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Abstract

There is growing interest in re-localization and re-connection of agriculture and food consumption, and Short Food Supply Chains (SFSCs) are becoming more and more popular. However, there are few studies on their environmental performance. Existing studies focus primarily on comparing imports and domestic consumption, often according to a single environmental criterion (i.e., energy or carbon footprint), without considering the great diversity of subnational commercialization patterns. This paper aims at assessing the environmental sustainability of different archetypes of food supply chains, from global ones to short ones, to identify hotspots and discuss the conditions under which a given supply chain performs better than another one. The overall methodology is based on a full Life Cycle Assessment (LCA) with a focus on a fresh and unprocessed product: apples purchased in an urban area. First, a consistent definition and classification of supply chains, is provided based on geographical and organizational features. An innovative approach is then developed to compute logistics data representative of these supply chains, using Geographic Information System tools. Finally, a comparison of the environmental performances of archetypes of apple supply chains is provided. The results show the relatively good environmental performance of the national long food supply chain which is used as the reference scenario in this study. Moreover, there are great differences in the environmental performance of SFSCs. Direct off-farm sales have the same level of performance as the reference. On the other hand, direct on-farm sales can be very impactful. Results also highlight the impacts of the final consumer trip which are significant and highly variable, depending on consumer-retailer distance, weight of apples purchased, and transport means used. This variability leads to reconsidering the questions frequently asked in LCAs of systems with extreme sensitivity to highly variable parameters. The concern is no longer whether one scenario is better than another, but to determine the values of those parameters that allow for better performance. Focusing on these parameters has direct implications in terms of decision-making by providing straightforward results with operational recommendations that are understandable to the general public, and not only LCA indicators.

Keywords

Environmental impacts, eco-design, tipping lines, GIS, decision making, fresh food products

Highlights

- Short Food Supply Chains (SFSCs) are increasingly promoted as more sustainable
- Yet there is a lack of full LCAs to assess their environmental impacts
- SFSC classification combining geographical and organizational distances is proposed
- An innovative approach is developed to compute logistics data using GIS tools
- Tipping lines are computed to determine conditions under which SFSCs perform better

1. Introduction

There has been growing interest in recent years in food sourcing. Many studies have focused on assessing the sustainability of global and local food supply (Brunori and Galli, 2016), and a particular emphasis has been placed on short food supply chains (SFSC) (Praly et al., 2014). The popular concept of “food miles”, which originated in the UK and provides a measure of how far food travels between the production stage and the final consumer (Weber and Matthews, 2008), often demonstrates that local sales can be a strategy to decrease the environmental impacts of supply chains. However, this concept has been defined as a poor indicator of environmental impacts of food production since a comprehensive analysis should include: (i) a life cycle perspective (including in particular the farm stage and the cold storage) and (ii) the consideration of multiple categories of environmental impacts (Edwards-Jones et al., 2008). In this context, Life Cycle Assessment (LCA), is a well-established and recognized methodology to be used for quantifying the environmental performance of food products (Sala et al., 2017).

Apples, which are the fruit with the second biggest production in the world after bananas and before oranges and grapes (Demaria et al., 2018), offer an interesting case study to discuss environmental performance of a fresh food supply chain where no transformation processes are required. Several LCA studies have been conducted to assess the environmental impacts of apples including entire apple supply chains, from the orchard stage to the last retailer or the final consumer. A particular emphasis has been placed on the origin of the products in order to compare the environmental impacts of domestic production and imported products (Goossens et al., 2018; Longo et al., 2017; Sim et al., 2007). These studies show the large contributions of transportation to the environmental performance of entire apple supply chains when products are imported over long distances by trucks or ships (e.g. contribution in the order of 70% for climate change impacts). This has also been demonstrated in similar works on energy balances (Blanke and Burdick, 2005; Milà i Canals et al., 2007).

However, aside from the discussion on the country of origin of the product, it is necessary to consider the environmental performance of different subnational supply chains, such as buying apples directly at the farm or outdoor markets rather than the supermarket (Goossens et al., 2019). Cerutti et al. (2011) and Jones (2002) assessed different retailing scenarios (i.e. direct selling, or grocery store) and concluded on the importance of retailing strategies for the environmental sustainability of food systems. They showed that localization is a direct approach reducing or avoiding the negative environmental impacts of international transportation, distribution and car use. However, Van Hauwermeiren et al. (2007) highlighted that distribution modes can affect the performance of these supply chains rather than the distances travelled. Coley et al. (2009) concluded that purchasing the most geographically local produce per se does not necessarily mean the lowest environmental impact. In addition, Mundler and Rumpus (2012) showed that there is an important potential for logistical optimization in local food chains. Finally, Milà i Canals et al. (2007) stressed that it is difficult to make general recommendations because of the variability in data and characteristics of these different food supply chains. For instance, the average distance travelled in French SFSCs is 70 km, with a standard deviation of 109 km (Vaillant et al., 2017). Consequently, the great diversity of SFSCs does not allow for generalization on their environmental impact or conclusions as to whether they are better or worse than other forms of distribution (Ademe, 2012).

That is why, ultimately, for individual or collective decision making, the main issue is not to decide definitively if one kind of supply chain performs better than another one, but rather to establish the extent to which, and the conditions under which, one supply chain can be more environmentally efficient than another one. To explore this issue, this paper: i) defines the different archetypes of supply chain that can be used to provide apples to final consumers, ranging from international ones to local ones; ii) computes average data to model these archetypes from a life cycle perspective; iii) assess their environmental impacts through LCA to identify hotspots; and iv) discusses how one type of supply chain can be more efficient than another one, by varying the values of the main hotspot drivers. Apples are used as a case study to discuss the method and results for all fresh products such as fruits and vegetables where no processing is required. A particular focus will be placed on SFSCs. Although there is a growing societal demand for SFSCs as a driver of change in the food system and a policy tool for rural development, SFSCs are still rarely investigated through full LCA studies. This paper is organized as follows: Section 2 describes the overall methodology applied according to the four LCA stages described in ISO standards (ISOa, 2006; ISOb, 2006) with a particular emphasis on the goal and scope definition, and the data collection stages; Section 3 presents, interprets and discusses the main results; and Section 4 outlines key research findings and follow-up research that could be conducted to improve sustainability assessment of food supply chains.

2. Material and method

2.1. Goal and scope definition

2.1.1 Aim of the study and functional unit definition

The aim of the study is to discuss the environmental sustainability of various supply chains that provide apples to final French consumers, from short and local supply chains to long and international ones under different conditions. As there is a wide diversity of final consumers with their specific purchasing patterns, the present study focuses on a typical French household defined as a family with at least one minor child living on the edge of a large city (Buisson and Lincot, 2016). The chosen city is the metropolitan area of Montpellier located on the Mediterranean coast, with approximately 465,000 inhabitants (INSEE, 2016). Montpellier is used as a proof of concept. Like all large French cities, it hosts all kinds of food supply chains that can be compared on the basis of representative data. There are several options for a family to buy apples (e.g., hypermarket, farm sale, open-air market, grocery store), which correspond to dedicated supply chains. In this paper, the environmental impacts of these different options are assessed through LCA. Archetypes of different supply chains are therefore defined from average data to identify the main hotspots within each one and to get first reference standards as a basis for comparison. The functional unit selected is the purchase of one kilogram of apples from a retail location. It is therefore a product-oriented study and attributional modelling is adopted according to ILCD guidelines (EC-JRC, 2010). In order to focus only on supply chain organization, from producer to consumer, it is assumed that apple variety and quality (Gala, conventional agricultural production) is identical in all the types of supply chain studied, meaning that the apple cultivation stage will be considered as the same in all the studied alternatives, no matter where the actual production takes place.

2.1.2 Definition of Short Food Supply Chains (SFSCs) and other supply chains

There is a large variety of types of SFSCs, and several attempts have been made to define what type of supply chain should be at the heart of the reflection on re-localization and re-connection of agriculture and food production (Kneafsey et al., 2013). Chiffoleau (2008) referred to the French legislation to determine the main features of SFSCs, and identified important characteristics, i.e. number of intermediaries, geographical distances, and type of sale system (individual or collective). According to her and the food supply chain typologies proposed by Malak-Rawlikowska et al. (2019), Figure 1 proposes a classification of food supply chains divided into SFSCs, medium supply chains and long supply chains.

Figure 1

2.1.3 Apple supply chain archetypes

Based on Figure 1 and the knowledge of experts on the French apple sector, five main archetypes of supply chain have been defined for apple provision to a French urban household in this paper. These are shown in Figure 2: i) international long supply chain (L1); ii) national long supply chain (L2); iii) medium supply chain (M); iv and v) two SFSCs (S1 and S2).

International long supply chain, L1, imports apples from Chile, one of the main suppliers during the European apple off-season (Agreste, 2019), and apples are sold in hypermarkets after having passed through several intermediaries including wholesalers, and Retail Distribution Centers (RDC). In national long supply chains, L2, apples are also sold in hypermarkets, but they come only from French orchards. It is assumed that they are placed on the market by producer organizations (i.e. cold-store in Figure2) which currently concerns 60% of the volume distributed (Agreste, 2014). Medium supply chains rely on a regional supply of apples and regional intermediaries such as markets of national interest in charge of supplying food to large living areas through supermarkets and specialist retailers in grocery stores or outdoor markets.

Finally, there are no intermediaries in the two SFSCs. In one case, the sale does not take place on the farm but via a collective structure (community supported agriculture, farmers' shop) or an outdoor market (direct off-farm sale, S1), and in the other case, the sale is made directly on the farm (direct on-farm sale, S2).

Figure 2

In all these supply chains, the system boundaries include apple production, sorting and packaging, storage, transportation, sale and the final consumer trip to buy apples. The consumption stage (e.g. consumer food waste) and the product end-of-life are not included in the study (e.g. management of organic apple waste such as cores and peelings). Only the packaging end-of-life is considered as well as sorting and losses until the final purchase.

Final consumers can choose between different modes of transport to make their purchases. This is facilitated by the fact that the study focuses on a household living in an urban environment where shops are generally close to residential areas and where alternatives to private cars are possible, including non-motorized vehicles or no vehicles (pedestrians), which are also assessed in this study (i.e. alternative scenarios Mb and S1b).

2.1.4 Seasonality of apple supply

In France, apple harvesting takes place from the end of August to the end of November, depending on the variety. Apples can withstand long periods of storage in cold rooms before being sold and consumed. The apple market in France is therefore dependent on the season and can be split into three main periods that have a direct effect on the average duration of cold storage: P1, from August to November (short storage duration – about 2 months); P2, from December to March (medium storage duration – about 5 months); and, P3, from March to July (long storage duration – about 3 months for Chilean apples and 9 months for French ones). In addition, the apple supply sources are seasonally dependent. Most Chilean apple imports take place in the off-season (P3), whereas M, S1 and S2 supply chains rarely take place during this same period.

2.1.5 Analytical design of scenario comparison

Different combinations of purchasing periods and supply chains are assessed and compared to a reference scenario to identify the main environmental hotspots concerning apple provision to a French urban household. The reference scenario is defined as the combination between the national long supply chain and the medium storage duration (noted L2-P2 in Figure 3).

Figure 3

The first point that will be tested is the comparison between different supply chains that are located entirely within France (i.e. comparison A in Figure 3), to analyze environmental performances of long and short supply chains. The second comparison will focus on the season effect to assess the storage effect on the overall performance of the reference scenario (i.e. comparison B in Figure 3). As the French electricity mix is particular (mainly composed of nuclear energy), the effect of the electricity mix will also be analyzed. The third comparison will assess the importation effect to analyze the trade-off between long distance transportation versus long storage periods (i.e. comparison C in Figure 3). Finally, the last comparison will assess the effect of consumer transportation mode to discuss the impacts of the final km (i.e. comparison D in Figure 3).

2.2. Life cycle inventory analysis

All supply chains studied are based on the same basket of unit processes, only the amounts used for each process vary from one scenario to another. Therefore, Life Cycle Inventory (LCI) analysis is divided into two steps. The first one is the LCI computation for each unit process included in the studied systems, from orchards to the purchase by the final consumer at different points of sale. The second step is to define the quantities used in each scenario for each of the unit processes to get the full LCIs of supply chains. These LCIs are based on average data to provide a preliminary modeling of archetype supply chains. All LCI modeling was done using the commercial LCA software SimaPro.

2.2.1 LCIs of unit processes included in apple supply chains

These unit processes cover all life cycle stages, from apple production to purchase by the final consumer, including transportation according to the types of vehicles that can be used, infrastructure for different types of building and equipment, materials (e.g. types of packaging), cooling and conservation systems, and electricity consumption of the different equipment used in the supply chains. Except for apple production, the LCI data used for these unit processes come from the ecoinvent database v3.2 (ecoinvent, 2015). When there were no processes directly usable in the ecoinvent database, processes were created by assembling existing ecoinvent LCI components as for the cold room. This assembly was done using data from the literature and the stakeholders' expertise (e.g. electricity consumption of a cold room to store one kg of apples for one day). All the detailed information regarding the LCI dataset of unit processes included in apple supply chains is provided in the appendices (see Appendix A). For the orchard step, an in-field dataset from an experimental orchard representative of French fruit grower practices was used with an average yield of 37.8 tons per year of commercialized fresh apples (national source Agreste 2015-2016). The dataset covers a 9-year period (Alaphilippe et al., 2016) in order to account for the climatic condition variability and thus to ensure both accuracy and representativeness.. The production system is conventional with applications of mineral N-fertilization (47 kg/ha/year) and pesticides (29 kg/ha/year active ingredients). LCA data for the orchard step was considered the same for all supply chain scenarios that occur in France or in Chili.

2.2.2 Full LCIs of apple supply chains

All LCI unit process quantities used in each of the scenarios are given in the Appendix B. These quantities are computed using supply chain archetypes described in section 2.1.3 (e.g. sea transport stage or not or purchase in hypermarket or outdoor market) and different types of data. All these data are summarized in Table 1, and the methods for estimating them are described below.

For this first modelling, some data are shared by all the archetypes of supply chains. This is the case for the packaging stage. Only secondary packaging has been taken into account as it is has been identified as an important hotspot compared to primary or tertiary packaging (Goossens et al., 2019). Moreover, secondary packaging is fairly similar among retailers, and it has been assumed that half of the apples are loaded in cardboard boxes (50%) or plastic crates (50%, IFCO boxes) according to Goossens et al. (2018). Cardboard boxes are equally disposed of in landfills, incinerated or recycled, while IFCO boxes are reused for 10 years and then recycled (Ademe, 2000).

Another common data between the supply chains concerns apple sorting and losses at each stage. Estimates were given after discussions with experts in the apple sector and the CTIFL (referent organization for applied research in the French fruit and vegetable sector). Apple sorting and losses during calibration are around 20%, those during storage (including water loss of the fruit, varying from 0.5 to 2% depending on storage time) and packaging are around 4%, and those in retail stores are around 5%. These are only orders of magnitude and deserve to be refined through field surveys. Yet these figures are close to those estimated in the recent study of Caldeira et al. (2019) on food losses and waste in Europe (i.e. for fruit, waste is around 16% in primary production, 9% in the processing stage, and 1% in the retail stage). It is assumed that a part of the apple sorting and losses is not wasted and is used for processing into juice, puree and compote.

Table 1

Other data differ greatly between supply chains, such as transport distances or consumer practices. An innovative procedure has been developed to directly compute consistent data on transport distances between the different intermediaries for each supply chain noted ai, bi, ci and di in Figure 2. Generally, data on average transport distances come from survey data or general statistics, which are often based on small datasets or samples not representative of real practices. To overcome this limitation, the proposed procedure computes transport distances using Python programming software and the open source route planner called Openrouteservice (2019). First, all apple orchards with information on the orchard surface area were localized in each French municipality using French statistics on agriculture (Agreste, 2014). Producer organizations were also localized across France according to national data from the French Ministry of Agriculture (MAAF, 2016). The road distances between production sites (orchards) and producer organizations were estimated by computing the average road distances between the centroids of the municipalities producing apples and the nearest producer organization (see Figure 4).

Figure 4

The same method has been used to calculate the road distance from producer organizations to the RDC that corresponds to logistics warehouses in the case of hypermarket sales or to the market of national interest in other sales networks. The road distances between each producer organization and the RDC were computed and the average of these distances was weighted by the production surface areas of the producer organizations. The latter is the sum of the apple production surface areas of every municipality for which this producer organization is the nearest to their centroid. This approach has been used to determine road distances for M, S1 and S2 alternatives, although the apple supply pool has been reduced within 200 km for M, 50 km for S1 and 25 km for S2 (see Figure 4). With this method, average transport distances for all the different supply chains were computed (see Appendix C to get the Python code). In order to give more importance to the high apple growing regions, the distances can be weighted by apple production surface areas in the municipality. However, this gives little variation in the results (see italics in Table 1).
For transport distances and the logistics in Chile concerning imported apples, literature data were used (Labouze et al., 2007). Distances between the consumer's home and the point of sale are derived based on the assumption that the household lives downtown and that shops are nearby. Finally, information on the types of vehicles used according to the different trips is provided (see Appendix D for the corresponding table of vehicles). It is assumed that long supply chains have optimized their logistics and use larger vehicles. To model consumer practices while purchasing apples, literature data were used. According to Rizet et al. (2008), share of apples in the total basket and the average weight of apples purchased were estimated for different archetypes of supply chains.

2.3. Impacts assessment

The impact assessment method chosen is the hierarchist approach of ReCiPe v1.11 (Goedkoop et al., 2009). The impact categories are characterized at both the midpoint (18 categories of impacts: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral depletion, and fossil depletion) and the endpoint level (3 categories of damages, i.e., human health, ecosystems and resources). Because ReCiPe combines midpoint and endpoint methods, the impact characterization at the endpoint level specifies the damage contribution of each midpoint impact category, which is very helpful for result interpretation. In addition, calculations are made with SimaPro v8.2.

3. Results and discussion

In order to present LCA results as clearly as possible, the preliminary contribution analyses are presented with midpoint indicators to maintain the multicriteria nature of LCA and to assess in detail the impacts of each stage of the apple life cycle. However, for scenario comparison, an endpoint indicator presentation is used to make interpretation easier, with only 3 impact categories corresponding to the 3 areas of protection commonly used in LCA (Human Health, Ecosystem, Resources).

3.1. Detailed contribution analysis for the reference scenario (L2-P2)

Figure 5 shows that life cycle stages that incur the main environmental impacts in the reference scenario (national long supply chain) are the production stage, refrigerated transportation, packaging, storage and the consumer trip. Their contribution depends on the given impact category.

Figure 5

Apple production has significant impacts (above 40%) on acidification, freshwater eutrophication, terrestrial ecotoxicity, agricultural land occupation and metal depletion, due to inputs such as fertilizers and pesticides. These inputs are correlated to orchards yields. Refrigerated transportation contributes substantially to climate change, fossil depletion, particulate matter formation, photochemical oxidant formation and impacts on natural, and urban lands due to fuel combustion and infrastructure. Packaging contributes significantly to marine eutrophication, ozone depletion, marine and freshwater ecotoxicity and agricultural land occupation generated by the primary products (i.e. cardboard box) and the processing stage. Cold storage contributes significantly to impacts induced by ionizing radiation due to electricity consumption but not so much to other impact categories. This is due to the particularity of the French nuclear electricity mix and therefore results are not representative of other countries. Finally, consumer trip for apple purchases is significant for almost all impact categories despite the low distance estimated between the consumer's house and the hypermarket in the supply chains studied (see Table 1). These results are in line with those of previous studies. For instance, the cultivation stage contributes little to the impacts on climate change (around 15% in Goossens et al. (2018)) or the use of fossil resources (less than 20% as in Longo et al. (2017)).

3.2. Comparison between different types of supply chains

The comparison between the reference scenario, defined as the national long supply chain, and alternative French options shows that there are few differences between the national, medium and direct off-farm sale supply chains (cf. Figure 6). Surprisingly, the main difference is with the direct on-farm sale supply chain when the final consumer goes directly to the farm to buy apples (S2-P2). This supply chain does not perform well because of the last transportation step, which is quite long (consumer-farm car transportation of about 23 km, or a 46 km round trip, for the specific case of Montpellier). The medium supply chain has a slight advantage over the other supply chains, followed by the reference scenario and the direct off-farm sale supply chain. However, these results are computed for a given set of data that do not reflect actual variability of practices and geographical particularities. It is therefore required to include this variability before providing any generic conclusions regarding food supply chains. This is what is proposed in Section 3.6 of the paper.

Figure 6

Figure 6 shows moreover that imported apples from overseas is the second most impactful supply chain (L1-P3). Import mainly occurs before the French apple harvest, when there are few domestic apples on the market. The impacts of import are much higher than the impacts of cold storage, regardless of storage time. In scenario L2-P1, apples are stored only for a period of two months, compared to five months in L2-P2, and nine months in L2-P3. Due to the particularity of the French electricity mix, based mainly on nuclear power, the impacts of electricity consumption during storage are relatively small compared to other life cycle stages, which makes it difficult to clearly distinguish the "storage time" effect (from 2 to 9 months). A comparison with another electricity mix is also proposed. The Polish electricity mix has been chosen in ecoinvent as it is mainly based on coal-fired power generation. It increases the total impacts for each variant of the reference scenario. This can change the damage to human health by up to 20% and to resources by up to 15%, but is not particularly damaging to ecosystems.
Finally, in the studied scenarios, the distances between the consumer's home and the retail point are very short: between 1 and 1.6 km. Even with these limited distances, the impacts of consumer trips are significant (see Figure 5). For scenarios L2-P2, M-P2 and S1-P2, consumer's car trip has been substituted by a walking trip. This substitution meaningfully decreases the total impacts of the original scenario, and the medium supply chain that relies on regional sourcing stands out as the most environmentally efficient one (see Figure 6). Moreover, the scenario based on direct off-farm sales (S1-P2) is almost as efficient as the reference scenario showing the importance of consumer choice on the total impacts of apple purchases.

3.3. Tipping lines for decision making in highly variable contexts

The results on the effect of the mode of transportation should be interpreted with caution as they do not reflect the high variability of consumer practices concerning ways of purchasing apples, nor the territorial context (i.e. structuring of the supply chains, and location of producers and of all intermediaries). In particular, the final consumer–retailer distance is highly relevant as the share of the consumer trip in the total impacts of the studied supply chains is substantial (see Figure 5). To address this issue and help decision making in highly variable contexts, abacus have been built to see in which cases one scenario may be better than another. For that purpose, Figure 7 proposes to search for "tipping lines" for which direct on-farm supply chain S2-P2 performs better than the reference scenario L2-P2 regarding three key parameters: (i) the quantity of apples purchased, (ii) the distance between consumer and farm and (iii) the share of apples in purchases (%).

Figure 7

Rationally, it appears that direct on-farm sales can perform better than average national supply chains if distances between the consumer and the farm are reduced (less than 15 km for an apple share of 21%, or less than 5 km for an apple share of 76%), or if the quantities of apples purchased at the farm are increased (more than 12 kg at 22.7 km for an apple share of 21%), or even if the share of apples purchased in the total basket is decreased. The latter point also emphasizes the fact that the purchase of apples might not be the main or the only purpose of the consumer's trip, and the share of the trip could also be reduced, which at the same time increases the environmental performance of the short supply chain.

3.4. Data consistency and comparison with other studies

Data is a major issue in the environmental assessment of food supply chains, as there is a wide diversity of individual and collective practices and situations, depending on many factors (socio-economic contexts, geography, demography, consumer habits, or cultural identity). Table 2 illustrates the wide range of transportation data used in different studies to assess the environmental performance of long and short apple supply chains.

There is a large discrepancy in the numerical data used at each step of the supply chains, which shows the difficulty to define references and to provide generic recommendations for the wide diversity of food supply chain parameters. This is all the more problematic as these stages and the related data contribute significantly to the impacts of the entire supply chain. This finding supports the idea that this is not a question of comparing long and short supply chains based on a fixed reference, but rather of identifying what the hotspots are for these different supply chains, and at which time one can perform better than another according to the real conditions in which supply chains operate. This will be more instructive and useful for the eco-design of food supply chains as well as for labelling them.
Important differences in data correspond to the distances travelled by trucks. Geographical and organizational contexts can differ substantially between studies and can partly explain the differences found in numerical data. However, for both studies located in the same country, i.e. Italy, there are large differences between the studied supply chains (up to more than 100 km). In comparison, there are smaller differences between distances travelled by ships, as shipping routes may be better documented and offer fewer opportunities for itineraries.

Table 2

Finally, data on the final kilometers are also important because they have a significant impact on the environmental performance of the whole supply chain. On this point too, data found in the literature are disparate (see Table 3).
In the proposed approach, average transport distances were computed using Python programming software and the open source route planner called Openrouteservice (2019) combined with ponderation of distances by the surface areas of apple orchards. This strategy seems more relevant (regarding in particular data heterogeneity) than combining national/global statistical data with local small sampling surveys on local practices. The big-data outlook should, in the near future, allow this type of approach to be further consolidated to provide more representative data.

Table 3

Studies show, however, (Table 3) that it is important to distinguish between rural and urban areas because the distances travelled in rural areas are generally greater.

3.5. Importance of the Functional Unit (FU)

The choice of the functional unit (FU) can largely determine the results obtained (Huijbregts, 1998). This is the general case in agricultural LCAs where, depending on the FU selected, the results of the study may modify the LCA results and the order of the alternatives studied, according to their environmental performance (Baumgartner et al., 2011; Haas et al., 2000). The choice of the FU is essential when assessing food supply chains because, as for agriculture, these systems can be multifunctional. The growth of SFSCs can be explained for various reasons and meets a wide range of needs corresponding to various FUs, depending on whether the perspective is that of producers, consumers or citizens (Fabbrizzi et al., 2014). The emergence of SFSCs can contribute to a better redistribution of the added value, the promotion of social and professional recognition of farmers, or the development of new skills from a producer's perspective (Mundler and Laughrea, 2016). Consumers can choose to rely on SFSCs to access better quality products that are fresher, more authentic or more reliable in terms of traceability (Giampietri et al., 2015). In addition, SFSCs can be a driver of local development through job creation, or the creation of new farms and of the welfare of the community (Mundler and Laughrea, 2016). Ultimately, SFSCs can provide a wide range of services and several FUs can be chosen. However, all LCA studies use the kg of apples provided to the retailer or the final consumer as the FU. Other FUs such as the euros that go back to farmers, the number of jobs created or the nutritional quality of the final products could be tested to assess the robustness of the conclusions that can be drawn (Poore and Nemecek, 2018).
This point is related to the modelling of the final consumer's trip, which has a major impact on the total performance of the supply chains studied. However, consumers may have several reasons for shifting to

farmers and local producers. In addition to buying products, travelling to a different place allows people to walk around and can be combined with other activities such as buying other products, visiting natural or cultural sites, or sport practices. The farm may also be on the way home from work. It is moreover an opportunity to communicate and create ties between producers and consumers around the product itself and beyond (cultural aspects), which are not embedded within the FU "a kg of apples". If these other reasons were taken into account, it would significantly increase the environmental performance of the supply chains studied, and in particular that of direct on-farm sales, whose environmental impacts are based solely on the final consumer's trip. Moreover, this study deals with a household living in an urban area. The conclusions could be completely different in a rural context where supermarkets were further away from dwellings and where there is generally no alternative to the use of private cars. To pursue this inquiry, different territorial and organizational contexts should be studied.

3.6. Other modelling choices

The study aims at providing a general overview on the environmental performance of different types of food supply chains, from long ones to short ones. In accordance with this objective, "theoretical" scenarios representing archetypes of supply chain have been defined (see figure 2). It is not the intention here to specifically describe a real example of a short supply chain, for instance. Therefore, only secondary data has been used in the modeling of the systems, as defined by the ILCD handbook (EC-JRC, 2010). To go further, it would be necessary to study existing supply chains to obtain primary data and model the foreground system in coherence with these specific cases. It could be interesting to also include the apple consumption stage because it can have a significant impact, depending on the product's preservation method and the final waste rate (Wikström et al., 2016). Loss and waste rates can moreover vary significantly, depending on the consumers and the type of supply chain studied. It has been shown that the SFSCs generate changes in practices among all actors in the chain, including consumers, who adopt more sustainable practices (Chiffoleau et al., 2019). This can affect the choice of products (purchases of downgraded products, limitation of losses when cooking, for example by using damaged products, etc.). These points should be further developed and included in future LCA studies of SFSCs by broadening the boundaries of the system through a cradle-to-grave perspective and conducting a sensitivity analysis on the consumption phase.

More generally, changes in practice throughout the whole chain should be assessed, particularly on the producer side. In this study, the choice was made to take the same apple as a starting point, but to go further, different apple production methods should be taken into account. For instance, it is shown that SFSCs promote alternative production methods with more organic producers (Aubert and Enjolras, 2016; Mundler and Laughrea, 2016). These parameters should be considered to deepen the knowledge on the environmental performances of food supply chains. Yet, in the case of apples, this modelling choice affects the results only slightly because, as the analysis of contributions shows (see Figure 5), the production stage is not the most impactful stage compared to the other life cycle stages. It is also important to discuss the choice of the city used as a case study. If a city is distant to a greater or lesser degree from the main production areas, this can significantly affect the performance of the different supply chains. With proximity to production areas, the performance of long and short circuits can be significantly improved. On the other hand, if the first production areas are far from the city studied, the performance of the supply chains can be quite poor, especially for the SFSCs where distance is one of the main drivers of efficiency. However, in France the main apple production areas are spread fairly well over the territory, and there are orchards all over the country. Therefore, the choice of another city should not radically change the results of the study.

4. Conclusions and future prospects

The aim of the study was to discuss the environmental sustainability of different supply chains that provide food to final consumers, comparing archetypes of short and local supply chains to long and international ones using LCA methodology. This was achieved through a case study on apple supply chains in France. LCA can provide a valuable contribution to the development of sustainable strategies in food supply by identifying environmental hotspots through a life cycle and multicriteria perspective and drivers of changes. The results here show that the logistics phase contributes significantly to the impacts and that there is still room for improvement in supply chain performance. However, it is necessary to pay attention to the question raised in the LCA. Given the wide diversity of practices and cases in food supply chains and the advances of traditional ones (longer and more globalized), our intention is not to compare these supply chains to those of SFSCs, which are in full expansion. The question to be asked is rather how these SFSCs can improve their environmental performance and up to what point they could perform better than traditional supply chains. The results show that the answers to these questions may differ, depending on the context and organization of the SFSCs. On the one hand, national and medium supply chains are optimized both in terms of distances, transportation modes, and loading rates. On the other hand, emerging short supply chains have wide margins for progress in terms of logistics to improve their environmental performance. If these short supply chains implement strategies to optimize their logistics, and consumers optimize their food supply trips, performance would be greatly improved and could exceed that of conventional supply chains (Vaillant et al., 2017). Finally, consumers have significant impacts through the way they purchase foods, and active mobility should be promoted, especially in urban environments.

The lessons learnt from our case study can be generalized to all fresh products such as fruits and vegetables requiring little or no processing, and where the production phase is not the most impactful (e.g. fruits and vegetables grown in the field). However, there are still avenues of research to be investigated in further depth. First, more knowledge is needed to better understand how the supply chains are organized according to the types of food product categories. GIS-based tools, can be useful for compiling logistics data, for example, and developments could make it possible to better model the movements of final consumers according to their places of residence and work, and the location of all the stakeholders involved upstream of the supply chains. Surveys and field visits are however also necessary to deepen the knowledge of the supply chains, particularly on the practices of stakeholders both upstream (producers, transformers) and downstream (consumers) of the supply chain, where behavior can differ greatly and have a significant impact on the environmental performance of the whole supply chain. This is all the more true for product categories where the stages of production, processing or consumption have a heavy impact, such as products of animal origin and processed products (Foster et al., 2006).

Second, a complete sensitivity and uncertainty analysis could be performed by stochastizing all input data. The method developed by Weidema and Wesnaes (1996) could be used to qualify the uncertainty on the input data. Note that stochasizing the calculations would not change the main conclusions of the study, particularly those presented in the abacuses in Figure 7. It would allow a fuzzy area to be drawn on these graphs where it would not be possible to differentiate the performance of a supply chain from another.

Furthermore, the study focused on the supply of one kg of apples to the final consumer. This functional unit may be restrictive. Food supply chains are multifunctional systems and provide a wide range of services that should be identified and quantified to consider them in LCA studies and move away from the strictly productivist rationale. Moreover, this choice implies modelling the system on a micro scale. Yet the supply of cities can also be studied at meso scales, through the use of territorial LCA approaches (Loiseau et al., 2018). In this context, an attributional approach such as the one adopted in this study is not necessarily appropriate. The choice of one supply chain over another can generate indirect socio-economic effects that should be considered in the assessment according to a consequential approach (EC-JRC, 2010). Therefore, adopting modelling approaches focusing on large-scale systems and considering the socio-economic consequences of a decision would provide a more comprehensive view on the issue of urban food supply.

Independently of food supply sustainability issues, a more generic conclusion on LCA use can also be drawn from this study. Stakeholders often expect LCA to give them a clear-cut answer to the question "is scenario A better than B?". Since LCA results are, in most of the cases, highly sensitive to specific local parameters, it would seem more relevant to reword the question as “under what conditions would A or B have the best environmental performance?”. This would avoid decisions being made on the basis of scenarios that are not representative of the diversity of all real practices. This is exactly what has been illustrated in this paper with the apple case study and the provision of abacus based on tipping line computations. These results have direct managerial and policy implications. Firstly, in terms of eco-design, LCA is traditionally used to identify the main hotspots of a system. The abacus provided goes further by quickly identifying conditions that can significantly improve the performance of a system. Secondly, there is currently much debate on environmental labelling of products and on how to communicate the LCA results (Minkov et al., 2020). The outcome here shows that, in addition to the complexity of a multicriteria assessment, LCA can be used to produce very educational and simple results for the general public (e.g., how many products does a final consumer need to purchase to amortize his or her private car trip). This type of approach needs to be continued in order to improve the communication of LCA results (often considered too complex) and to determine what is important to share with the public (identifying the appropriate means of action) and in what form.

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Figure 4 Main apple production areas in France and calculation of average transport distances between intermediaries up to final consumers in the metropolitan area of Montpellier (see zoom). Distances from the different orchard locations are weighted by their respective surface areas.

Figure 5 Contribution analysis for the reference scenario (L2-P2) using ReCiPe midpoint (H) LCIA method.

Figure 6 Comparison of the environmental impacts of national apple supply chains (reference scenario L2-P2) with other types of supply chain, from international (L1-P3) to medium (M2-P2) and short (S1-P2 and S2-P2), including seasonal effect (L2-Px) and consumer transport mode effect (x2-x2 foodpath), using the ReCiPe endpoint (H) LCIA method for all types of supply chain.

Figure 7 Search for tipping lines where the direct on-farm sale performs better than the reference scenario due to optimal distance between consumer and point of sale, and quantities of apples purchased for two different apples' share in the final basket (21 and 76%).

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Appendices

Appendices include: all the detailed information regarding the LCI dataset for all unit processes included in supply chain scenarios (A); the amounts of the unit processes used to model full LCIs of apple supply chains (B); the Python code used to compute average road distances between apple supply chain scenarios (C); and the corresponding table of vehicles used in the different supply chain scenarios described in Figure 2 (D).

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Tables

Table 1 Data used to model full LCIs of supply chains based on LCIs of unit processes (VP = private vehicle, types of vehicles C1, C2, C3, C4, C4R described in Appendix D) (*Labouze et al., 2007)(**Rizet et al., 2008). Shaded cells mean that the corresponding steps are not included in the systems studied.

	Long supply chains		**Medium supply chains**	**Short supply chains**	
	L1	**L2**	**M**	**S1**	**S2**
Apple production	Gala, conventional agricultural production, yield: 37.8 t/y				
Apple sorting and losses after calibration	**20%**				
Packaging	**Half** plastic boxes (reused and recycled) and **half** cardboard boxes (with a balanced distribution between recycling, landfill and incineration at the end of life)				
Apple sorting and losses after storing	**5%**				
Import Chile: Farm → Harbor (Valparaiso)*	**500** km Road C4R				
Import Chile: Ship (Valparaiso → Rotterdam)*	**13,852** km Ship				
European Harbor (Rotterdam) → RDC*	**462** km Road C4R				
Distance **(ai)**: Farm → Cold-store		**13.4 km /** *22.2 km* Road C4	**10.1 km /** *15.5 km* Road C3	**2.1 km** Road C2	
Distance **(bi)**: Cold-store → RDC		**371.2 km** Road C4R	**116.9 km** Road C3R		
Distance **(ci)**: RDC →Retailer	**9.4** km Road C4R		**6.8 km** Road C2	**30.5 km** Road C1	
Distance **(di)**: Retailer → Consumer	**1.6 km** (Hypermarket) Road VP		**1km** (Specialist retailer sale) Road VP *+ a variant*	**1 km** (Outdoor market sale) Road VP+ *a variant*	**22.7** km (on-farm sale) Road VP
Apple sorting and losses at retailer	**5%**				
Average weight (kg) of apples purchased **	**1.7 kg**		**1.9 kg**	**1.5 kg**	**8 kg**

Share of apples (%) in purchases**	**11%**	**20 %**	**21 %**	**76 %**

Table 2 Review of the wide range of transportation data used in other apple studies, n/a = not available, ((l) = local distribution, (r) = regional distribution, (n) = national distribution, (i) = international) ((o) = organic production, (c) = conventional production), UK = United Kingdom, NZ = New Zealand, BE = Belgium, GWP = Global Warming Potential. Shaded cells mean that the corresponding steps are not included in the systems studied.

Transportation distances (km) ↓	Jones (2002)	Blanke and Burdick (2005)	Milà i Canals et al. (2007)	Labouze et al. (2007)	Cerutti et al. (2011b)	Webb et al., 2013	Keyes et al. (2015)	Vinyes et al. (2017)	Longo et al. (2017)	Zhu et al. (2018)	Goossens et al. (2018)	La Ruche Qui Dit Oui (2019)
If importation: Farm → port	n/a	20	n.a	500 (C4R)		220 (n) 18 340 (i, NZ)	103		n/a		20	
If importation: Departure port → Arrival port	23 000 (NZ)	23 000	23 000 (NZ) 12 000 (other)	13 851 (Chile)			4638 (UK)		180		21 000 – 29 000 (NZ)	
If importation: Port → RDC	n/a	200 (40t)	250 (40t)	462 (C4R)			147		1530 (c) 1750 (o)		84.8	
Farm → cold-store	n/a	10	40 (C4)	n/a	2		n/a	30 (l) 80 (n)	20	560 (c) 850 (o)	20 (BE) / 8 (NZ)	49 km
Cold-store → RDC	n/a	20 (28t)	100 (C4R)	283 (40t)	125 (l) 600 (n)		103 (r) 1275 (n) (train + truck)		30 (r) 344 (n,o) 1530 + 100 (i,o) 570+155 (n,c) 1750 +180 (i,c)		94.5 (BE)	
RDC → Retailer	n/a	150 (40t)	150 (C4R)	30 (19t)	15 (l) 50 (n)						80 (NZ/BE)	
Retailer → consumer	8.3 to 9.1	n/a						n/a			5	
Type of retailer	Hyper market	Hyper market	n/a	Super market	Fresh markets (l) Super markets (n)		n/a	Super market	n/a	n/a	Super market	Direct on- farm selling
Details of the study												
Country of purchase or production	UK (purchase)	Germany (purchase)	EU (purchase)	France (purchase)	Italy (purchase)	UK (purchase)	Canada (productio n)	Spain (purchase)	Italy (production)	China (product ion)	Belgium (purchase)	France (purchase)
Product concerned	Dessert apples	Apples	Apples	Apples	Apple	Apple	Apple	Apple	Apple	Apple	Apple	Local food products
Type of assessment	*Energy & GWP*	*Energy Balance*	*Primary energy & cost*	*Energy & GWP*	*LCA (EDIP method)*	*Primary energy, GWP, five LCA indicators*	*Full LCA indicators (ReCiPe)*	*GWP and full LCA (ReCiPe)*	*Full LCA indicators (ILCD)*	*GWP + four LCA indicato rs*	*Full LCA indicators (ILCD)*	*None*

Table 3 Distances of transportation between retailer and final consumer according to different types of retailer and geographic context (urban / rural).

Sources		MTES (2008)	Rizet et al. (2008)		AGAM (2012)
			Urban	**Rural**	**Urban** (Marseille)
Distances: retailer → consumer (km)	Hypermarket	8.6 km	4.4 km	9.3 km	6.5 km
	Grocery	n/a	0.8 km	8.1 km	2.9 km
	Outdoor market	n/a	2.3 km	3.5 km	n/a

Figures

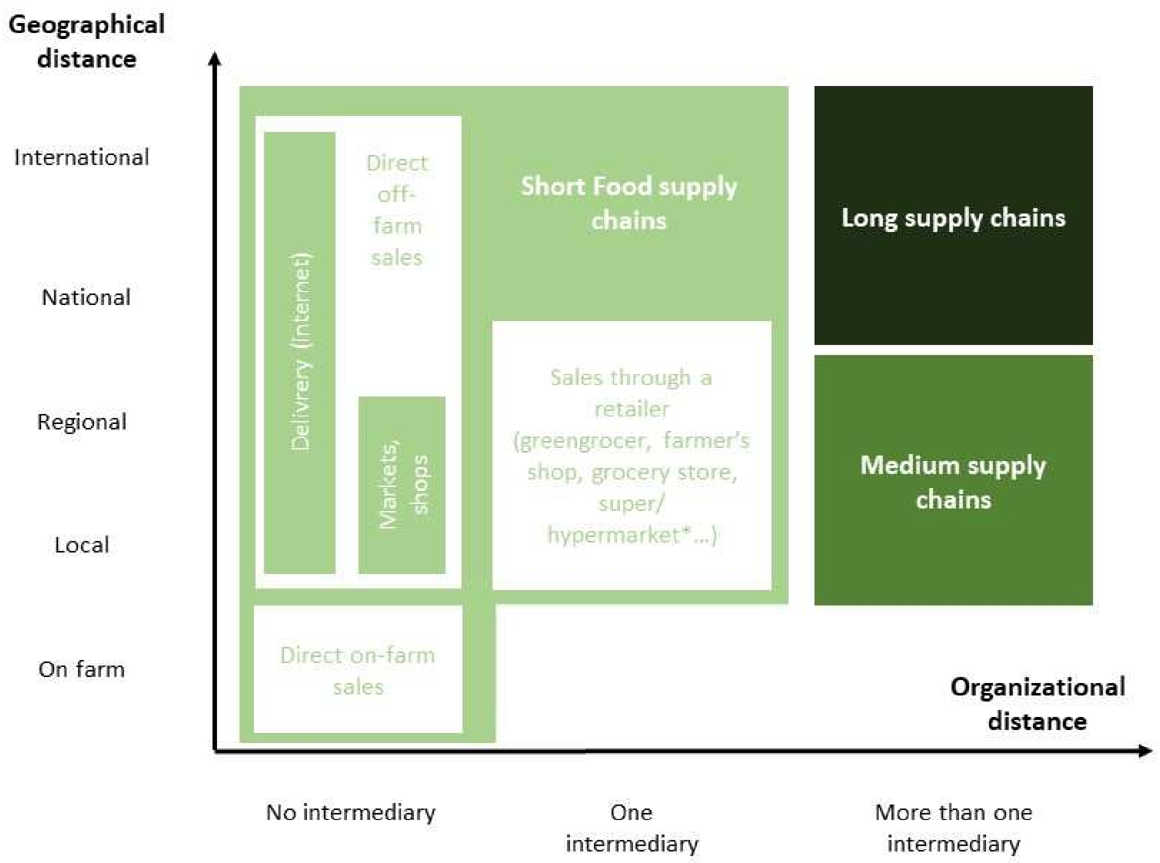

Figure 1 Proposals for food supply chain classification according to Chiffoleau (2008) and Malak-Rawlikowska et al. (2019) (*supermarkets and hypermarkets are now offering some products directly from the producer).

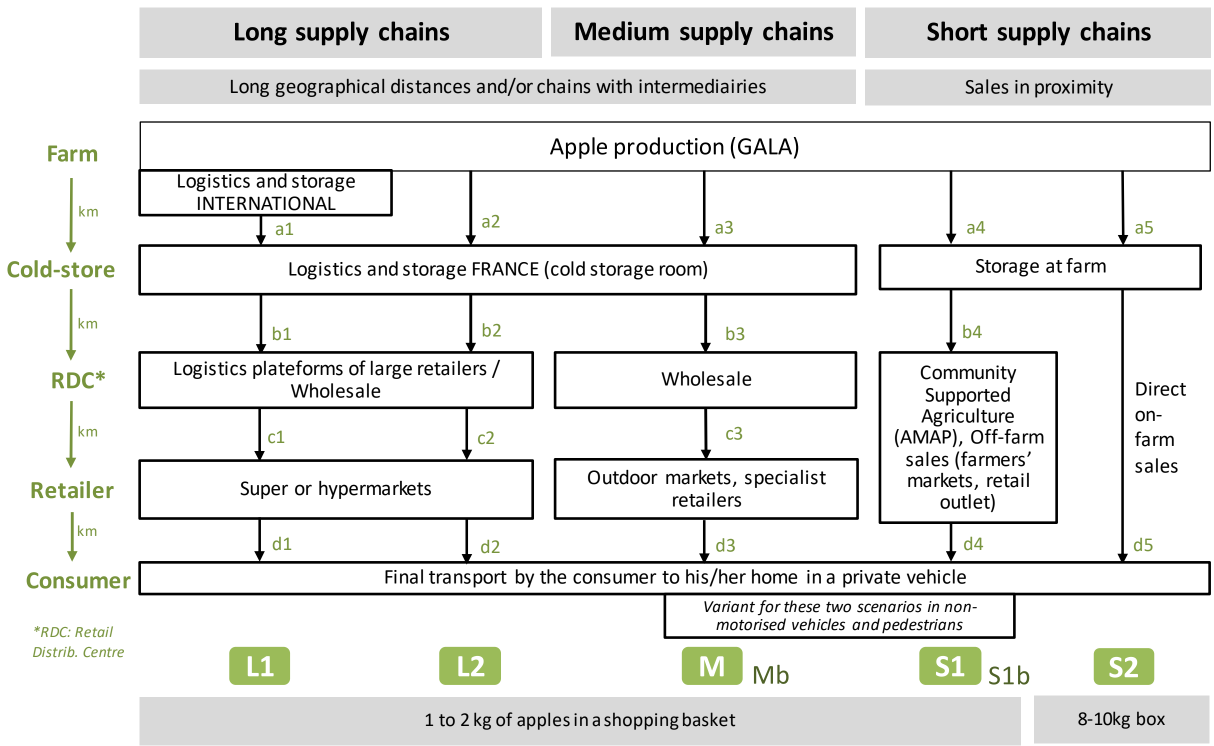

Figure 2 Description of different apple supply chains, from international long supply chain (L1), to direct on-farm sales (S2), through a wide range of combinations including national long supply chains (L2), medium supply chains with intermediaries (M) and direct off-farm sales (S1). Two variants are proposed for M and S1 with the possibility to rely on non-motorized vehicles or no vehicles (pedestrians) (scenarios Mb and S1b respectively). Distances between each stage of a supply chain are different for each scenario and are noted: ai for the distance between the farm and the cold store; bi for the distance between the cold-store and the RDC; ci for the distance between the RDC and the retailer; and di for the distance between the point of retail and the consumer.

		L1 CHILI	**L2** FRANCE	**M** Regional	**S1** Direct off-farm sales	**S2** Direct on-farm sales
Purchasing periods	**P1** – august to oct./Nov. *short storage duration*	*	L2-P1[B] (2 months)	M-P1 (2 months)	S1-P1 (2 months)	S2-P1 (2 months)
	P2 – Dec. to Feb./march *medium storage duration*		L2-P2 = REF [A, B] (5 months)	L3-P2[A,D] (5 months)	S1-P2[A, D] (5 months)	S2-P2[A] (5 months)
	P3 – March/april to June/July *long storage duration*	L1-P3[C] (3 months)	L2-P3[B, C] (9 months)	*		

Scenario comparison

- A – Comparison national long and short supply chains
- B – Season effect (+ electricity mix weight)
- C – Importation effect
- D – Consumer transport mode effect

Figure 3 Summary of the main comparisons performed in the study to exhaustively assess the environmental impacts of food supply chains, from international to direct selling (in parenthesis, storage duration in cold rooms).

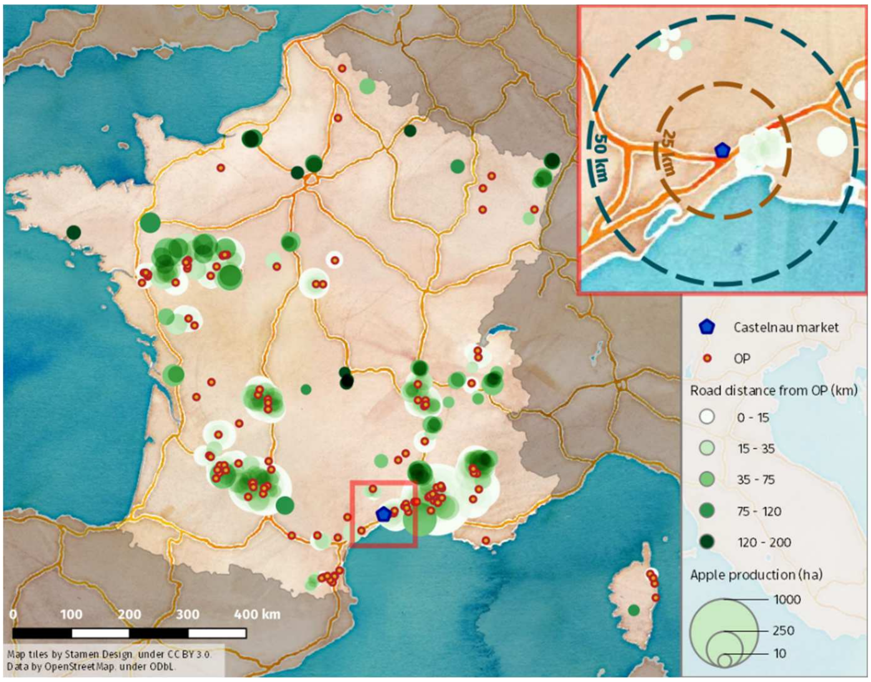

Figure 4 Main apple production areas in France and calculation of average transport distances between intermediaries up to final consumers in the metropolitan area of Montpellier (see zoom). Distances from the different orchard locations are weighted by their respective surface areas.

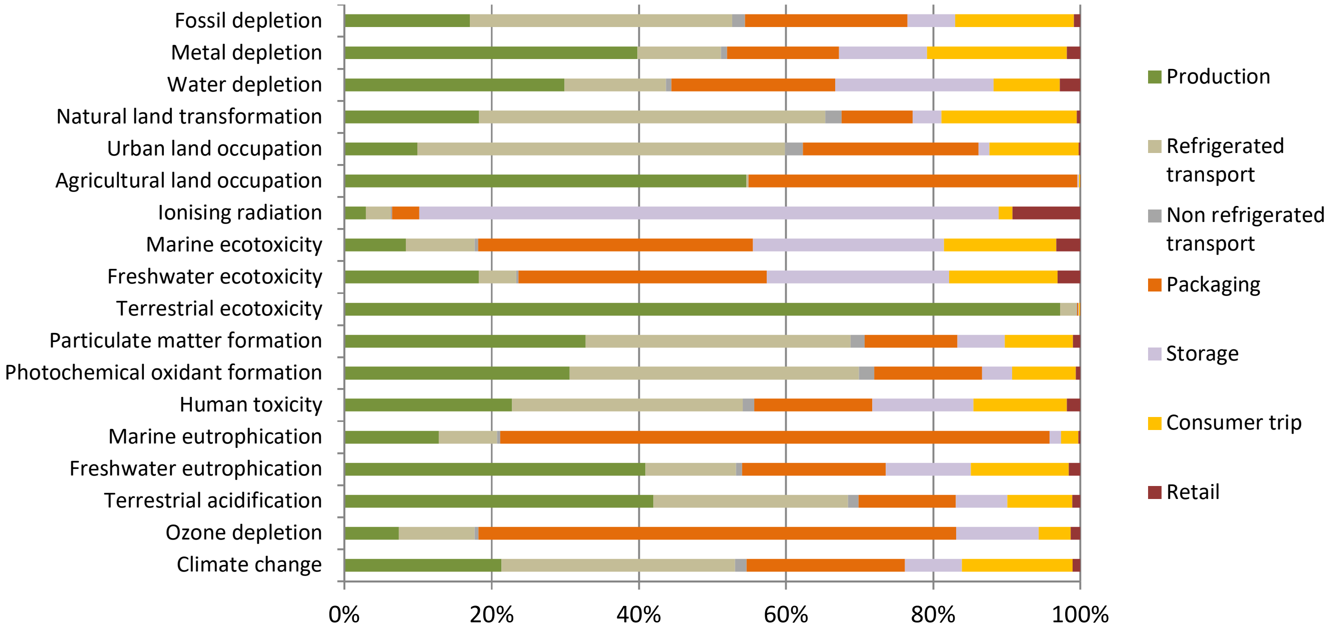

Figure 5 Contribution analysis for the reference scenario (L2-P2) using the ReCiPe midpoint (H) LCIA method.

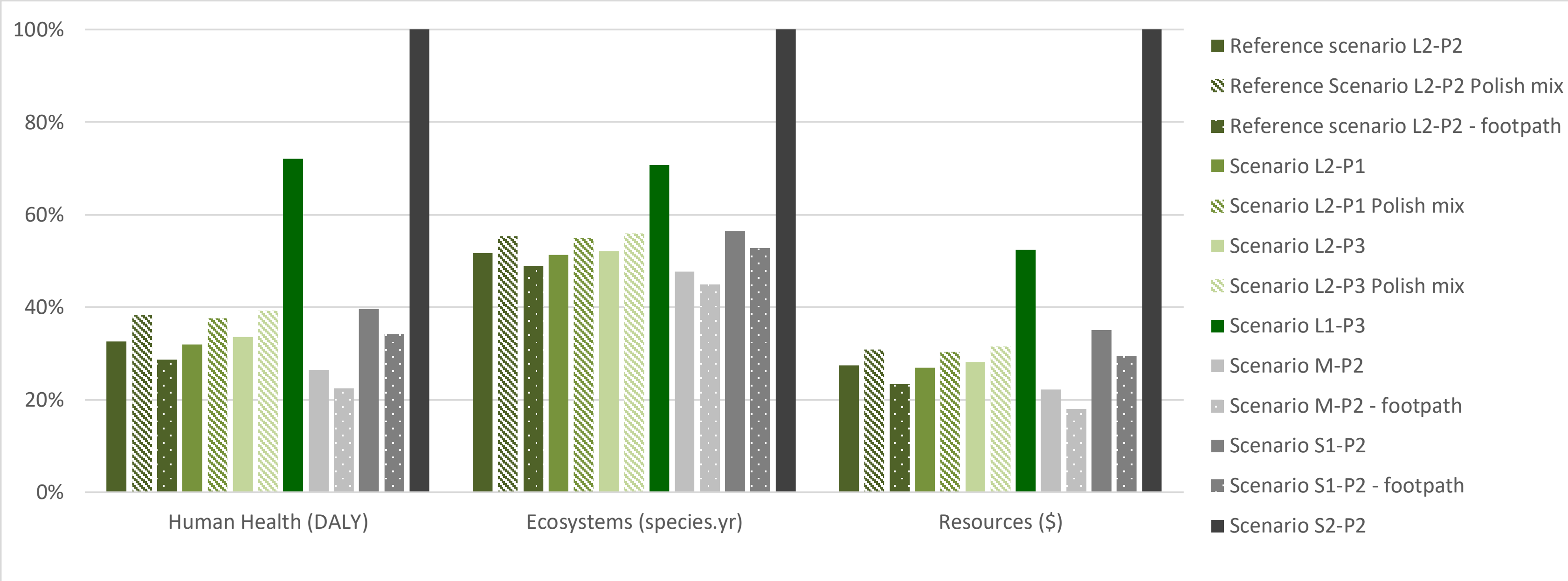

Figure 6 Comparison of the environmental impacts of the national apple supply chain (reference scenario L2-P2) with other types of supply chain, from international (L1-P3) to medium (M2-P2) and short (S1-P2 and S2-P2), including seasonal effect (L2-Px) and consumer transport mode effect (x2-x2 foodpath), using the ReCiPe endpoint (H) LCIA method.

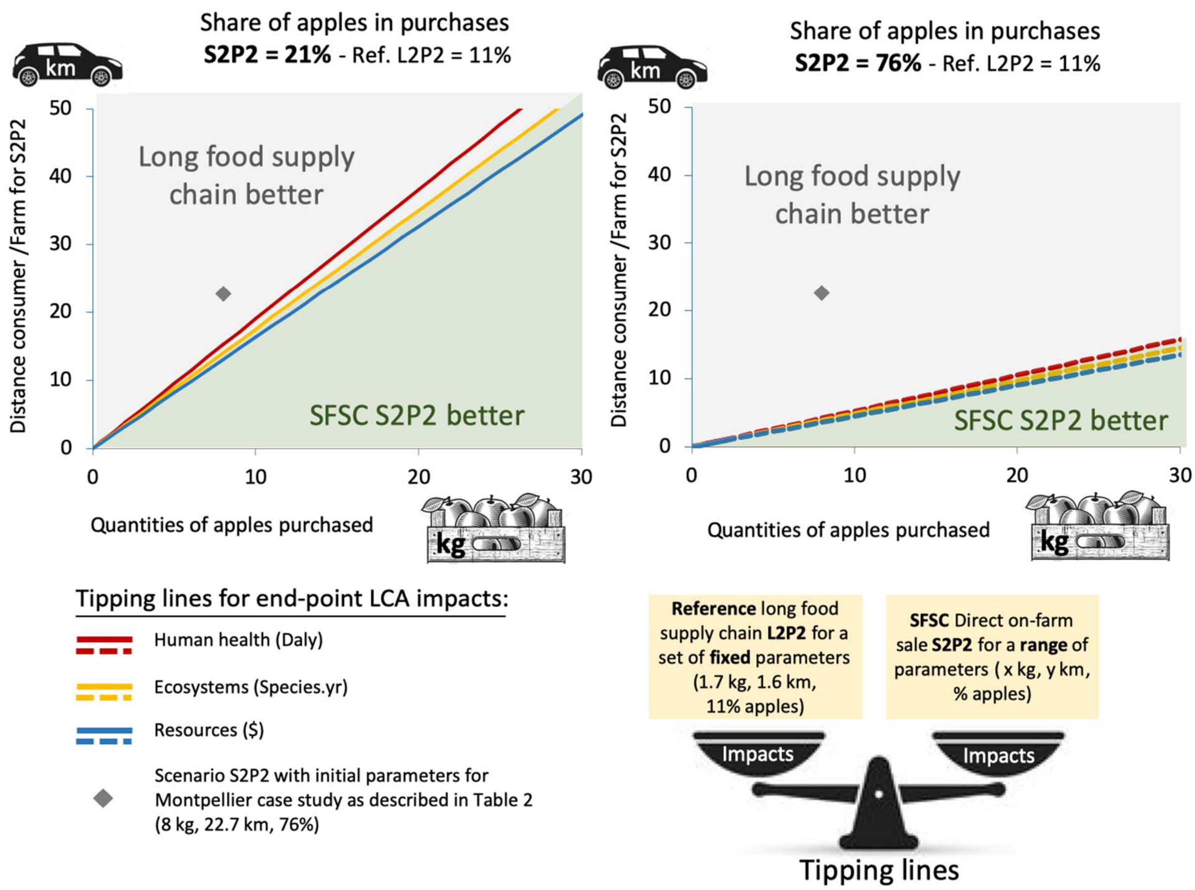

Figure 7 Search for tipping lines where the direct on-farm sale performs better than the reference scenario due to optimal distance between consumer and point of sale, and quantities of apples purchased for two different apple shares in the final basket (21 and 76%).

To what extent are Short Food Supply Chains (SFSCs) environmentally friendly? *Application to French apple distribution using Life Cycle Assessment*

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GRAPHICAL ABSTRACT