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2 **To what extent are Short Food Supply Chains (SFSCs) environmentally** 3 **friendly? Application to French apple distribution using Life Cycle Assessment**

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11 **Abstract**

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

36 **Keywords**

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

38 **Highlights**

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

44 1. Introduction

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

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

67 However, aside from the discussion on the country of origin of the product, it is necessary to consider the
68 environmental performance of different subnational supply chains, such as buying apples directly at the
69 farm or outdoor markets rather than the supermarket (Goossens et al., 2019). Cerutti et al. (2011) and
70 Jones (2002) assessed different retailing scenarios (i.e. direct selling, or grocery store) and concluded on
71 the importance of retailing strategies for the environmental sustainability of food systems. They showed
72 that localization is a direct approach reducing or avoiding the negative environmental impacts of
73 international transportation, distribution and car use. However, Van Hauwermeiren et al. (2007)
74 highlighted that distribution modes can affect the performance of these supply chains rather than the
75 distances travelled. Coley et al. (2009) concluded that purchasing the most geographically local produce
76 per se does not necessarily mean the lowest environmental impact. In addition, Mundler and Rumpus
77 (2012) showed that there is an important potential for logistical optimization in local food chains. Finally,
78 Milà i Canals et al. (2007) stressed that it is difficult to make general recommendations because of the
79 variability in data and characteristics of these different food supply chains. For instance, the average
80 distance travelled in French SFSCs is 70 km, with a standard deviation of 109 km (Vaillant et al., 2017).
81 Consequently, the great diversity of SFSCs does not allow for generalization on their environmental
82 impact or conclusions as to whether they are better or worse than other forms of distribution (Ademe,
83 2012).

84 That is why, ultimately, for individual or collective decision making, the main issue is not to decide
85 definitively if one kind of supply chain performs better than another one, but rather to establish the extent
86 to which, and the conditions under which, one supply chain can be more environmentally efficient than
87 another one. To explore this issue, this paper: i) defines the different archetypes of supply chain that can
88 be used to provide apples to final consumers, ranging from international ones to local ones; ii) computes
89 average data to model these archetypes from a life cycle perspective; iii) assess their environmental
90 impacts through LCA to identify hotspots; and iv) discusses how one type of supply chain can be more
91 efficient than another one, by varying the values of the main hotspot drivers. Apples are used as a case
92 study to discuss the method and results for all fresh products such as fruits and vegetables where no

93 processing is required. A particular focus will be placed on SFSCs. Although there is a growing societal
94 demand for SFSCs as a driver of change in the food system and a policy tool for rural development,
95 SFSCs are still rarely investigated through full LCA studies. This paper is organized as follows: Section 2
96 describes the overall methodology applied according to the four LCA stages described in ISO standards
97 (ISOa, 2006; ISOb, 2006) with a particular emphasis on the goal and scope definition, and the data
98 collection stages; Section 3 presents, interprets and discusses the main results; and Section 4 outlines key
99 research findings and follow-up research that could be conducted to improve sustainability assessment of
100 food supply chains.

101 **2. Material and method**

102 **2.1. Goal and scope definition**

103 *2.1.1 Aim of the study and functional unit definition*

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

122 *2.1.2 Definition of Short Food Supply Chains (SFSCs) and other supply chains*

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

130 **Figure 1**

131 *2.1.3 Apple supply chain archetypes*

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

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

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

149 **Figure 2**

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

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

160 *2.1.4 Seasonality of apple supply*

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

170 *2.1.5 Analytical design of scenario comparison*

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

175 **Figure 3**

176 The first point that will be tested is the comparison between different supply chains that are located
177 entirely within France (i.e. comparison A in Figure 3), to analyze environmental performances of long and
178 short supply chains. The second comparison will focus on the season effect to assess the storage effect on
179 the overall performance of the reference scenario (i.e. comparison B in Figure 3). As the French electricity
180 mix is particular (mainly composed of nuclear energy), the effect of the electricity mix will also be
181 analyzed. The third comparison will assess the importation effect to analyze the trade-off between long

182 distance transportation versus long storage periods (i.e. comparison C in Figure 3). Finally, the last
183 comparison will assess the effect of consumer transportation mode to discuss the impacts of the final km
184 (i.e. comparison D in Figure 3).

185 **2.2. Life cycle inventory analysis**

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

193 *2.2.1 LCIs of unit processes included in apple supply chains*

194 These unit processes cover all life cycle stages, from apple production to purchase by the final consumer,
195 including transportation according to the types of vehicles that can be used, infrastructure for different
196 types of building and equipment, materials (e.g. types of packaging), cooling and conservation systems,
197 and electricity consumption of the different equipment used in the supply chains. Except for apple
198 production, the LCI data used for these unit processes come from the ecoinvent database v3.2 (ecoinvent,
199 2015). When there were no processes directly usable in the ecoinvent database, processes were created by
200 assembling existing ecoinvent LCI components as for the cold room. This assembly was done using data
201 from the literature and the stakeholders' expertise (e.g. electricity consumption of a cold room to store one
202 kg of apples for one day). All the detailed information regarding the LCI dataset of unit processes
203 included in apple supply chains is provided in the appendices (see Appendix A). For the orchard step, an
204 in-field dataset from an experimental orchard representative of French fruit grower practices was used
205 with an average yield of 37.8 tons per year of commercialized fresh apples (national source Agreste 2015-
206 2016). The dataset covers a 9-year period (Alaphilippe et al., 2016) in order to account for the climatic
207 condition variability and thus to ensure both accuracy and representativeness.. The production system is
208 conventional with applications of mineral N-fertilization (47 kg/ha/year) and pesticides (29 kg/ha/year
209 active ingredients). LCA data for the orchard step was considered the same for all supply chain scenarios
210 that occur in France or in Chili.

211 *2.2.2 Full LCIs of apple supply chains*

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

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

223 Another common data between the supply chains concerns apple sorting and losses at each stage.
224 Estimates were given after discussions with experts in the apple sector and the CTIFL (referent
225 organization for applied research in the French fruit and vegetable sector). Apple sorting and losses during
226 calibration are around 20%, those during storage (including water loss of the fruit, varying from 0.5 to 2%
227 depending on storage time) and packaging are around 4%, and those in retail stores are around 5%. These

228 are only orders of magnitude and deserve to be refined through field surveys. Yet these figures are close to
229 those estimated in the recent study of Caldeira et al. (2019) on food losses and waste in Europe (i.e. for
230 fruit, waste is around 16% in primary production, 9% in the processing stage, and 1% in the retail stage).
231 It is assumed that a part of the apple sorting and losses is not wasted and is used for processing into juice,
232 puree and compote.

233 **Table 1**

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

246 **Figure 4**

247 The same method has been used to calculate the road distance from producer organizations to the RDC
248 that corresponds to logistics warehouses in the case of hypermarket sales or to the market of national
249 interest in other sales networks. The road distances between each producer organization and the RDC
250 were computed and the average of these distances was weighted by the production surface areas of the
251 producer organizations. The latter is the sum of the apple production surface areas of every municipality
252 for which this producer organization is the nearest to their centroid. This approach has been used to
253 determine road distances for M, S1 and S2 alternatives, although the apple supply pool has been reduced
254 within 200 km for M, 50 km for S1 and 25 km for S2 (see Figure 4). With this method, average transport
255 distances for all the different supply chains were computed (see Appendix C to get the Python code). In
256 order to give more importance to the high apple growing regions, the distances can be weighted by apple
257 production surface areas in the municipality. However, this gives little variation in the results (see italics
258 in Table 1).

259 For transport distances and the logistics in Chile concerning imported apples, literature data were used
260 (Labouze et al., 2007). Distances between the consumer's home and the point of sale are derived based on
261 the assumption that the household lives downtown and that shops are nearby. Finally, information on the
262 types of vehicles used according to the different trips is provided (see Appendix D for the corresponding
263 table of vehicles). It is assumed that long supply chains have optimized their logistics and use larger
264 vehicles. To model consumer practices while purchasing apples, literature data were used. According to
265 Rizet et al. (2008), share of apples in the total basket and the average weight of apples purchased were
266 estimated for different archetypes of supply chains.

267 **2.3. Impacts assessment**

268 The impact assessment method chosen is the hierarchist approach of ReCiPe v1.11 (Goedkoop et al.,
269 2009). The impact categories are characterized at both the midpoint (18 categories of impacts: climate
270 change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human
271 toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater
272 ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation,
273 natural land transformation, water depletion, mineral depletion, and fossil depletion) and the endpoint
274 level (3 categories of damages, i.e., human health, ecosystems and resources). Because ReCiPe combines

275 midpoint and endpoint methods, the impact characterization at the endpoint level specifies the damage
276 contribution of each midpoint impact category, which is very helpful for result interpretation. In addition,
277 calculations are made with SimaPro v8.2.

278 **3. Results and discussion**

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

284 **3.1. Detailed contribution analysis for the reference scenario (L2-P2)**

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

288 **Figure 5**

289 Apple production has significant impacts (above 40%) on acidification, freshwater eutrophication,
290 terrestrial ecotoxicity, agricultural land occupation and metal depletion, due to inputs such as fertilizers
291 and pesticides. These inputs are correlated to orchards yields. Refrigerated transportation contributes
292 substantially to climate change, fossil depletion, particulate matter formation, photochemical oxidant
293 formation and impacts on natural, and urban lands due to fuel combustion and infrastructure. Packaging
294 contributes significantly to marine eutrophication, ozone depletion, marine and freshwater ecotoxicity and
295 agricultural land occupation generated by the primary products (i.e. cardboard box) and the processing
296 stage. Cold storage contributes significantly to impacts induced by ionizing radiation due to electricity
297 consumption but not so much to other impact categories. This is due to the particularity of the French
298 nuclear electricity mix and therefore results are not representative of other countries. Finally, consumer
299 trip for apple purchases is significant for almost all impact categories despite the low distance estimated
300 between the consumer's house and the hypermarket in the supply chains studied (see Table 1). These
301 results are in line with those of previous studies. For instance, the cultivation stage contributes little to the
302 impacts on climate change (around 15% in Goossens et al. (2018)) or the use of fossil resources (less than
303 20% as in Longo et al. (2017)).

304 **3.2. Comparison between different types of supply chains**

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

316 **Figure 6**

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

336 **3.3. Tipping lines for decision making in highly variable contexts**

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

347 **Figure 7**

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

355 **3.4. Data consistency and comparison with other studies**

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

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

375 **Table 2**

376 Finally, data on the final kilometers are also important because they have a significant impact on the
377 environmental performance of the whole supply chain. On this point too, data found in the literature are
378 disparate (see Table 3).

379 In the proposed approach, average transport distances were computed using Python programming software
380 and the open source route planner called Openrouteservice (2019) combined with ponderation of distances
381 by the surface areas of apple orchards. This strategy seems more relevant (regarding in particular data
382 heterogeneity) than combining national/global statistical data with local small sampling surveys on local
383 practices. The big-data outlook should, in the near future, allow this type of approach to be further
384 consolidated to provide more representative data.

385 **Table 3**

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

388 **3.5. Importance of the Functional Unit (FU)**

389 The choice of the functional unit (FU) can largely determine the results obtained (Huijbregts, 1998). This
390 is the general case in agricultural LCAs where, depending on the FU selected, the results of the study may
391 modify the LCA results and the order of the alternatives studied, according to their environmental
392 performance (Baumgartner et al., 2011; Haas et al., 2000). The choice of the FU is essential when
393 assessing food supply chains because, as for agriculture, these systems can be multifunctional. The growth
394 of SFSCs can be explained for various reasons and meets a wide range of needs corresponding to various
395 FUs, depending on whether the perspective is that of producers, consumers or citizens (Fabbrizzi et al.,
396 2014). The emergence of SFSCs can contribute to a better redistribution of the added value, the promotion
397 of social and professional recognition of farmers, or the development of new skills from a producer's
398 perspective (Mundler and Laughrea, 2016). Consumers can choose to rely on SFSCs to access better
399 quality products that are fresher, more authentic or more reliable in terms of traceability (Giampietri et al.,
400 2015). In addition, SFSCs can be a driver of local development through job creation, or the creation of
401 new farms and of the welfare of the community (Mundler and Laughrea, 2016). Ultimately, SFSCs can
402 provide a wide range of services and several FUs can be chosen. However, all LCA studies use the kg of
403 apples provided to the retailer or the final consumer as the FU. Other FUs such as the euros that go back to
404 farmers, the number of jobs created or the nutritional quality of the final products could be tested to assess
405 the robustness of the conclusions that can be drawn (Poore and Nemecek, 2018).

406 This point is related to the modelling of the final consumer's trip, which has a major impact on the total
407 performance of the supply chains studied. However, consumers may have several reasons for shifting to

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

419 **3.6. Other modelling choices**

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

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

452 **4. Conclusions and future prospects**

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

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

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

490 Furthermore, the study focused on the supply of one kg of apples to the final consumer. This functional
491 unit may be restrictive. Food supply chains are multifunctional systems and provide a wide range of
492 services that should be identified and quantified to consider them in LCA studies and move away from the
493 strictly productivist rationale. Moreover, this choice implies modelling the system on a micro scale. Yet
494 the supply of cities can also be studied at meso scales, through the use of territorial LCA approaches
495 (Loiseau et al., 2018). In this context, an attributional approach such as the one adopted in this study is not
496 necessarily appropriate. The choice of one supply chain over another can generate indirect socio-economic
497 effects that should be considered in the assessment according to a consequential approach (EC-JRC,
498 2010). Therefore, adopting modelling approaches focusing on large-scale systems and considering the

499 socio-economic consequences of a decision would provide a more comprehensive view on the issue of
500 urban food supply.

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

518 **List of tables and figures**

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

522 **Table 2** Review of the wide range of transportation data used in other apple studies, n/a = not available,
523 ((l) = local distribution, (r) = regional distribution, (n) = national distribution, (i) = international) ((o) =
524 organic production, (c) = conventional production), UK = United Kingdom, NZ = New Zealand, BE =
525 Belgium, GWP = Global Warming Potential.

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

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

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

539 **Figure 3** Summary of the main comparisons performed in the study to assess in an exhaustive way the
540 environmental impacts of food supply chains, from international supply chains to direct selling (In
541 parenthesis, storage duration in cold rooms).

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

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

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

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

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561 **Appendices**

562 Appendices include: all the detailed information regarding the LCI dataset for all unit processes included
563 in supply chain scenarios (A); the amounts of the unit processes used to model full LCIs of apple supply
564 chains (B); the Python code used to compute average road distances between apple supply chain scenarios
565 (C); and the corresponding table of vehicles used in the different supply chain scenarios described in
566 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%
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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		20		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 (l) 80 (n)	30 (r) 344 (n,o) 1530 + 100 (i,o) 570+155 (n,c) 1750 +180 (i,c)	560 (c) 850 (o)	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	
<i>Details of the study</i>													
Country of purchase or production	UK (purchase)	Germany (purchase)	EU (purchase)	France (purchase)	Italy (purchase)	UK (purchase)	Canada (production)	Spain (purchase)	Italy (production)	China (production)	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 indicators	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

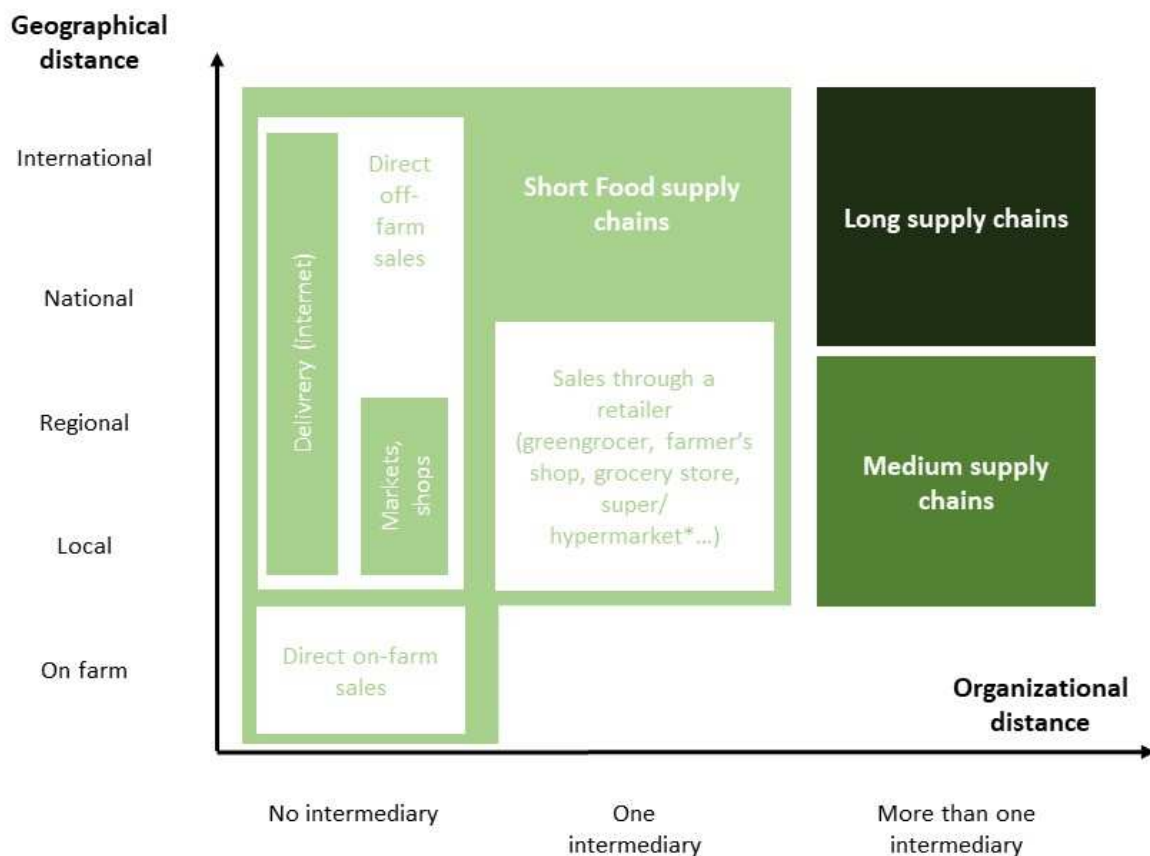


Figure 1 Proposals for food supply chain classification according to Chiffolleau (2008) and Malak-Rawlikowska et al. (2019) (*supermarkets and hypermarkets are now offering some products directly from the producer).

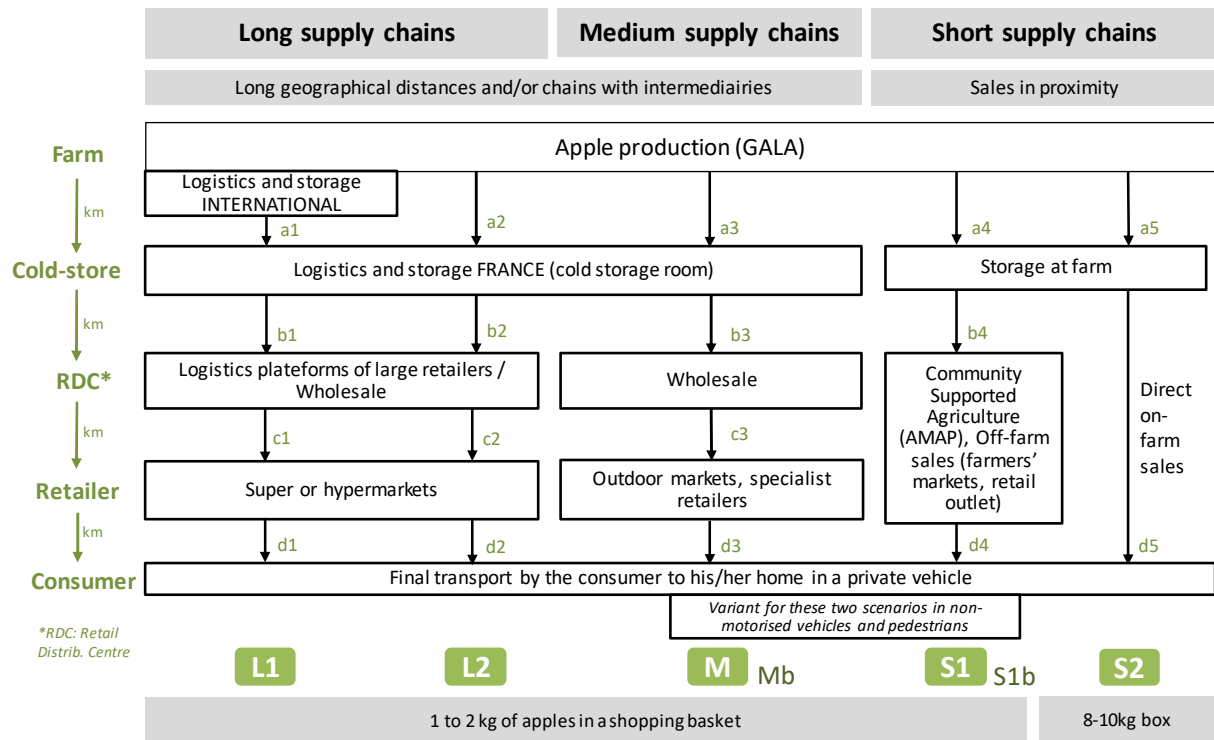


Figure 2 Description of different apple supply chains, from international long supply chain (L1), to direct on-farm sales (S2), through a wide range of combinations including national long supply chains (L2), medium supply chains with intermediaries (M) and direct off-farm sales (S1). Two variants are 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. <i>short storage duration</i>	*	L2-P1 ^B (2 months)	M-P1 (2 months)	S1-P1 (2 months)	S2-P1 (2 months)
	P2 – Dec. to Feb./march <i>medium storage duration</i>		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 <i>long storage duration</i>	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).

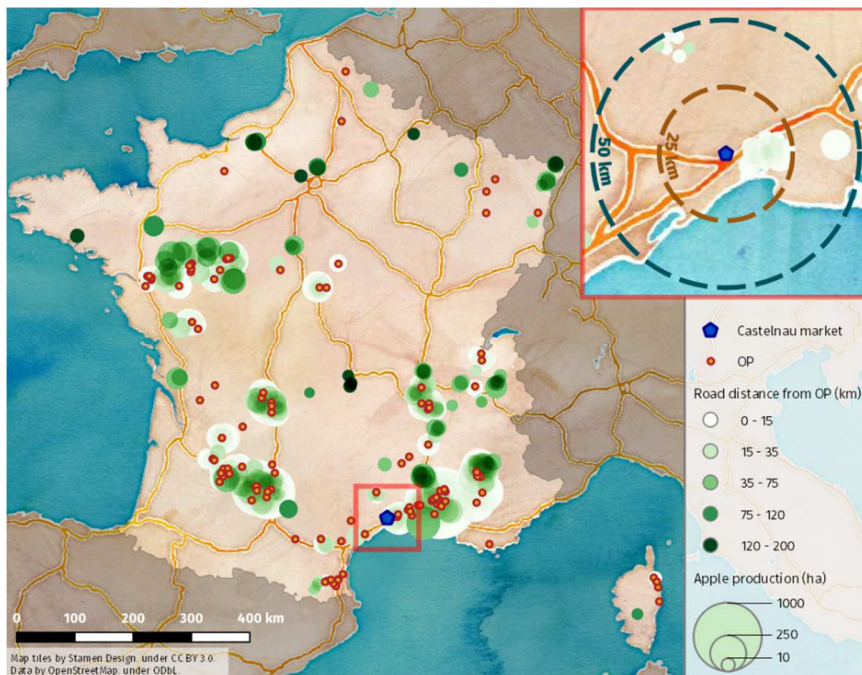


Figure 4 Main apple production areas in France and calculation of average transport distances between intermediaries up to final consumers in the metropolitan area of Montpellier (see zoom). Distances from the different orchard locations are weighted by their respective surface areas.

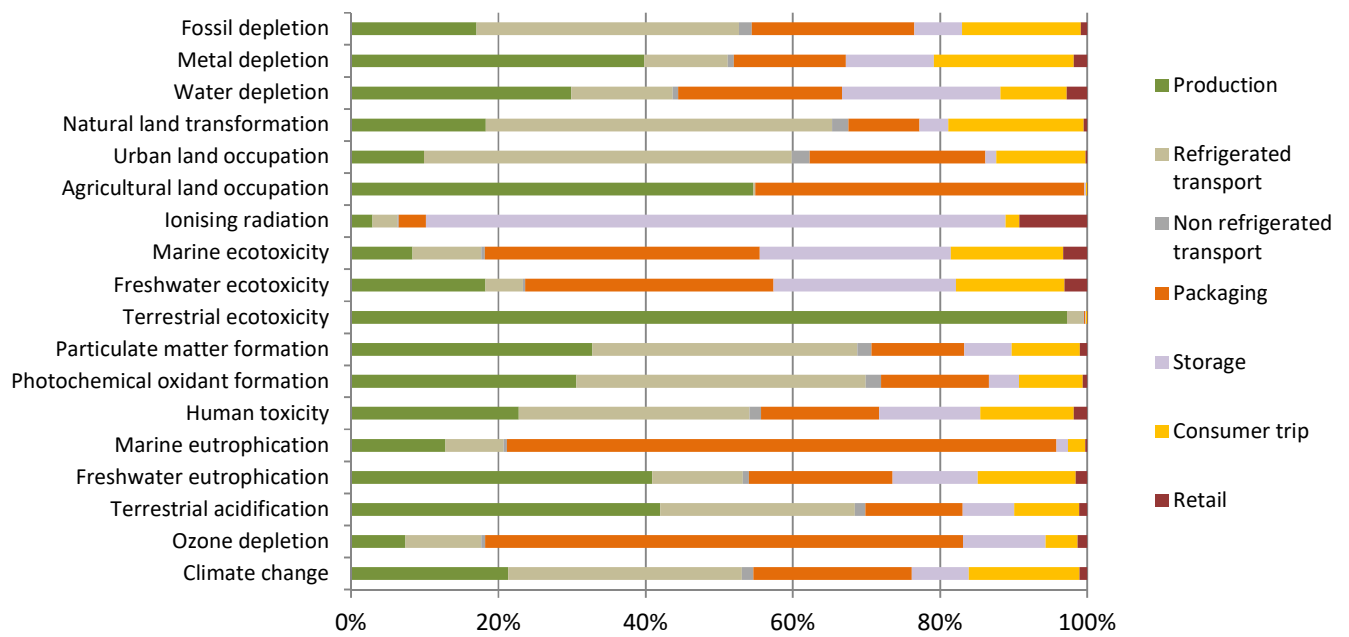


Figure 5 Contribution analysis for the reference scenario (L2-P2) using the ReCiPe midpoint (H) LCIA method.

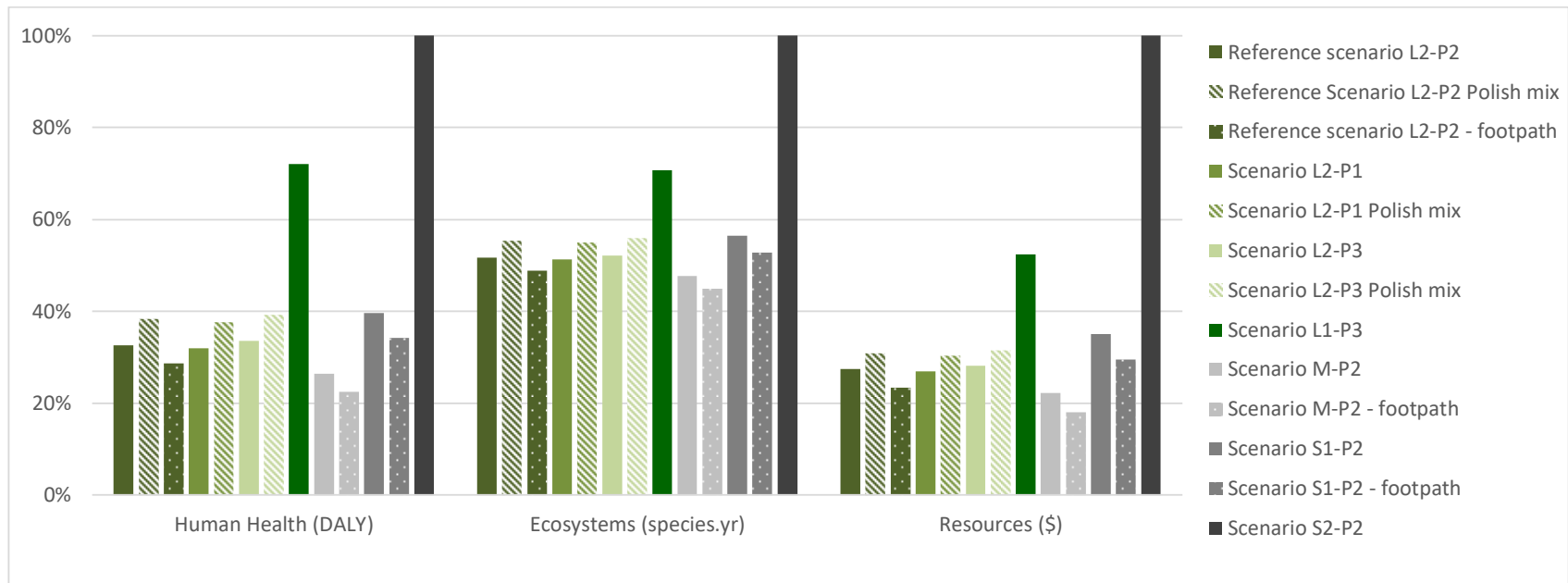


Figure 6 Comparison of the environmental impacts of the national apple supply chain (reference scenario L2-P2) with other types of supply chain, from international (L1-P3) to medium (M2-P2) and short (S1-P2 and S2-P2), including seasonal effect (L2-Px) and consumer transport mode effect (x2-x2 foodpath),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

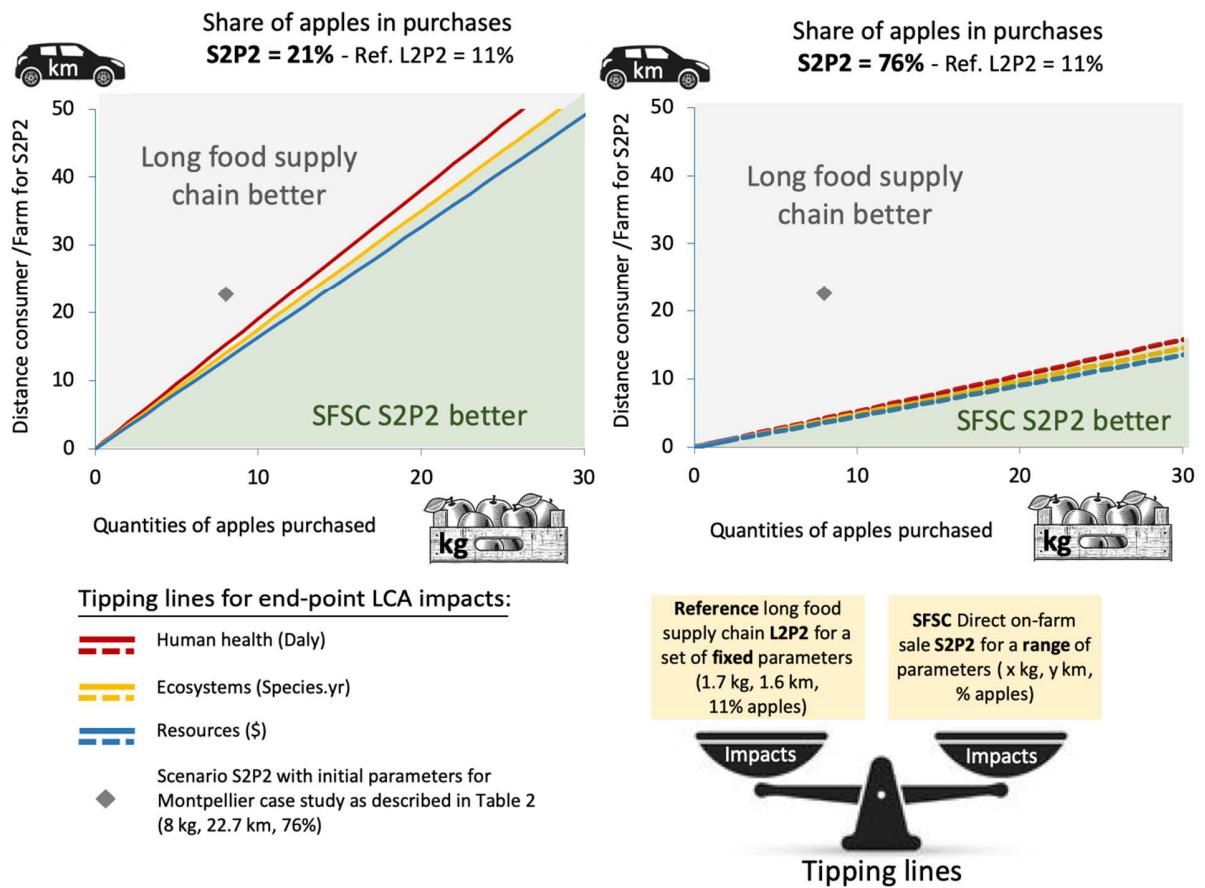


Figure 7 Search for tipping lines where the direct on-farm sale performs better than the reference scenario due to optimal distance between consumer and point of sale, and quantities of apples purchased for two different apple shares in the final basket (21 and 76%).

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

