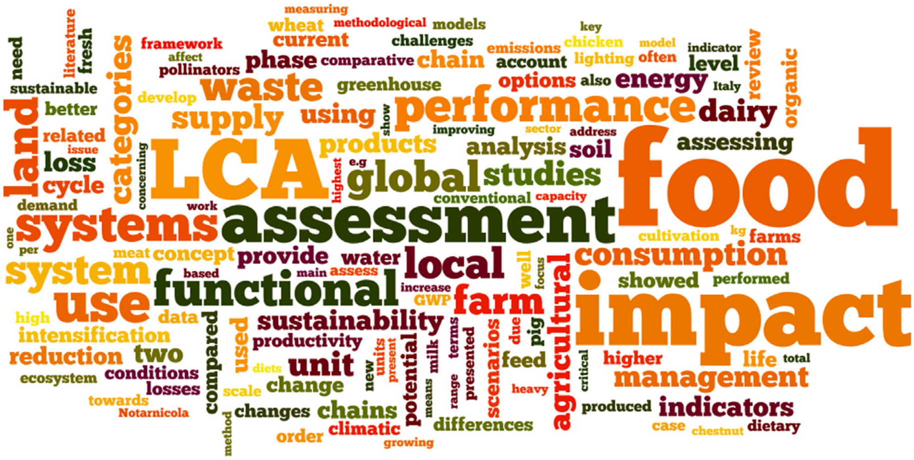

Fig. 1. An overview of the keywords used in the special volume illustrating the variety of issues covered.

Portugal comparing irrigated and rainfed systems and different land use change scenarios. One of the most important findings of this study was that an increase on the sunflower productivity, associated with an intensification of inputs level, not always results in a reduction on the environmental impacts per kilogram of sunflower. Higher uncertainty levels were observed for the impacts of irrigated sunflower compared with rainfed due to field emissions. Additionally, the uncertainty ranges for the emission factors proposed by IPCC for the calculation of nitrogen (N) field emissions are very large and dominates the overall uncertainty in all impact categories for irrigated sunflower.

Salou et al. (2016) assess environmental impacts of dairy system intensification to identify production systems that combine high productivity and low environmental impacts, adopting the concept of the Technological Management Route, i.e. a logical set of technical options designed by farmers, to describe the diversity of milk production systems. Impacts were estimated for two functional units: t milk and hectare of total (on- and off-farm) land occupied, demonstrating that the choice of functional unit leads to radically different conclusions. Using only a mass-based functional unit, which is predominant in current life cycle assessment practice, does not provide a balanced view of the impacts of intensification and could mislead decision makers in identifying promising dairy systems. More generally, current LCA practice seems largely blind to the negative environmental consequences of agricultural system intensification, as revealed by the area-based functional unit. The authors recommend the use of both mass-based and area-based functional units in the life cycle assessments of agricultural goods.

Focusing on 21 bread types, Notarnicola et al., 2016b performed an assessment of the embedded energy and GHG emissions, testing three functional units: mass, nutritional value and price-based. Energy consumption in the production phase represents a hotspot for most bread types, and the efficiency of ingredient production, bread shape and size influence the results.

In the last 5–10 years, the need of rethinking functional units and its focus has emerged. Sonesson et al. (2016) proposed a new approach based on digestible protein which should reflect better the functionality of food with limited additional data. The purpose of this study was to develop a functional unit to be used in LCA of foods that builds on the nutritional value of food products. The content and quality of proteins was used as a basis and included dietary context as part of the method, since the nutritional value of a nutrient depends on the total dietary intake. The results showed that the relative differences between products changed when using a protein-based functional unit, with the largest change occurring when going from mass as the functional unit to protein.

2.2. Life cycle inventories

Lovarelli et al. (2016) analysed environmental impact results of different ploughing solutions and soil conditions comparing two different approaches to fulfil inventories, either average data coming from databases or local datasets. Results show that differences are not negligible being environmental impacts deeply affected by using average datasets instead of local data. In order to avoid unrepresentative environmental impacts authors strongly recommend the use of primary or secondary data evaluated considering local conditions. In contrast to the static and generic nature of conventional LCAs, the paper of Maier et al. (2016) address the use of dynamical information in LCI, temporally and spatially explicit, to determine the localised emissions over time. The proposed framework could potentially transform the way LCA is currently performed, and could offer significantly improvement for processes such as agricultural production, which has high spatial and temporal heterogeneity.

2.3. Life cycle impact assessment and interpretation of results

New or improved model of impact characterisation are needed, specifically for those impact categories which are crucial for any assessment of agricultural supply chains. For example, in their study, Vidal Legaz et al., 2016, carry out a systematic and qualitative evaluation of up-to-date models connecting land occupation and land transformation to soil impact indicators (e.g., soil properties, functions, and threats) concluding that no model is currently fully capable to address comprehensively the impact of land intervention on soil quality. The results of the review provide common ground for the development and identification of models that provide a comprehensive and robust assessment of land use change and land use impacts on soil quality. One of the limitations of the models reviewed by Vidal Legaz et al. (2016) was the lack of specificity in addressing impact related to land management.

Rugani and Rocchini (2016) focused on the land use impact on biodiversity, which is considered another controversial aspect to be covered in LCIA due to local variability and complexity of the assessment (Curran et al., 2016). In the domain of nature conservation and landscape ecology, spectral heterogeneity (SH) derived from remotely sensed imagery is considered a viable proxy for species diversity detection. The assessment rationale is based on the 'spectral variation hypothesis': the higher the spectral variability, the higher the ecological heterogeneity and species community diversity, occupying different niches. Rugani and Rocchini (2016) studied computing SH at a local scale of crops cultivation in Southern Alps (Trentino province, Italy), and then combining this information with land use over 30 years. We observe and analyze the relationships between land cover maps and habitat heterogeneity at different time and spatial resolutions. The detection of spectral heterogeneity (SH) patterns can provide with actual state references on the conditions of biodiversity at multiple time and spatial scales. In principle, such information can be exploited to extend the current knowledge on life cycle impact assessment of land occupation and transformation on biodiversity.

Beyond the land use related impacts, other drivers of impacts have not been properly addressed yet. Crenna et al. (2016) focussed on insect pollinators and on the essential functional they play in terrestrial ecosystems, supporting ecological stability and food security worldwide. Since different drivers are leading to pollinator populations' declines, the improvement of a supply-chain oriented assessment of the occurrence of pressure and impacts on pollinators is needed. However, current methods assessing impact along supply chains, such as LCA, do not assess impact on pollinators. In order to devise a pathway towards the inclusion of impact on pollinators in LCIA, a literature review of environmental and anthropogenic pressures acting on insect pollinators, potentially threatening pollination services was carried out. The study provide recommendation on how future research should be oriented to improve the current models and how novel indicators should be developed in order to cover the existing conceptual and methodological gaps.

A novel characterisation model for nitrogen emissions from spring barley production is presented by Cosme and Niero (2016). The main improvement to the LCIA midpoint CFs is the inclusion of ecosystem exposure and effects to biota, by improving the commonly used 'increase in N concentration' in marine water to a 'fraction of species (as PAF) affected' by the eutrophication impacts in the marine coastal compartment. The study proposed taking into account further scenarios of climate change in marine eutrophication modelling. A 2050 scenario was implemented, based on corresponding altered emission flows and modified parameterisation in the CF estimation.

Another crucial impact category is water depletion. An example of the different results coming from different perspective in accounting is shown by Murphy et al. (2016) who investigated water use on 24 dairy farms in Ireland. They found that the majority of water was used for pasture production i.e. "green water". However, when assessing water scarcity which focuses on blue water, the imported concentrate feeds made the biggest contribution to the result (using the Water Stress Index method of Pfister et al. (2009)).

The work of Castellani et al. (2016) contributes to a better understanding of impact assessment results, including normalization and weighting. Due to some methodological weakness of LCA, results of their study show possible drawbacks on LCA interpretation. The authors concluded that LCA could be suitable for assessing single products' environmental performance, but it needs to be complemented by knowledge coming from other methods and disciplines, especially when LCA is applied for policy support.

Several studies explored the use of different footprint metrics (e.g. ecological footprint, water footprint, carbon footprint, exergy analysis etc). Bartocci et al. (2016) assessed the impact of aged vinegar, complementing LCA with ecological footprint as well as water footprint. The results were similar with those previously published for wine, but the additional transports and processing contributed markedly. Differences between vinegars stemmed from differences in transport and processing, hence there were several improvement options identified on post-farm activities, as reduced use of packaging materials, energy efficiency and logistics. Musikavong and Gheewala (2016) present the application of ecological footprint of fresh fruit bunches (FFB) from oil palm and fresh latex, and hevea wood and branches from rubber plantations. Ratios between economic benefit to EF of oil palm and rubber plantations were considered as indicators for zoning oil palm and rubber plantations as economic crops of Thailand. The authors suggest that policymakers should include EF and benefit to EF ratio for zoning suitable oil palm and rubber plantations to enhance sustainable production. New varieties of oil palm and rubber trees with high yields and the policy for supporting the establishment of rubber industry for producing the valuable products should be promoted. Soufiyan et al. (2016) presented the potential application of the exergy concept for improving the performance of dairy processing plants at industrial scale. The results indicated that the largest exergy destruction rate occurred in the compressor and boiler combination of the steam generation system, accounting for 89% of the total exergy destruction of the system. The steam generation system had the greatest contribution to the specific exergy destruction of the long-life milk processing followed by above-zero refrigeration system, UHT milk processing unit, and milk reception, pasteurization, and standardization line, respectively. Hence, a small improvement in the exergetic performance of the steam generator could profoundly lower the specific exergy destruction of the long-life milk processing.

3. How to better assess intensive, extensive and organic systems agricultural systems

Agri-food industries face increasing pressure to quantify and improve their environmental performance over time, while simultaneously increasing production to meet global demand. Many LCA studies overtime have reported benefit associated with intensification whereas intensification may lead additional burdens not always accounted for. Several examples are reported in the special volume, focusing on different aspects related to intensification, conventional versus organic farming, traditional agriculture versus newly introduced systems.

Salem Ali et al. (2016) estimated the emission intensity generated from the production of 1 kg of durum wheat in a typical wheat cultivation area of southern Italy, under different crop management systems and input of nutrients. Results showed relatively higher emissions resulting from the pre-farm phase, whereas the cultivation phase was responsible for 49%, most of which was due to soil emissions (37.4%). The results show that the key strategy in lowering the carbon footprint of wheat is to reduce the input intensity and increase grain yield by improving N use efficiency through the introduction of N-fixing crops. The overall findings of this study indicate that achieving the synchrony between minimum input requirements and crop demand without excess or deficiency of nutrients is the key for optimizing a trade-off between yield and environmental protection.

A comparative life cycle assessment of the current rural rice parboiling used in a rural village versus a newly developed integrated steaming and drying system (ISDS) is presented in Kwofie and Ngadi (2016). The analysis showed that with the ISDS process up to 80% reduction in total environmental impact can achieved. They performed a sensitivity assessment of the results with different impact assessment methods and rice husk assumption confirming that the ISDS resulted the preferred options. The sensitivity of the LCA results was tested using an alternative evaluation method and the variation in rice husk availability. The results indicated that the choice of evaluation method matters in LCA results since different normalization factors and midpoint indicators are used for different LCA evaluation methods. The variation in rice husk availability did not influence overall normalized emission as only 5.2% increment in impact was observed for a 20% reduction in rice husk use.

LCAs on the production of wheat and maize in an Italian farmers' cooperative was performed by Fantin et al. (2016) with a high degree of details in the modelling. The major hotspot for both cereals in all impact categories is the agricultural phase, due to fertilizers and pesticides use. The authors conducted a sensitivity analysis, using different methods for the calculation of on-field nitrogen and pesticides emissions, in order to assess their effects on LCA results. It showed that choice of model mainly affected results for toxicity impacts, but other impacts also showed sensitivity of model choice.

Dijkman et al. (2016) compared the environmental impacts of spring barley cultivation in Denmark under current (year 2010) and future (year 2050) climatic conditions. Both under 2010 and 2050 climatic conditions, assessing four scenarios based on a combination of two soil types and two climates. Included in the assessment were seed production, soil preparation, fertilization, pesticide application, and harvest. The results show that the impacts for all impact categories, except human and freshwater eco-toxicity, are higher when the barley is produced under climatic circumstances representative for 2050. The comparison between the 2010 and 2050 climatic scenarios indicates that a predicted decrease in barley yields under the 2050 climatic conditions is the main driver for the increased impacts.

Longo et al. (2016) analysed the energy and environmental impacts of organic and conventional apples cultivated in the North of Italy. The results showed that, despite a lower productivity, preferring organic apples versus conventional apples could help to reduce the environmental impacts for most of the examined impact categories. With a few exceptions, differences lower than 7% occur between the eco-profiles of the two examined products. A detailed analysis of the farming step shows that a significant share in the overall energy and environmental impacts is due to the use of fertilizers and pesticides and to the consumption of diesel for agricultural machines.

Chobtang et al. (2016) compared two levels of dairy farming intensification (i.e. high versus low) in pasture-based milk production systems in New Zealand. The high intensification group produced more milk both per cow and per hectare. For the high intensification group, the results for 10 out of 12 environmental indicators per kg of fat- and protein-corrected milk were higher. The differences were driven by production and transportation of off-farm inputs, which should be optimised. The results highlight that pasture-based dairy farm intensification options should focus firstly on increasing pasture intake in order to reduce the use of supplementary feeds.

Wiedemann et al. (2016) assessed chicken production in Australia, aiming to quantify resource use, environmental impacts and hotspots for Australian chicken meat production using updated inventories and new methods. Two contrasting states (Queensland and South Australia) and two housing systems (conventional and free range) were analysed to indicate the variation expected between regions and systems. Feed production was the largest contributor to all impact categories, and also showed the largest variation between regions, highlighting the importance of spatially specific feed grain datasets to determine resource use and greenhouse gas from chicken meat production. From their results there were no substantial differences between conventional and free range production when feed related differences were removed, while they demonstrated that regionally specific datasets are required to accurately quantify resource use.

Bava et al. (2016) provided a first evaluation of the environmental impact potentials of heavy pig production in Italy through an LCA of 6 intensive pig farms. Environmental impacts per kg live weight were generally higher than those generated in the production of pigs slaughtered at lower weight. The feed chain was the major source of impact for all the categories and the most important hotspot of heavy pig production. Farm size and reproductive efficiency appeared important factors in the environmental burden of heavy pig production. The study confirms the important role of feed chain in the environmental load of pork production as underlined by many authors: feed components are the main contributors of all the impact categories. In particular, as substances contributing to the main impacts are in many cases N compounds, a more efficient use of N from swine, through decreasing the dietary protein level and optimizing the amino acid profile on the basis of the physiological phase, will improve the environmental performances of heavy pig production.

3.1. Farm environmental performances

Appropriately assessing farm environmental performance poses another challenge: a number of indicators have been used for this purpose, sometimes missing a clear conceptual framework. Repar et al. (2016) undertook a critical review of the indicators used to assess farm environmental performance proposing a framework for defining and measuring farm environmental performance distinguishing between local and global farm environmental performance. This distinction should prevent environmental problem shifting from one scale to another, complying with the environmental sustainability concept viewed from an ecological perspective. Implementing separate local and global environmental performance indicators, as opposed to using only global or local indicators without distinguishing between them in conceptual terms, provides a more appropriate assessment of the environmental performance of farms, as well as a better basis for comparison between farms.

In regards to environmental performance of farm, other aspects could be taken into account. For example, the study of Zhang et al. (2016) reported a comparative LCA of different lighting systems applied in greenhouse crop production. Benefits of substituting LEDs for incandescent lighting for greenhouse applications lead to a significant reduction (67%–90%) on most environmental impact categories considered.

Sharma et al. (2016) presented an estimation of the potential of solar industrial process heating (SIPH) and corresponding mitigation of greenhouse gas emissions in dairy industry in India. The dairy sector in India has a significantly large potential for solar energy-based process heating to meet its demand for pasteurization and other thermal energy requirements. The solar energy based process heating systems without any storage are estimated to meet 20–30% of the total process heating demand of the milk processing in the organized sector of the dairy industry. An assessment of availability of solar radiation as well as of the ambient conditions at various locations with milk processing plants has been made. The results showed that the use of solar energy for meeting milk processing related thermal energy demand is expected to mitigate between 32 and 144 thousand tonnes of CO_2 emissions annually.

3.2. Distribution systems

Environmental performance of food production and consumption could be affected by both alternative cultivation practices but also by many other drivers of impact, such as distribution systems. The work of Tasca et al. (2016) described different distribution systems for organic and conventional endive taking into account packaging and product presentation, that is fresh or ready—to-use product as well as delivery media. The assessment for the agricultural production stage revealed that none of the examined farming techniques is absolutely more sustainable than the other. Specifically, fertilization practices, mulching techniques, and achievable production yields appear to be the areas where more improvements are needed. It is also highlighted by the authors the lack of methods to quantify potential environmental benefits achievable by adopting a cultivation method such as organic, which maintain and enhance biodiversity of soil and of the surrounding environment. Regarding distribution system stage, the direct delivery of a raw product with returnable packaging is preferable for all the considered impact categories, regardless of the cultivation method applied. The reduction of the use of disposable packaging thus represents, if feasible, one effective measure to reduce the impact of ready-to-use vegetable products and, more in general, of fresh vegetable distribution. Finally, authors advise about the importance of means of transport because the potential benefits of local distribution could be hampered with the use of smaller and less efficient type of vehicle (i.e. a delivery van) compared to large-scale supply of a ready-to-use product.

Rosa et al. (2016) presented a “cradle-to-plate” LCA of fresh and frozen chestnut produced in Portugal, intended both for export and domestic consumption. As often highlighted in literature, the agricultural phase contributes the most to the life-cycle impacts of both fresh and frozen chestnut. Freezing the chestnuts, especially for long periods can considerably increase the overall impacts as does shipping by air. Overall, out of season chestnut consumption presents significantly higher impacts than fresh consumption. The impacts of the domestic phase are influenced by the electricity mix of the importing countries which is why the authors suggest, as a possible environmental impact reduction practice, the minimisation of energy use in storage and cooking. Transportation, storage and cooking phases would benefit from the use of more efficient means of transportation (environmentally-friendly vehicles), storage (facilities and equipment) and cooking devices.

3.3. Moving from farm to meso and macro scales

Food systems need to consider the performance of single products, as well as the overall market system. For example, Notarnicola et al. (2016c) quantified the impact of average European food consumption. A basket of 17 food products was identified as representative of the average food and beverage consumption in Europe by mass. Then a highly disaggregated inventory model was developed based on a modular approach, and built using statistical data to quantify the environmental impacts. Meat and dairy lead the overall environmental impacts and are considered the key areas needing optimisation. The study of Notarnicola et al., 2016c has been then subject to an extensive sensitivity analysis of the results for improving the interpretation thereof. The sensitivity has been performed adopting different impact assessment methods, normalization and weighting sets as well as assessing hotspots identified beyond the LCA domain (Castellani et al., 2016). The sensitivity analyses showed diverging results about the relevance of the different impact categories. However, in terms of product groups, the consumption of meat and dairy products shows the highest environmental impact irrespectively of the method adopted. Overall, the relevance of impact categories was more influenced by normalization than by weighting.

Clune et al. (2016) presented results for different 168 food products focusing on global warming potential (GWP). While individual results from LCA studies should not be directly compared with other individual results because of the different methodological choices, authors suggested that the use of meta-analysis of a large body of LCA work that draws on different methods, geographies and farming provides a stronger information. In fact, the meta-analysis indicates a clear greenhouse gas hierarchy emerging across the food categories, with grains, fruit and vegetables having the lowest impact and meat from ruminants having the highest impact. Building on the provided data, streamline calculations of the global warming potential of human diets could be performed.

Several reduction of impacts measures are related to urban systems, in terms of food consumption habits and the potential of local production, Urban and Peri-Urban Agriculture (UPA) may assume a relevant role in food systems sustainability. A study on this potential has been presented by Benis and Ferrão 2016, which focused on a case study for the reduction of greenhouse gas emissions and land use impacts in the Lisbon Metropolitan Area (LMA) food system. Focusing on dietary changes following a Recommended Healthy Diet (RHD) model (GWP by up to 22% and LU by up to 23.7%), reduction of food losses and wastage in supply chain (GWP by 8.2% and LU by 7.3%) and producing food within the borders of LMA (GWP by 2.6%). The results show that the highest potential for environmental impacts mitigation is related to dietary changes. However, strategies for enhancing the efficiency of the food supply chain are relevant, as reducing losses and wastage, shortening transportation distances and taking into account technology improvements can further increase the mitigation potential.

3.4. Integrating LCA with methods for system optimisation

Sustainable solutions for agricultural systems requires that not only environmental impact are reduced but also that benefits are maximized. This entails: i) assessing the need of complementing the analysis with other methods; ii) the development of methods and indicators for addressing socio-economic concerns; and iii) the development and the implementation of optimisation methods for ensuring a balanced and improved combination environmental and socio-economic aspects. LCA researchers and practitioners often promote the idea of combining LCA with other analytical method in order to provide better support for decision-making.

Antonini and Argilés-Bosch (2016) addressed the need of finding new ways of measuring the environmental and economic consequences of farming, by inquiring into the impacts that excessive intensification has on productivity and environmental costs in the long term. Results provide empirical evidence that the regions under study have a negative trend of productivity and a positive trend of environmental costs over the time frame mentioned. Environmental unsustainable practices are linked with increasing financial costs in the long term. Paying attention to financial costs of external inputs needed in intensive practices could help to achieve a social awareness of the value of natural resources, which is an essential cultural factor needed to mitigate the environmental impacts of food production.

Mousavi-Avval et al. (2016) applied a multi-objective genetic algorithm (MOGA) to find the best combination of mixing energy, economic and environmental indices concerning oilseed canola production. Life cycle assessment of canola production from cradle to farm gate was investigated to calculate the environmental emissions. Econometric modelling was applied to find the relationship functions between energy inputs and three individual output parameters including environmental emissions, output energy and economic productivity. A multi-objective model was formulated in order to maximise the output energy and benefit to cost ratio, and minimise the final score of environmental emissions in order to obtain a set of Pareto frontier. The outcomes revealed that, global warming potential was 1181 kg CO_2eq per ton of produced rapeseed from which 3367 kg CO_2eq was derived from off-farm emissions and 845 kg CO_2eq was belong to on-farm emissions. Emissions due to production and application of chemical fertilizers and also diesel fuel burning had a pivotal effect on environmental burdens. Integrating a legume into the crop rotation by developing rapeseed-bean rotation compensates a part of required chemical nitrogen by nitrogen fixation and consequently, it can be a possible alternative management strategy for lowering high dependency of rapeseed to chemical fertilizers, and consequently, establish more environmental friendly rapeseed production systems in the region.

Galán-Martín et al. (2016) developed a systematic multi-objective optimisation tool for crop area allocation, integrating life cycle assessment principles and water footprint accounting, towards the identification of optimal cropping patterns for simultaneously maximizing the crop production and minimizing the impacts. The tool provides a set of alternatives for optimally reallocating these wheat areas that ultimately achieve significant reductions in environmental impact while maintaining or even increasing the production level. The solutions simultaneously maximise the crop production and minimise the impact. Their results demonstrated that the optimal allocation of rainfed and irrigated cropping areas is a potential pathway to minimise the environmental impact of water consumption in food production, and may be used to support decision-makers suggesting optimal cropping patterns.

Another example of assessing mutual benefit between agriculture and other systems is provided by Dias et al. (2016), who assessed the life cycle environmental performance of Canadian greenhouse tomato production. The paper provides a broader sustainability analysis that could be applied to other regions when considering improvements, considering both growing biomass on degraded land and industrial symbiosis to recover wastes so that appropriate strategies are implemented to provide environmentally and economically sustainable vegetables.

4. Resource-smart food systems: LCA supporting the assessment of food waste and nutrient recovery

Assessing food systems with LCA includes assessment of the end of life phase, namely the food loss and the food waste production, as well as the potential for resource efficiency in terms of recovery of material and energy from food waste. The interest in food waste (FW) in the scientific community has been growing consistently in the most recent years as highlighted in the review by Chen et al., 2016. The predominance of Chinese institutions in terms of article count and a predominance of industrialized countries' institutions in terms of citation score were compared. Overall, clean energy, treatment and valorization, and management innovations are the key areas on which research is flourishing, often assessing options -in terms of their sustainability – by adopting LCA as reference method.

Modelling food waste in LCA needs a systematization of knowledge and potentially a new way of inventorized food losses and waste (Corrado et al., 2016). Corrado et al. (2016) addressed food losses with a focus on current LCA practices and their limits; consequently, proposed a definition of food loss and a respective methodological framework to increase the robustness and comparability of LCA studies concerning food loss along the food supply chain. The authors suggest to account separately between avoidable, possibly avoidable and unavoidable food loss by means of specific indicators. The most relevant recommendations concern the following aspects: the systematic accounting of food loss generated along the stages of the food supply chain; the modelling of waste treatments according to the specific characteristics of food; a sensitivity analysis on the modelling approaches adopted to model multi-functionality and the need of transparency in describing the modelling of food loss generation and management.

Food loss and waste is increasing worldwide due to a set of different production and consumption drivers. The increasing food demand may provide new market opportunities in the agro-farming sector, when focusing on reduction of impacts and maximization of resource recovery. For example, as presented in the study of Willersinn et al., 2016, in Switzerland, more than half of the initial potato production is not directly consumed by humans but lost. To analyze the environmental impacts caused by these losses, they conducted a Life Cycle Assessment concerning the demand for non-renewable energy resources, the global warming potential, human toxicity and ecotoxicity (terrestrial and aquatic), coupling the assessment with an analysis of how potential loss reduction scenarios and various loss treatments (animal feed, biogas, incineration) might affect the total environmental performance of the supply chain. The results indicated in general that environmental benefits due to the loss treatments were bigger than benefits achieved by the loss reduction scenarios. Loss treatments, in particular feeding and fermentation, could reduce the examined impacts, but not generating losses represented a better option, especially at the household stage (the impacts here were 8–42 times as high as the impacts of losses at agricultural production).

As managing properly food waste is gaining more public attention, Salemdeeb et al. (2016) provide a timely and interesting comparative analysis of four food waste disposal options. According to their study, recycling food waste as pig feed delivers the lowest environmental impact. Results of 14 mid-point impact categories show that the processing of food waste as a wet pig feed and a dry pig feed present the best environmental score. Recycling food waste as pig feed has the lower environmental impact than anaerobic digestion or composting.

Palmieri et al. (2016) illustrate an Italian LCA case study on liquid whey usage in animal nutrition. Three dairy chains and cow diets were assessed and compared by combining traditional hay, silages and liquid whey as feed. Results showed that raw milk production was the most impactful phase along the considered supply chain and whey usage could represent an environmentally sustainable option among the different diets. Moreover, recycling the liquid whey and strengthening the relation at local level between dairy farms and cheese factories, may have several economic benefits: the cost of whey transportation to treatment plants in charge of dairy factories and the disposal costs of liquid whey would be eliminated. More importantly, the environmental burden of whey treatment could be avoided. The benefits of liquid whey use in dairy cow feeding could be relevant especially in the traditional dairy chain because this practice is simple, cheap and suitable even in small farms.

There have been few LCA studies on the potential for using insects to convert food waste into useful products. Salomone et al. (2016) presented an LCA of feeding *Hermetia illucens* on food waste and potentially produce livestock feed and/or biodiesel as well as compost. Comparisons were made with conventional production of protein and lipids. When compared with alternative sources of raw material for feed or biodiesel, these results show that the most significant benefits of insect production are connected to Land Use, while Energy Use is the main burden, and the estimation of Global Warming Potential is still affected by many uncertainties. This study pointed out that significant environmental benefits are connected to the replacement of the production of N fertilizers, even though current studies on insect-based products are mainly focused on the value and role of larvae production rather than the residue of the bioconversion process (the larvae manure used as compost), also due to the higher economic value of larvae compared to compost. However, in order to appreciate the real potential of larvae manure to replace N fertilizers, their effect on field production should be further explored.

Silalertruksa et al. (2016) showed how an integrated utilization of biomass residues through the entire chain can help reduce the environmental impacts of the main products derived from sugarcane. Mechanized farming with cane trash and vinasse utilization reduces several environmental impacts. In fact, the potential impacts on climate change, acidification, photo-oxidant formation, particulate matter formation and fossil depletion could be reduced by around 38%, 60%, 90%, 63% and 21%, respectively. The results revealed that the mechanized farming (and green cane harvesting) along with integrated utilization of biomass residues such as cane trash and vinasse for fuels and fertilizers can help to reduce several environmental impacts of products derived from sugarcane e.g. sugar and ethanol.

In the frame of circular economy, Fiala et al. (2016) assessed the environmental performance of rice cultivation fertilised with urban sewage sludge in the Pavia district. They also evaluated different mitigation strategies: the substitution of urban sewage sludge with compost, the introduction of an additional aeration and the collection of straw. Among the three mitigation strategies evaluated the most effective involve the substitution of urban sewage sludge with compost and the implementation of an additional aeration period during the cultivation. The authors advise to develop country specific emission factors, instead of using standard emission factors for methane estimation as a way to improve assessment.

Muino et al. (2016) presented a promising approach for using olive waste extracts as natural antioxidants in meat products reducing food wastes at the point-of-sale and at consumer level, as a win-win solution between environmental concerns and economic aspects. This application reduced lipid and protein oxidation while maintaining an acceptable colour of the meat for a longer time period, representing a 3-day in the shelf-life extension compared to patties without the added the extract. Therefore, the patties would not only be better considered for overall preference as well as over longer periods of time, but deal with the current initiatives carried out by governments focused on reducing agricultural and food wastage. On the one hand, the potential of olive oil waste use decreases accumulation and encourages the olive oil industry to manage these wastes in an environment-friendly approach. On the other hand, increasing shelf-life of meat products leads to a reduction of food waste, providing economic benefits to the meat industry and diminishing the environmental impact that food waste has along the food supply chain.

Regarding the nutrient recovery, this is considered a priority action since the introduction of synthetic fertilizers has transformed our agricultural systems close to irreversible self-feeding process referred to as “food system lock-in”, which threatens planetary boundaries of nitrogen and phosphorus, hence the food security in the future. Through an evolutionary analysis, Kuokkanen et al. (2016) showed how three separate but interdependent processes in the production, in the policy and institutions, and in the supply chain create systematic resistance towards sustainability transition. The authors suggest that more attention should be paid at the public policies that are currently too narrow in focus when dealing with nutrient recovery.

Phosphorus is a limited non-renewable resource that is indispensable as an essential nutrient for the growth of organisms in most ecosystems. It is recognized as a critical raw material (listed by the European Commission, EC, 2014) affected in its global availability by the massive demand by agricultural systems. Chowdhury et al. (2016) reviewed recent literature on global extraction and use of phosphorus, and provide a synopsis of the challenges in developing more sustainable management systems for phosphorus. The study of Li et al. (2016) demonstrated the reuse of phosphorus resources from sewage sludge ash (SSA), testing its recovery from a pilot circulating fluidized bed kiln.

Faria et al. (2016) illustrated an example of biological system designed to add value to useless organic sub-products while generating off-grid electricity. This is possible thank to the capacity of some microorganisms to transfer electrons generated during organic carbon oxidation directly to an anode in a so-called microbial fuel cell (MFC), which might be an asset in a sustainable management context, e.g. in a dairy industry. The MFC technology is a valuable option for simultaneous wastewater treatment and energy recovery and deserves to be tested and scaled-up in the dairy industry.

Another important issue to be considered for the resource efficiency of a system is the competition among different land uses. Ertem et al. (2016) compared the co-digestion of chicken manure with macroalgae and with crops, demonstrating that macroalgae have lower environmental impacts compared to crops and that a production of energy relying on macroalgae could be sustainable, if it is regionally accessible. In fact, when the aim is producing higher amounts of energy, substituting energy crops with macroalgal biomass is liable, because it helps solving the dilemma between bioenergy and food production. However, when the amount of feedstock to be transported and fed into the digesters are the concern, it would be beneficial to analyze the whole system based on the FU of 1 kg feedstock: In this case, the energy crops could be more favorable to mitigate the negative environmental effects of biogas plants.

It is evident that all these ecoinnovations benefit from being assessed in an integrated manner to avoid burden shifting between categories of impacts and steps along the supply chain. Again the role of LCA for supporting an integrated environmental assessment is crucial.

5. LCA supporting consumers and stakeholders' choices

Public and private consumers are key actors for food sustainability. Informing them transparently on the performance of a product along the supply chain is still a major challenge. Goossens et al. (2016) argued that current systems fail at enabling consumers to make adequate decisions, based on a consumer survey on the sustainability of fruits and vegetables. A potential intention–performance gap is found for producers, and in the wider sense, for the entire supply chain. Since current labels found on fresh produce are input or practice based labels, farmers adhering to those labels can be considered as having the intention to produce sustainably. However, this intention alone cannot guarantee good environmental performance. In order to close the potential intention–performance gap for the supply chain and provide more adequate information to consumers, they concluded that performance-based labels, covering the entire food chain of fresh produce, using LCA and including situational parameters such as time of consumption, origin and production and distribution mode, are indispensable.

García-Muros et al. (2016) showed that carbon-based food taxes may reduce emissions and, at the same time, help to change consumption patterns towards healthier diets. Mitigation policies have focused mainly on the energy and transport sectors, but recent studies suggest that food related measures can also deliver cost-effective emission reductions. They estimated specific elasticities for the food demand system based on a dataset of around 20,000 households, using a demand system model. The results showed that this policy can reduce emissions and, at the same time, help to change consumption patterns towards healthier diets. For the first time in the related literature, this paper also explores the distributional implications. The results show that carbon-based food taxation tends to have more effect on specific social groups.

Under the light of recent surveys, Olson (2016) examined the

Table 1
Overview of the main open issues and recommendations emerging from the studies presented in this special volume.

System boundaries	Many LCA studies in literature focus on the agricultural phase only and few impact categories (Pernollet et al., 2016; Baldini et al., 2016). Assessing the entire supply chain and expanding the number of impact categories adopted may help a more comprehensive identification of hotspots and trade-offs.
Functional unit	There is a need for consensus on more meaningful FUs for food products, e.g. developing functional units covering the nutritional function of food. Moreover, a sensitivity analysis of the results using different FUs may offer useful insights, e.g. comparing FU's based on output mass, land use, price-based, nutritional value (Salou et al., 2016; Notarnicola et al., 2016b; Sonesson et al., 2016).
Variability of agricultural systems	Variability is affecting the assessment at the inventory, impact assessment, and interpretation phases as food systems are inherently more variable both in the inventory data and in the possible impacts (e.g. the impact on biodiversity due to a particular land use may change dramatically from one ecoregion to another). This requires building as much as possible dataset representative of local conditions (Lovarelli et al., 2016), moving towards dynamic LCA (e.g. temporally explicit information as in Maier et al., 2016), accounting for spatial variability (Wiedemann et al., 2016). Specific guidelines for agricultural inventories are needed, including improving the quality of the data available in LCA databases and their geographical representativeness. Assessing separately local and global environmental performance of farm is crucial (e.g. in Repar et al., 2016), as in many case studies the agricultural phase is the one driving the overall impacts. Moreover, testing different scenarios is crucial, including future scenarios e.g. due to different climate conditions (Dijkman et al., 2016).
Life cycle impact assessment	Several impact categories - which have a high relevance for agri-food supply chain – still need better modelling. For example, available soil quality models widely applicable still lack a good modelling of land management aspects (Vidal Legaz et al., 2016), land us impact on biodiversity may require sophisticated approaches to modelling (Rugani and Rocchini, 2016), eutrophication models need a better exposure and effect assessment (Cosme and Niero, 2016), different water models highlight different drivers of impacts, suggesting the need of systematic sensitivity analysis (Murphy et al., 2016). Besides, there are still impacts not modelled in LCA despite being potentially critical to food production, such as those on pollinators (Crenna et al., 2016). Moreover, there is also the lack of methods to quantify potential environmental benefits associated to certain practice (e.g. improvements in soil and biodiversity due to organic practices, as discussed in Tasca et al., 2016). Overall, there is the need to find a balance between quantities and qualities as well as exploring possibilities for implementation of semi-quantitative models in LCA.
Interpretation	Clear guidelines for interpretation of results are needed (Castellani et al., 2016), including additional guidance by life cycle impact method developers in clarifying what their models is actually assessing and which are possible limits and uncertainties in the assessment. Use of meta-analysis is also suggested to understating major source of impacts (Clune et al., 2016). As well as sensitivity analysis (Kwofie and Ngadi, 2016; Fantin et al., 2016).
Hotspots commonly identified	Several studies are pointing at the agricultural stage as the one that impact the most in the agri-food supply chain (Notarnicola et al., 2016c, Rosa et al., 2016). Moreover, when animal feeding is involved, usually the feed appears as one of the main driver of impact (Bava et al., 2016; Notarnicola et al., 2016c; Murphy et al., 2016; Chobtang et al., 2016; Wiedemann et al., 2016). This highlight the importance of testing the role of food waste as feed (Salemdeeb et al., 2016; Palmieri et al., 2016; Salomone et al., 2016).
Agriculture intensification	The simple rationale that more output per hectare is sufficient to ensure increasing eco-efficiency is questioned (Figueiredo et al. (2016) for sunflowers; Longo et al. (2016) for apples; Chobtang et al., 2016 for diary production). In fact, notwithstanding that increased efficiency of land use seems a logical way forward, in face of the increasing pressure on agricultural land for other purposes as bioenergy, and pressure from urbanisation and desertification, current LCA methodology is incomplete and does not comprehensively assess some aspects that are critical for long-term sustainable food production.
Food waste	There is a growing interest on food waste (Chen et al., 2016), both to reduce overall food supply chain impacts as well as for nutrient and energy recovery. A proper and harmonised way to model food waste in LCA is needed Corrado et al., 2016. Not generating food waste at all seems to be the best option (Willersinn et al., 2016), including use of biomass residues through the entire supply chain (Silalertruksa et al., 2016). However, when the food waste is produced, there are several options for closing the loop, e.g. recycling food waste as feed Salemdeeb et al. (2016), biodiesel or compost (Salomone et al., 2016) and fertilisers (Fiala et al., 2016), promoting industrial symbiosis options (Muino et al., 2016). Regarding nutrient recovery, Kuokkanen et al. (2016) stressed that more attention should be paid at the public policies that are currently too narrow in focus when dealing with this topic. A specific focus is given to phosphorous (Chowdhury et al., 2016; Li et al., 2016), to which specific intervention should be addressed.
New technologies linking food and energy	As for other production sectors, new technologies applied to agri-food production may play an important role for reducing environmental burden e.g. promoting energy efficiency (Zhang et al., 2016) or the use of renewable energy derived from the production processes (Sharma et al., 2016). Faria et al. (2016) illustrated an example of biological system designed to add value to useless organic sub-products while generating off-grid electricity. Ertem et al. (2016) compared the co-digestion of chicken manure with macroalgae and with crops, demonstrating that macroalgae have lower environmental impacts compared to crops. In all this cases, LCA is crucial to avoid burden shifting, namely ensuring that the reduction of impacts in one life cycle stage or in one impact category is not achieved at the expenses of other life cycle stages or impacts.
Complementarity with other approaches and method	Current LCA modelling approaches should be complemented by other approaches in order to improve the understanding of what is happening in-field (and potentially subject to specific comparisons, e.g. organic versus non-organic agriculture), and what is off-field (aka background systems) and which is affected by the reliability of secondary datasets. Example of case studies coupling LCA with ecological footprint (Bartocci et al., 2016; Musikavong and Gheewala, 2016), exergy analysis (Soufiyan et al., 2016) etc, demonstrate the added value of complementing the LCA assessment with other approaches.
System optimisation	Win-win options should be identified in order to maximise output while reducing overall environmental burdens. This require the identification of feasible options (e.g. Salem Ali et al., 2016; Bava et al., 2016; Rosa et al., 2016), also adopting optimisation models and methods such as multi-objective optimisation tools (Mousavi-Avval et al., 2016; Galán-Martín et al., 2016). Socio-economic concerns should be also part of the evaluation both at production (Antonini and Argilés-Bosch, 2016; Dias et al., 2016; Arcese et al., 2016) and at the consumption stage (e.g. optimisation of public food procurement, Caputo et al., 2016).
Consumer choice and behaviour	A better understanding of consumer choice and behaviour lead to consideration of the main different aspects that influence the choice of a product, the potential for dietary shifts towards less impacting diets, changes in the perceived environmental quality associated with different products, the way in which products are consumed and, even, the amount of wastage associated with food systems. Surveys may support an identification of consumer behaviours and information needs (Goossens et al. (2016) Olson 2016). To support a transition toward more sustainable behaviours, the use of taxation is a possible option (García-Muros et al., 2016) notwithstanding possible distributional implications.

persistence of organic food health beliefs of a group of 710 people exposed to a Stanford University meta-analysis concluding that organically produced foods do not offer significant nutritional advantages versus conventionally produced food. The analysis of the online survey showed that for the ‘pro-organic’ the benefit of organic food is often linked with food produced by small/local farms and efforts to increase the yield of organic food production might be viewed negatively.

Public procurement may also benefit from LCA-based information, e.g. to be used for supporting green public procurement. Caputo et al. (2016) proposes a new method and a tool for the optimisation of public food procurement for institutional catering in the school sector. Their research took into account different crop managements (i.e. organic agriculture and adoption of local products) and different dietary choices able to guaranty the same nutritional contents. The non-renewable energy consumed for the production of foods managed by the institutional catering system is proposed as indicator to compare different policies together with other indicators as productive land and productive cost. A case of study is presented to test the overall method. The outcomes of the work could support a reorientation of both the production and consumption systems. In general, the shift towards local and organic products implies a reduction of the impacts evaluated. Further, the important impacts of beef consumption, in particular in terms of energy and land consumption are demonstrated.

Beyond environmental performance, stakeholders are more and more interested in social performance of food products. Arcese et al. (2016) performed a Social LCA analysis for providing a theoretical basis for practical applications in wine sector in Italy that could be generalized as a starting point for Social LCA application in other agri-food sectors. They modelled a conceptual framework defining the stakeholders' categories, the related impact categories and indicators. The main conclusions were the lack of subcategories to assess impacts related to aspects that are at a higher level in the hierarchy of needs, and that systems analysed with SLCA should include not only the material flow but also the service flow, which are interdependent.

6. Conclusions

As food production systems and consumption patterns are among the leading drivers of impacts on the environment, over time the applications of life cycle thinking and assessment to food-related supply chains have flourished. Life cycle assessment has been applied extensively to assessment of agricultural systems, and processing and manufacturing activities, and for comparing alternatives “from field to fork” and up to food waste management. However, despite the increasing number of LCA food studies and a flourishing literature on both methodological aspects and case studies, several challenges still need to be addressed in order to ensure that LCA is delivering robust results.

The aims of this special volume - and the conference underpinning it - were quite ambitious: i) identify hotspots, in terms of impacts, along food supply chain with a focus on major global challenges; ii) compare options related to food supply chain optimisation (increase of productivity, reduction of food losses, etc.) aiming at sustainable solutions; and iii) assess future scenarios linked both to technological improvement and behavioural changes under different environmental conditions.

This special volume shows that significant steps forward in the field of Food LCA have been made. The increasing number of case studies on food LCA have contributed to better knowledge of the method and, therefore, to better define research needs. In addition, the 57 papers included are a clear representation of the major challenges that the LCA community is facing when apply LCA to the agri-food sector: i) need of a clear definition of functional units; ii) problems in inventories mainly because lack of data or extreme variability; iii) need of improving the LCIA models for better characterising impacts; iv) improving the interpretation of the results and the contextualisation of the results accounting for other scientific domains and disciplines; v) improving the modelling framework for supporting policies related to resource efficiency, resource recovery, food waste, circular economy; vi) need of accounting for consumer choice and behaviours when assessing potential impacts. An overview of main recommendations and elements emerging from the papers in the volume is provided in Table 1.

There is a long way to go to enable food systems to be more sustainable. Ensuring a transition towards more sustainable production and consumption patterns requires a holistic approach and life cycle thinking is increasingly seen as a key concept for supporting this aim. Beyond specific methodological improvements to better tailor LCA studies to food systems, there is a clear need for the LCA community to “think outside the box”, exploring complementarity with other methods and domains.

We hope that the concepts and the case studies presented at the conference and in this special volume will further support cross fertilization among difference science domains (such as technological, environmental, social and economic ones) in pursuit of a sustainable “today and tomorrow” in feeding the planet.

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