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Abstract

Although many aspects of environmental accounting methodologies in food production have already been investigated, the application of environmental indicators in the fruit sector is still rare and no consensus can be found on the preferred method. On the contrary, widely diverging approaches have been taken to several aspects of the analyses, such as data collection, handling of scaling issues, and goal and scope definition. This paper reviews studies assessing the sustainability or environmental impacts of fruit production under different conditions and identifies aspects of fruit production that are of environmental importance. Four environmental assessment methods which may be applied to assess fruit production systems are evaluated, namely Life Cycle Assessment, Ecological Footprint Analysis, Emergy Analysis and Energy Balance. In the 22 peer-reviewed journal articles and two conference articles applying one of these methods in the fruit sector that were included in this review, a total of 26 applications of environmental impact assessment methods are described. These applications differ concerning e.g. overall objective, set of environmental issues considered, definition of system boundaries and calculation algorithms. Due to the relatively high variability in study cases and approaches, it was not possible to identify any one method as being better than the others. However, remarks on methodologies and suggestions for standardisation are given and the environmental burdens of fruit systems are highlighted.

Keywords:

Life Cycle Assessment, Ecological Footprint Analysis, Emergy Analysis, Orchard management, Sustainability

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1. Introduction

The goal for industrial fruit production is simply to obtain the highest quantity of fruit of the best possible quality. During the last decades of the 20th century, perceptions of the relationships between agriculture and the environment changed markedly and the demand for more environmentally friendly food production is steadily increasing. Following the publication of the Brundtland report (WCED, 1987), numerous studies on agricultural production systems have been carried out within the framework of sustainable development. Those studies apply a number of sustainability assessment methods in order to evaluate the environmental performance of farms or distribution companies. Although many aspects of the environmental accounting methodologies used in food production have already been investigated, the application of environmental indicators in the fruit sector is still rare (Gaillard and Nemecek, 2009) and no consensus can be found on which indicator to use. On the contrary, widely diverging approaches have been adopted to several aspects of the analyses, such as data collection, handling of scaling issues and the overall objective (Dantsis et al., 2010).

In this study, we focus on sustainability in the fruit production sector through: (i) reviewing studies assessing the sustainability or environmental impacts of fruit production under different conditions and (ii) identifying aspects of fruit production that are of environmental importance according to the studies reviewed.

1.1 Fruit production and sustainability

The most widely accepted definition of sustainable agriculture can be summarised as follows: ‘To be sustainable, a farm must produce adequate yields of high quality, be profitable, protect the environment, conserve resources and be socially responsible in the long term' (Reganold et al., 2001). Some authors argue that agricultural ecosystems are only sustainable in the long term if the outputs of all components removed from the system balance the inputs (Lal, 2008).

This view of sustainable agriculture, although accepted by most scientists and field technicians, is vague in terms of practical ways of achieving sustainability (Lichtfouse et al., 2009). In fruit production there are different agricultural protocols ranging from those seeking to optimise profitability (conventional production) to those abiding by certain rules relating to sustainability (organic production), with intermediate systems (integrated production). Several studies have evaluated these three production protocols from an environmental point of view (e.g. Sanjuán et al., 2003; Kaltas et al., 2007; La Rosa et al., 2008; de Barros et al., 2009). The results do not consistently identify one production system as being the best, as this depends e.g. on the assessment methods and environmental indicators used, but organic production is generally considered the most environmental friendly option (Granatstein and Kupferman, 2006) and integrated production the option with the best resource use efficiency per unit product (e.g. Reganold et al., 2001).

In general, fruit production is considered to be a sector with low environmental impacts in comparison to herbaceous crops (Granatstein and Kupferman, 2006) and other food sectors (Carlsson-Kanyama et al., 2003; Garnett, 2006; Cuadra and Bjorklund, 2007; Frey and Barrett, 2007). Some authors underline that fruit production requires less bioproductive land compared with animal and some horticultural products (Gerbens-Leenes et al., 2002). Others argue that perennial habitats can (potentially) host natural pest predators and therefore benefit food webs (Simon et al., 2009).

Traditionally, environmental burdens in orchards have been studied in terms of consumption of resources, (e.g. water, soil, air, energy and other) or impacts (e.g. pollution, human and ecosystem health risks, decreasing biodiversity and others) (Reganold et al., 2001). Some recent studies have attempted to assess the total environmental burden of specific fruit production systems through their entire life cycle by applying life cycle assessments (Mila i Canals and Polo, 2003; Mouron et al, 2006), ecological footprint analysis (Cerutti et al., 2010) and other assessment methods.

1.2 Environmental assessment methods investigated

Many studies claim that indicators which consider many aspects of the environmental impacts at the same time are more useful to address the complexity of agricultural systems (Bastianoni et al., 2007). Thus, one of the most important features of an indicator is its ability to summarise, focus and condense extensive datasets (obtained from complex environmental parameters) to a manageable amount of meaningful information (Godfrey and Todd, 2001).

In this review, four environmental assessment methods which may be applied to assess fruit production systems are evaluated. In particular, the assessment methods considered are:

- Life Cycle Assessment (LCA); defined by ISO standard (ISO14040:2006) as the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. The origin of LCA can be found in the late 1960s within an American industrial context (Hunt and Franklin, 1996) and numerous studies have been carried out in order to adapt this method to the agricultural sector (Audsley et al., 1997). Nowadays, LCA is considered a useful tool in order to compare alternative food products, processes or services, and as background for environmental product declaration (Schau and Fet, 2008). The results of an LCA are commonly presented as impacts in a range of different impact categories such as global warming, acidification, nitrification, ozone depletion, toxicity, etc. (Pennington et al., 2004). However, as an optional step of the analysis these categories can be weighted against each other to produce an indicator of the total impact of a given amount of product.
- Ecological Footprint Analysis (EFA); introduced by Rees (1992) and further developed by Wackernagel and Rees (1996). This method leads to an aggregated indicator which quantifies the total area of the terrestrial and aquatic ecosystems necessary to supply all resources utilised and to absorb all resultant emissions involved in the production of particular products. The indicator is

considered an ecosystem-based index (Singh et al., 2009) because it is a composite index of different ecological parameters. As EFA results are both scientifically robust and easy to understand by non-experts, the method is a useful pedagogic instrument to make our dependence on ecosystems visible (Cuadra and Bjorklund, 2007).

- Emergy Analysis (EM); the emergy concept was formalised by Odum (1988) and it represents all the work which has to be carried out by the environment and human labour to sustain a certain system and produce a given unit of product. This method is also called emergy accounting and it uses the thermodynamic basis of all forms of energy and materials, converting them into equivalents of one form of energy, usually sunlight (Odum, 1996). The result of this analysis shows how much a certain activity drains a system of energy (Cuadra and Bjorklund, 2007) and indicates the sustainability of a production system in a thermodynamic framework. Thus EM is considered one of the most appropriate approaches for analysing the systems that are at the interface between natural and human systems (e.g. Bastianoni et al., 2001).
- Energy Balance (EB); produces an indicator from an energy input-output analysis of a system and results in a measure of the energy efficiency of the system. The main principle of this method is that efficient use of energy is one of the main requirements of sustainable agriculture (e.g. Strapatsa et al., 2006; Guzman and Alonso, 2008). The EB is commonly used to indicate ways to decrease energy inputs and increase energy efficiency without impairing the economics of crop production (Kaltas et al., 2007). Thus energy efficiency is frequently used in combination with other environmental or economic indicators in order to obtain the best management strategies.

2. Case studies using environmental assessment methods on orchards

The choice of environmental impact assessment method to use in a study case is strongly influenced by the background of the authors (Bockstaller et al., 2008). For example, authors specialised in the assessment of biodiversity use abundance of species for a given taxon as an indicator of ecosystem health (e.g. Cotes et al., 2009). Authors with an agronomic background prefer to apply resource use indicators or input/output models, while authors with an engineering background prefer to use energy balances, aggregate indicators of emissions or LCAs. The use of multiple perspectives is very important in the evaluation of sustainability because of the multidisciplinary nature of such issues, but at the same time it introduces variation into the assessments and produces results that may appear discordant.

At present, most of the work carried out on environmental impact assessments in orchards is based on LCAs and various types of EBs. Recently EFA has also been applied, with some interesting results. This review examined 22 peer-reviewed journal articles and two conference articles applying one of these methods in the fruit sector. We preferentially included studies that considered the part of the life cycle until the fruit was produced. Studies that considered the whole production of derivates (e.g. fruit juice production) were only included if they added to the analysis in the plantation stage (e.g. Yusoff and Hansen, 2007). We also decided to include studies that considered fruit production as part of the whole farm, if the orchard system was sufficiently well described to allow us to collect the data needed for our evaluation (e.g. Cuadra and Bjorklund, 2007).

The papers reviewed included a total of 26 applications of environmental impact assessment methods; 9 EBs, 9 LCAs, 5 EMs and 3 EFAs.

2.1 Objectives of case studies

In the studies included, the application of an environmental assessment method had one of four research objectives:

1. Development of methodology. The objective of these studies is to develop methodology and create a common analytical base which can be used to assess the environmental impact of fruit production. These studies are usually more important in terms of methods and protocols than direct results.

2. Environmental profiling. These studies aim at assessing the environmental profile of a study crop in a specific region by examining a number of orchards (or farms) that are representative of the

region. The main result is quantification of the ecological burden for the study crop and – often – an analysis of aspects of the production system which can be improved in order to improve environmental performance.

3. Comparison of agronomic protocols. The objective of these studies is to evaluate the environmental performance of different agricultural practices in the fruit sector. The studies mainly compare conventional, integrated and organic fruit production. This comparison is often made on experimental orchards or representative farms.

4. Domestic versus imported fruit. The objective of these studies is to compare fruit produced locally with fruit produced elsewhere and transported to the site of consumption. These studies discriminate between the impacts generated in the production phase and in the distribution and commercialisation phase, i.e. transportation and packaging.

A summary of the studies falling into each of these categories is given in Table 1.

2.2 Systems studied and system delimitation

All papers reviewed are case studies where environmental impact assessment methods are applied to specific fruit production systems. They describe the investigated systems thoroughly but only a few of them attempt to cover the complete life cycle of fruit production. Rather, two different perspectives are taken, cradle-to-gate and cradle-to-market. In the first category, the environmental impacts are quantified for the production phase including all upstream impacts until the farm gate (12 papers) or at the end of the industrial processing transformation process for products derived from fruit (3 papers). The cradle-to-market category includes studies in which the distribution and commercialisation phase is included in the assessment. The distribution and commercialisation phase mainly comprises packaging for fresh consumption and transportation to local (6 papers) or international markets (3 papers). None of the studies reviewed here considered the consumption and the waste handling stages, as commonly considered in food production environmental assessments (Roy et al., 2009). However, quantification of product loss in the consumption phase would be needed in order to evaluate the environmental impact of the product actually consumed (Schau and Fet, 2008). The nursery where orchard seedlings are produced should be considered an upstream process delivering grafted plants to the orchards and the impact during this stage should be included in assessments of fruit production systems. However, this has only been done in two studies (Yusoff and Hansen, 2007; Cerutti et al., 2010), and in both cases general data instead of case-specific data are used. Although many authors stress that it is important to consider the nursery in environmental impact assessments (Mila i Canals and Polo, 2003; Cerutti et al., 2010), the lack of data makes this difficult.

Establishment and destruction of orchards are rarely considered in assessment of fruit production, mainly for two reasons: Some crops (e.g. bananas) have a biological life cycle in which replanting techniques are applied instead of installation/destruction procedures (de Barros et al., 2009); and it is very difficult to collect statistically representative field data on orchard destruction. Impacts arising from installation or replanting are considered in five of the studies reviewed here, but the influence of this stage on the final results is not shown explicitly.

Another important aspect that has to be considered when the assessment is done on the entire life cycle of the orchard and not just on a productive year is the yield in relation to the age of the plantation (Cerutti et al., 2010). Most of the temperate fruit cultures reach maturity in 2-4 years after installation of the orchard. Before that age, the yield may be significantly lower (or even zero) because the plants are still too young. This may significantly affect the average yield, and has to be considered.

The impacts from the production of capital goods (e.g. machinery) are considered in 10 papers (four of which are LCAs) on the basis of the machine time used as a proportion of the predicted useful lifetime. This approach, although not common in environmental assessments in the food sector (Schau and Fet, 2008), can be important when comparing different crops (Cuandra and Bjorklund, 2007) or the environmental performance of different farms (Mouron et al., 2006).

2.3 Data collection

An interesting observation can be made looking at the studies reviewed here. Most studies (18) are based on data collected from commercial orchards, either directly in field surveys or with questionnaires or interviews with farmers. Sometime these approaches are mixed and the data collection method used for the different data in the study is not always clearly described. Four studies investigate commercial orchards and then compare the field dataset obtained with reference values. This approach allows conclusions about specific orchards to be drawn, while the validation allows identification of unusual agricultural practices only of interest for the specific farm (Mila i Canals et al., 2006; Cuadra and Bjorklund, 2007). The other method used to obtain statistically robust datasets is to consider a larger number of commercial orchards and look at average values for these farms. The largest number of farms considered was in the study by Guzmán and Alonso (2008) with 241 commercial olive orchards, followed by the study by Kizilaslan (2009) which considers 87 cherry orchards.

Five studies used literature and available databases in order to obtain data instead of surveying commercial orchards.

2.4 Functional unit

The functional unit is a concept used in LCA to allow for comparison of alternative products and services (ISO 14040, 1997). The functional unit is a quantitative description of the service provided by the production system. For fruit products, typical functional units are 1 kg of fruit packed and delivered to the customer or 1 ton of fruit at the farm gate. Although the functional unit is derived from LCA methodology, other environmental impact assessment methods apply similar concepts in order to make the comparisons valid. Thus, it is interesting to discuss the functional unit used in studies of orchards.

In most cases, the definition of a functional unit is considered straightforward, using a functional unit such as 1 kg of product. However, the choice of functional unit has profound effects on the results and, as agricultural system are naturally multi-functional systems, the definition of functional unit is not always straightforward (Mila i Canals and Polo, 2003).

The functional units used in the papers reviewed here can be divided into four main categories, depending on whether they are based on: (i) mass of product, (ii) land area, (iii) energy use, or (iv) economic value. The distribution of these categories in the papers studied is depicted in Figure 1.

(i) Mass-based. In mass-based functional units, the environmental impacts are related to a specific amount of products produced. In total, there are 16 applications of this type of functional unit in the papers reviewed here. The mass-based functional unit is the most widespread type of functional unit used in the LCA papers studied (8 applications). The EFAs (2 applications) use a mass-based functional unit by assessing global hectares used per ton of fruit, while energy analyses (6 applications in total) use a mass-based functional unit by evaluating the amount of energy used per mass unit of product, commonly MJ/kg and GJ/ton.

When using a mass-based functional unit, problems may arise in how to account for fruit quality (Mila i Canals and Polo, 2003). The same orchard can usually produce fruit of different quality (e.g. size, colour, firmness or sugar content) that is targeted to different markets (e.g. fresh market or industrial processing). This issue should be considered in the definition of the functional unit and an allocation procedure allocating the environmental impacts to the different products which is consistent with the goal of the study should be devised (Mila i Canals and Polo, 2003).

The mass-based functional unit is easy to comprehend and widely used, but carries the problem of evaluating efficiency within sustainability research. By simply looking at environmental impacts per unit product, it is possible to evaluate the eco-efficiency of production, but it is not possible to estimate the sustainability of such production because efficiency does not necessarily lead to sustainability (e.g. Wackernagel and Rees, 1997). In their paper, Wackernagel and Rees (1997) underline that only using mass-based functional units may well lead to a preference for high input-high output systems, which, when concentrated at regional scale, have been shown to cause major pollution problems (van der Werf et al., 2007).

(ii) Land-based. In these cases, the environmental impacts are related to a specific amount of land. In total there are 13 applications of this type of functional unit in the papers reviewed here. This category is mainly represented in energy analyses (both EMs and EBs, comprising 9 applications in total), in which the assessment is based on energy per hectare (mostly MJ/ha or GJ/ha). This category is not commonly used in LCA and EFA, partly because land use is not directly a service and does not provide a productive function, but it can give interesting results. LCA papers (2 applications) investigated impacts per unit land in order to compare production with similar yield. EFA papers (2 applications) assessed global hectares per cultivated hectares, as a secondary result after the conventional EFA. Values of ecological footprint per hectare of crop allow visualisation of the difference between the area occupied by the orchard and the total area used considering all upstream processes (Niccolucci et al., 2008) expressed in global hectares (gha). In general, converting resource consumption or environmental impacts to units of land use allows evaluation of the impacts of cultivating a certain area. This parameter is also called the impact intensity of a farm (Mouron et al., 2006).

The land-based functional unit in fruit production is complementary to the mass-based functional unit because they give different results and both should be used. Indeed, when considering just impacts per unit area, low input-low output systems will have better ranking for decreased impacts at regional level, but may create a need for additional land use elsewhere, giving rise to additional impacts (van der Werf et al., 2007).

(iii) Energy-based. This type of functional unit considers the amount of chemical energy bound in the final product. EBs (2 applications) consider energy-based flows when accounting for energy productivity (Mohammadi et al., 2010). This is done by using the amount of energy bound in the fruits per unit energy consumed during production as an ecological indicator. Using an energy-based functional unit in EFA of fruit production is uncommon, but it can highlight interesting results. Cuadra and Bjorklund (2007) mixed EM and EFA in an evaluation of environmental burdens related to the production of a calorific unit in fruits, and thus their unit is gha/Gcal. This reference flow can be useful to compare the impact of different kinds of agricultural products on a common base.

(iv) Economic value-based. In this case the functional unit is related to the economic value of the products produced. This functional unit is useful when the economic eco-efficiency of the systems is to be optimised (Mouron et al., 2006). The economic value-based functional unit is applied in LCA (1 application), in EFA considering global hectares per unit of income (1 application) and in EB considering energy applied per unit income (1 application).

Economic value-based functional units can be very useful for comparison of different fruit production and commercialisation systems on a common base, and can also be used to resolve quality issues. However, the results can be strongly localised to the economic context where the farms are located.

2.5 Impact assessment categories

Using different environmental impact assessment methods may lead to different conclusions. In LCA, environmental impacts are assessed in different impact categories and defining these categories is a fundamental part of the assessment. Typical impact categories can be eutrophication, global warming, acidification, toxicity, etc. When defining the impact categories for fruit production, it is very important to consider the typical environmental problems that may arise in orchards (Mila i Canals and Polo, 2003). Fruit is usually produced in sunny regions because sun increases yield and improves fruit quality. However, these regions are also prone to water scarcity and resulting losses of nutrients and pesticides to the surrounding environment. These effects can influence all impact categories, but particularly nutrient enrichment potential and acidification potential (Coltro and Mourad, 2009).

Another typical environmental concern in fruit production is related to the permanency of the plantation. Permanent habitats such as orchards tend to increase the diversification and stabilisation of their arthropod community, including beneficial and harmful species (e.g. Simon et al., 2009). As a consequence pesticide input may be very high, which may be associated with many environmental impacts but in particular human toxicity and ecotoxicity (Mila i Canals et al., 2006; Yusoff and Hansen, 2007).

As in a number of other agricultural systems, another important impact category that should be considered is global warming potential. This category is strongly connected to fuel consumption and energy use, and may thus be important in studies involving comparison of systems with different transport distances (e.g. Blanke and Burdick, 2005).

3. Environmental burdens in orchards

In order to evaluate the environmental burdens of fruit systems it is necessary to identify the processes involved, the resources being used and the resulting emissions. From the papers studied here, it is possible to identify the field operations generally resulting in the greatest environmental impacts in fruit production systems. The field operations associated with the greatest impacts can be grouped into six major groups: pest management, irrigation, fertilisation, soil management, weather damage prevention and tree management. All of these operations have to be investigated carefully in order to apply any of the environmental impact assessment methods.

3.1 Pest management

Pest and disease management involves a number of operations aimed at mitigating fruit damage caused by pests. The main goal of these operations is to keep as high a proportion of fruits suitable for the market as possible. Pest management can vary greatly according to the production protocol used. In conventional farming, the main approach to pest management is spraying with pesticides to eradicate the harmful organisms. At present, it is well known that synthetic pesticides have several limitations and can have serious harmful effects on the environment and on human health (Holb, 2009). Furthermore, the complete eradication of orchard pests is considered impossible without seriously compromising the environment, due to increasing pest resistance (Suckling et al., 1999). In integrated and organic farming, different strategies are applied and the approach is to consider pests as natural organisms with their own life cycle and natural enemies. By intervening in specific periods of the life cycle (e.g. disrupting mating) or supporting natural pest enemies, it is possible to achieve improvements in fruit quality with less resource consumption (e.g. Suckling et al., 1999; Reganold et al., 2001; Mila i Canals et al., 2006). However, most of the non-chemical control measures are not widely used due to their high labour costs and/or time limits during the season. (e.g. Suckling et al., 1999; Holb, 2009).

Orchards are among the most intensively sprayed agricultural systems, in order to avoid visible fruit damage and to satisfy international commercial quality standards (Simon et al., 2010). Furthermore, pests and diseases that are host-tree permanent may remain in the orchard for many years and require continuous control. The main environmental risks relating to the use of conventional pesticides are the negative effects on the animal and plant communities exposed, both in the orchard and in the other terrestrial and aquatic ecosystems to which pesticides are lost (Gliessman, 2006). Another important environmental aspect associated with pesticide use that has to be considered is the resource consumption and environmental impacts associated with the production and distribution of synthetic pesticides. Mila i Canals et al. (2006) found that pesticide use represents up to 11-18% of total energy consumption in integrated apple production in New Zealand. Pesticide spraying consumes different amounts of energy and results in widely differing pesticide emissions depending on the spraying system, concentration of active ingredient and climate conditions, especially wind speed during spraying.

Because of the development of resistant strains of some pests, there is a tendency for increased frequency of treatments (Simon et al., 2010) and for increased application rates (around 500 litres per ha) in order to retain more pesticides on the leaves and fruit. Climate change is also likely to modify the life cycle of most arthropod pests, increasing the period of risk and introducing new pests (Simon et al., 2010)

As a general remark, it is of interest to note that pesticide use in the studies reviewed here is assessed in different ways: EFA, EB and EM consider the quantity of pesticides used, while LCA considers the quantity of pesticide that leaves the system boundaries and is thus considered to be emissions. These emissions are quite difficult to quantify and models of pesticide dispersion have to be used (e.g. the PestLCI model presented by Birkveda and Hauschild, 2006).

3.2 Fertilisation

In orchards, fertilisation is required in order to supply the nutrients needed by the trees. Fertilisers are the result of industrial synthesis processes or mining, or they can be by-products such as manures or plant residuals. The most important elements are nitrogen, phosphorus and potassium. Nitrogen (N) plays an important role in the vegetative development of the trees and thus on tree management strategies (Nesme et al., 2006). As a consequence, N fertilisers result in more pruning time and associated impacts. Deciduous fruit trees have low N demands compared with open field crops (Sanchez et al., 1995) and nutrient surpluses are often lost from orchards, especially during the winter and early spring when trees are not actively taking up N. Thus, both the amount and timing of fertiliser application are relevant in nutrient management (McDonald, 2007) and in environmental assessment of orchards (Page, 2009). Fertilisers are also a source of air pollution in terms of air emissions of ammonia and nitrous oxide, while phosphate and nitrate are the main emissions to groundwater and surface water. Traditionally, fertilisers were given to the plant through application directly on the soil, but nowadays several alternative techniques are used especially fertigation, in which fertilisers are mixed into the irrigation water, and foliar application, in which they are supplied directly to the tree canopy. Different agronomic techniques require machinery with different environmental impacts. When the irrigation system is used for the application of fertiliser, the only extra equipment needed is a tank in which fertilisers are mixed with water and fertigation can therefore often result in reduced environmental impacts (Mila i Canals and Polo, 2003).

The other main impact related to the use of fertilisers is the environmental cost of fertiliser production. Almost all the studies included in this review indicate that the production of fertilisers contributes significantly to the overall impacts of the system (e.g. Audsley et al., 1997). These impacts mainly derive from high energy consumption and use of non-renewable resources such as phosphate.

From a systematic point of view, the best way to fertilise is by using by-products from other production systems, in order to close the production cycles (e.g. Wei et al., 2009).

Although some authors point out that fertilising with manure is common practice in fruit production (Amiri and Fallahi, 2009; Wei et al., 2009), only a few studies can be found where the use of different manures is compared in fruit orchards. In general, these papers show that manures can improve soil characteristics and plant growth and yield, especially in poor soils, but manures are ineffective on nutrient-rich soils or in combination with fertigation and high irrigation.

3.3 Irrigation

Many studies demonstrate that water has a major influence on fruit growth and quality. If precipitation does not fulfil the demands of the culture, an irrigation system is needed to reach market standards of fruit quality. There is a wide range of different irrigation systems available, each associated with different environmental impacts (Mila i Canals and Polo, 2003) mostly because of differences in energy consumption. The energy consumption in irrigation systems is strongly related to the climate conditions in the area, the water source (surface water or groundwater), the water consumption of the culture and the irrigation type. In general, the higher the water requirement, the higher the energy consumption for irrigation.

As for fertilisation, the best environmental practices can be achieved with the reuse of wastewater from other systems. Recent studies have demonstrated the potential of applying treated municipal wastewater in orchards, where the risk of transmitting diseases is minimal (Palese et al., 2009). Further studies are needed to assess the application of such water in the production of fruits consumed without processing.

3.4 Soil management and weed control

Soil quality is considered a key factor for human wealth because the soil is linked with several aspects of socio-ecosystems, e.g. food production, water quality, energy demand and waste disposal (Lal, 2008). It is well known that inappropriate agricultural practices, such as over-fertilisation, excessive use of pesticides and irrigation, removal of crop residues and others, dramatically decrease soil quality (Lal, 2008). Therefore, soil management and the effects on soil quality are important aspects to be considered in evaluating the sustainability of fruit production systems.

The soil plays an important role in the orchard system as it is a major determinant of fruit quality (e.g. Glover et al., 2000; McDonald, 2007) and owing to the environmental impacts associated with fruit production (Mila i Canals and Polo, 2003). Nutrients, water and organic matter meet in the soil and careful management can improve fertiliser use efficiency and reduce the need for application of pesticides, thus affecting both commercial and environmental aspects of production.

The goals for good orchard floor management are to improve soil quality, control erosion and weeds and reduce surface runoff and leaching of pesticides and fertilisers (Glover et al., 2000). An important agricultural technique used to prevent soil erosion and maintain good soil structure for water infiltration is the use of cover crops (with either pure stands or stands where the legumes are mixed with other crops) under the fruit trees. The purpose of these cover crops is to improve soil fertility because of N fixation and recovery of nutrients from deep soil layers, enhance biological control of pests by providing a reservoir for pest predators, and modify the microclimate of the orchard (Gliessman, 2006).

Different orchard floor management techniques are associated with different environmental impacts related to the consumption of resources (principally fuel, land and water) and production of pesticides and fertilisers.

From an agricultural point of view, the debate about the use of chemical or mechanical weeding is still open (McDonald, 2007). The use of residual herbicides has been shown to be beneficial to tree growth and yield, but they leave the soil surface without a protective cover for much of the year, which can have a range of undesirable effects such as induction of soil compaction and reduction in water holding and infiltration capacity. On the other hand, mechanical weeding degrades the soil structure, decreases nutritional reserves and can harm tree growth by injuring shallow growing fine roots. Furthermore, mechanical weeding requires consumption of diesel, which can offset the environmental benefits of avoiding chemical products.

At present, the most environmentally friendly technique to control weeds is to utilise post-emergent foliar acting herbicides such as glyphosate, because they allow regrowth of weeds during the winter so the soil is not permanently bare (Merwin et al., 1995). The use of post-emergent herbicides allows the production of biomass that returns to the soil and helps build organic matter and biological activity in the soil. Although various studies have investigated the different effects of approaches to weed control in orchards, proper environmental assessments are still lacking.

Mulching is attracting increasing attention as an environmentally friendly method for weed control, but not very much is known about how organic mulches affect biological activity and nutrient availability in perennial cropping systems (Forge et al., 2003).

3.5 Tree management and harvest

Reaching equilibrium between growth and fruiting is one of the main objectives of the fruit grower. There are several different practices aimed at maximising efficiency of fruit load, increasing fruit size, guaranteeing homogeneous colour and preventing biennial bearing. These operations can be divided into three main categories: branch pruning, thinning and tree training. Collectively, these techniques are used for tree management.

Branch pruning is usually carried out by hand, using hand-operated pruners, loppers and saws, most often from ladders. Commonly used machine-operated equipment includes compressed air-powered pruners and motorised hydraulic ladders (hydra-ladders) when trees are tall. Thinning can be performed by hand, usually on hydra-ladders, or with chemical thinning agents, usually used only in conventional or integrated fruit production. Mila i Canals and Polo (2003) suggest that the fate of chemical thinners should be included in the pesticide emissions in an LCA, as they might be relevant from a toxicity point of view.

It is very important to consider carefully the tree management plan in environmental assessments of orchards. Although this phase may produce impacts related only to fossil fuel consumption (e.g. Mila i Canals et al., 2006), it influences several other aspects of the orchard system such as pest management efficiency, water and nutrient requirements and commercial yield (Lauri et al., 2009), all affecting the results of environmental assessments to a great extent.

In most cases fruit harvesting is carried out by hand with the use of mechanical ladders, but completely mechanical harvesting is possible for fruits that are going to be processed, such as olives and grapes. Thus, the environmental impacts of that stage are mainly related to the fossil fuel use and they can vary greatly from orchard to orchard depending on parameters such as cultivar, climatic conditions, orchard design, production system and tree management. For example, stone fruits and apples in the Mediterranean area may require up to five harvesting passages on the same block to optimise fruit maturity, colour and size.

Some authors (Granatstein and Kupferman, 2006) suggest that the most environmentally friendly harvest can be achieved with a manual orchard management regime, in which all agronomic procedures are aimed at restricting plant height in order to avoid use of machinery. They argue that such an orchard management regime is beneficial for three reasons: economic, because of faster returns, higher quality fruit and lower labour costs for maintenance; environmental, because of optimal pest management using integrated pest management methods; and social, because of less use of ladders leading to less worker injuries. Nevertheless, specific studies comparing manual and mechanical orchard management in environmental impact assessment are absent in the literature.

3.6 Weather damage prevention

Approaches to weather damage prevention in orchards may be very different in different parts of the world, but such damage prevention is almost always considered an important aspect of successful fruit production. Weather damage, although often related to short extreme weather events, can strongly reduce yield by destroying flowers, lowering the commercial quality of fruits or even harming trees. The most widely studied extreme weather events that can inflict damage on the crop are hail and frost. The first problem is mainly resolved by the use of hail protection nets, which are photo-neutral in order to reduce light interception. These protection nets are the result of advanced technology and may generate environmental impacts in all their life cycle stages. Frost damage may be avoided by several different techniques, the choice of which depends on the likely frequency of frost events, water availability and the economic importance of the plantation. Frost prevention generates environmental impacts mainly related to energy consumption. Mila i Canals et al. (2006) describe an apple orchard where one-third of total diesel consumption is due to prevention of frost damage. The reason is that extreme weather is treated as an emergency and high energy-consuming machinery is involved and has to be maintained even in low-risk periods.

4. Conclusions

This paper reviewed applications of environmental impact assessment methods to fruit production systems. Although there are not very many studies of environmental assessment methods in fruit production, a multitude of assessment methods have been applied to a large variety of orchards. Orchard systems, agricultural practices and commercial chains may vary greatly depending on climate conditions and social context. However, standardisation of research methods and protocols when applying environmental assessment methods in fruit production is needed, in particular regarding the way of modelling the orchard system and the settings for the different methods. Otherwise the results may be impossible to compare from system to system and risk remaining isolated to the study case. Being able to compare the results from different studies is important in identifying their sustainability.

Suggestions for standardisation of assessment methods include:

- The whole lifetime of the orchard should be considered using historical data or through orchard modelling. As a consequence, impacts from orchard installation should also be assessed.
- The nursery may be associated with environmental impacts and should be considered as the production system of a fundamental input (grafted plants) of the orchard. Thus, more studies on the nursery stage are required to improve knowledge in this area.
- More information on pesticide emissions is often necessary and could be obtained through measurements and through the use of an assessment tool (such as PestLCI).
- Impacts from fertilisation should be accounted for, both in terms of impacts during production and distribution of the total amount of fertiliser plus the effect the surplus nutrients, assessed through a nutrient balance.
- Solutions for choosing functional unit vary according to the study case. In ‘environmental profiling’ study cases, mass-based functional units allow the environmental impacts in the study region to be precisely described according to the mass produced in that area. In comparisons of agronomic systems, mass-based and land-based functional units should be used together in order to avoid overvaluation of resource use efficiency and delocalisation of environmental impacts. Otherwise, an economic value-based functional unit is suggested if the agronomic system under study produces different commercial fruit categories (e.g. conventional and organic). In ‘development of methodology’, as many different functional units as possible should be considered in order to cover the complexity of orchard systems. Furthermore, there are several other ways of

defining the functional unit that are used in other food sectors but almost never in fruit production systems, for example nutrient content, which is often related to quality. In order to make significant comparisons of different cultivation systems, the functional unit used should be just the edible part of the fruit instead of the full weight as these may be significantly different, for example comparing strawberries (95% edible) and pineapple (51% edible).

The methods applied in the studies reviewed here differ concerning the overall objective, the set of environmental issues considered, the definition of the system boundaries and the calculation algorithms. As a consequence, it is not possible to say whether one method is better than the others. We therefore recommend that environmental evaluation methods should be used with great caution, considering the most appropriate method given the specific study case.

Finally, looking at the literature on the sustainability of fruit production, it can be seen that orchard systems are among the production systems interacting most with natural systems. Orchards, more than other food production systems, can be seen as an interlink between the natural and the technical sphere. Thus complexity in such interactions and relationships should be considered when applying environmental assessment methods.

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Table and Figure descriptions

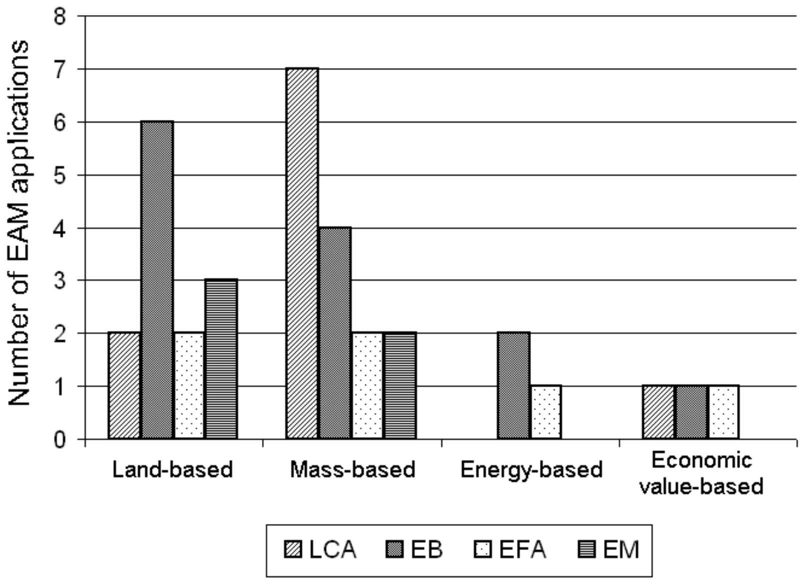

Figure 1. Distribution of the four functional unit categories (land-based, mass-based, energy-based and economic value-based) in each of the environmental assessment methods studied.

Table 1. List of all papers presenting applications of environmental indicators in orchards since August 2010 from ISI Journal and conferences. Indicators considered are: Life cycle assessment (LCA); Ecological footprint analysis (EFA); Emergy analysis (EM); Energy balance (EB). Country category considers the area of the study and not necessarily the origin of the research group. The dataset column shows the kind of dataset, with the number of farm or scenarios considered in brackets. In boundaries, different kinds of limitation of the system are considered; cradle to gate* refers to a cradle-to-gate scenario, but considers the final product at the gate (e.g. juice or oil); cradle to market (int) considers a cradle-to-market scenario with an international market. Other information about the orchards include: cg=capital goods, n=nursery, p=plantation of the orchard, d=destruction of the orchard

TABLE 1

	Reference	Product	Country	Indicator	Dataset	Reference flow	Boundaries
Methodological issues	Mouron et al., 2006	Apple	Swiss	LCA	Commercial orchards (12)	Land based (FU=ha); Receipt based (FU=$)	Cradle-to-gate (cg)
	Cerutti et al, 2010	Nectarine	Italy	EFA	Commercial orchards (1) + validation	Mass based (gha/t)	Cradle-to-gate (n,p,d,cg)
	Strapatsa et al., 2006	Apple	Greece	EB	Commercial orchards (26)	Land based (GJ/ha)	Cradle-to-gate (cg)
	Panzieri et al., 2001	Cherry	Italy	EM	Commercial orchards (3)	Land based (seJ/ha)	Cradle-to-gate (cg)
Regional/National profile	Mila i Canals et al., 2006	Apple	New Zealand	LCA	Commercial orchards (3) + validation	Mass based (FU=t)	Cradle-to-market (int)(cg)
	Soler-Rovira and Soler-Rovira, 2008	Apple	Spain	LCA	Literature and other databases	Land based (FU=ha); Mass based (FU=t)	Cradle-to-market (int)
	Williams et al., 2006	Strawberry	UK, Spain	LCA	Literature and other databases	Mass based (FU=t at distribution)	Cradle-to-market (int)
	Coltro and Mourad, 2009	Orange	Brazil	LCA	Commercial orchards (30)	Mass based (FU=t)	Cradle-to-gate
	Yusoff and Hansen, 2007	Palm oil	Malaysia	LCA	Literature and other databases	Mass based (FU=t final product)	Cradle-to-gate* (n)
	Cuadra and Bjorklund, 2007	Pineapple	Nicaragua	EFA; EM	Commercial orchards (3) + validation	Land based (gha/ha; seJ/ha); Energy based (gha/Gcal); Receipt based (gha/$)	Cradle-to-market (p,cg)
	Mohammadi et al., 2010	Kiwifruit	Iran	EB	Commercial orchards (86)	Energy based (MJout/MJin); Mass based (MJ/kg); Receipt based (MJ/$)	Cradle-to-gate
	Kizilaslan H.,2009	Cherry	Turkey	EB	Commercial orchards (87)	Land based (MJ/ha)	Cradle-to-gate
Comparison agro-techniques	Niccolucci et al., 2008	Grape	Italy	EFA	Commercial orchards (2)	Mass based (gha/t); Land Based (gha/ha)	Cradle-to-market (p,cg)
	Reganold et al., 2001	Apple	Washington	EB	Experimental field	Land based (MJ/ha)	Cradle-to-gate
	Pizzigallo et al., 2008	Grape	Italy	LCA; EM	Commercial orchards (2)	Mass based (FU=t final product; seJ/t)	Cradle-to-gate* (p,cg)
	de Barros et al., 2009	Banana	Guadalupe	EM	Commercial orchards (8)	Land based (seJ/ha)	Cradle-to-market (p)
	Kaltas et al., 2007	Olive	Greece	EB	Commercial orchards (24)	Land based (MJ/ha)	Cradle-to-gate (cg)
	Sanjuán et al., 2005	Orange	Spain	LCA	Literature and other databases	Mass based (FU=kg)	Cradle-to-gate
	Gundogmus, 2006	Apricot	Turkey	EB	Commercial orchards (20)	Land based (MJ/ha)	Cradle-to-gate
	Guzmán and Alonso, 2008.	Olive	Spain	EB	Commercial orchards (241)	Land based (GJ/ha); Energy based (GJout/GJin); Mass based (GJ/l)	Cradle-to-gate*
	La Rosa et al., 2008	Orange	Italy	EM	Commercial orchards (4)	Mass based (seJ/g)	Cradle-to-gate
	Liu et al. 2010	Pear	China	LCA	Commercial orchards (5)	Mass based (FU=t)	Cradle-to-market
Domestic versus Imported	Mila i Canals et al., 2007	Apple	UK, New Zealand	EB	Literature and other databases	Mass based (FU=kg)	Cradle-to-market (int)
	Blanke and Burdick, 2005	Apple	Germany, New Zealand	EB	Literature and other databases	Mass based (FU=kg)	Cradle-to-market (int)