A detailed quantitative comparison of the life cycle assessment of bottled wines using an original harmonization procedure

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Highlights:

- A quantitative review of 10 LCA case studies of bottled wine has been conducted
- An original harmonization procedure has been proposed to compare the results of the studies
- The procedure harmonizes the goal and scope, life cycle inventories and impact assessment method
- The LCI elements and the impact driving the results have been identified
- Based on these findings, recommendations can be made to simplify the LCA of bottled wine

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Abstract:

The wine industry is facing two major environmental challenges: consumers are increasingly aware of the impacts of wine making, and production is jeopardized by environmental changes such as global warming. Therefore, there is a growing need to measure and minimize the environmental footprint of the sector.

Life cycle assessment has already proven its worth in evaluating the environmental impacts and hotspots of bottled wine production. However, the methodological discrepancies in the LCA conducted do not allow conclusions regarding the most sustainable production systems or the most significant impacts for the sector. Moreover, LCA application in the field remains scarce due to the complexity of the method and the lack of readability of its results. In this study, 10 LCA papers corresponding to 17 different products were reviewed. Methodological discrepancies have been reduced through harmonization of the functional unit, the life cycle inventory and the life cycle impact assessment method, enabling provision of a range of results for different impact categories, as well as comparisons between different wines. The LCI elements that drive the results have been identified. This can be useful to simplify the data collection and the comparability of the products in this sector. Impact clusters (indicators that follow the same behaviour and are driven by the same LCI elements) have been proposed. Three clusters of impacts ((i) climate change, fossil depletion and particulate matter formation; (ii) terrestrial ecotoxicity; (iii) agricultural land occupation) are responsible for more than 90% of the single score. Nonetheless, the proposed harmonization procedure has limitations, and no conclusion can be made on the most sustainable products due to the remaining discrepancies in the system boundaries.

1. Introduction

The oldest trace of wine making is estimated to have occurred approximately 8000 years ago (6000 years BC) in Georgia (McGovern, 2003). Since that time, wine has been produced worldwide and constitutes an industry with significance in economic terms, playing an important cultural and traditional role. In 2017, the International Organization of Vine and Wine (OIV) reported a global consumption of 243 million hectolitres, which represents a slight increase, following a positive trend that can be witnessed since the 2008/2009 economic crisis (OIV, 2017). Moreover, production has undergone a decrease by 8.6% in 2017 compared with 2016, mainly due to the difficult climatic conditions in Western Europe. The decrease is representative of the dependence of the sector on its natural environment and current environmental pressures. Wine producers are confronted with different challenges and pressures: on the one hand, vine growing is very sensitive to climate; therefore, producers have to develop strategies to ensure their annual production and adapt to future climate evolution. On the other hand, interest regarding the environmental profile of a product is growing among local communities and consumers, notably with the issue of pesticide use and the contribution of agricultural activities to climate change, holding producers accountable for the environmental performance of their product. In this context, it becomes crucial for producers to monitor and reduce the environmental burdens related to the production of a bottle of wine to ensure the sustainability of their activities.

From the perspective of environmental sustainability, life cycle assessment (LCA), as a methodology to evaluate the environmental performance of a production system, has proven to be a relevant and powerful tool. LCA studies of wine have successfully accounted for the environmental impact of different life cycle stages of wine production, highlighting the contribution of different inputs considering multiple impact categories and providing useful feedbacks to decision makers to reduce their impacts. Most of these studies remain within the field of academia, and deployment of the LCA approach in industry to assess, reduce and communicate the environmental impact remains scarce. The wine sector mainly consists of small enterprises with limited resources. According to France Agrimer, 87400 farms were referenced in 2010 only in France (FranceAgriMer, 2016), representing an important impediment to the development of the application of LCA. To overcome this issue and facilitate implementation of the method, LCA for the wine sector should be harmonized into an assessment tool. The harmonization should include inventory generation, the developed hypothesis, the impact assessment method used, and the indicators chosen for communication purposes to enable comparison and understanding of the results. This harmonization is a first step towards standardization. Standardization implies a normative organization imposing a framework to conduct LCA, which is the case for the construction sector in France, for which life cycle assessment of a building is standardized (NF EN 15978 – Afnor). Based on this standard, the Scientific and Technical Centre for Building has developed a specific tool (ELODIE) to evaluate the environmental performance of a building, which uses datasets that are shared and produced by the construction materials industries gathered for a single database: INIES.

Regarding wine production, the sector was part of the French 2012 “environmental labelling” programme, which aimed at proposing a standardized method to evaluate the environmental impact using LCA for several consumer goods and propose a communication standard for the results. However, the experimentation did not lead to the same results as the building sector since the programme has been stopped. More recently, the European commission has published the Product Environmental Footprint Category Rules for still and sparkling wine (CEEV, 2018 - referenced as PEF later in the paper). This document, co-constructed by stakeholders from the industry, public bodies and academia, provides guidelines and recommendations for conducting an LCA in the wine sector.

Two critical reviews focusing on LCA applied to wine have been published with different objectives. The first one, written by Rugani et al., (2013), reviews 35 studies and focuses on one single criteria, the carbon footprint (CF). Their objective is to assess the advantages and drawbacks of CF for assessing the environmental performance of wine production and its relevance as a single indicator for efficient dissemination and communication of the environmental profile of a bottle. Notably, the study provides a mean value the range of carbon emissions for the production of a wine bottle, with contributions from the different life cycle stages. It also highlights the heterogeneity of the boundaries of the systems studied, in the assumptions for data collection and in the choice of emission factors, thus facilitating the need for standardization of the carbon footprint assessment to allow comparability and communication of the indicators to the consumers and decision makers. While the review provides relevant insights of the LCAs conducted in the wine sector, the use of a unique criterion (carbon footprint) is debatable. It appears that other environmental issues are more significant in the mind of consumers, e.g., the issue of pesticide use in the region of Bordeaux, where media and civil society have vehemently criticized the sector for the toxicity caused by the phytosanitary products, or the issue of water use in South Africa, where water constraints are high and where 85% of the vineyards are irrigated (Briers-louw, 2016).

The second review (Ferrara and De Feo, 2018) compares and discusses the results of 34 studies, pointing out the main environmental hotspots of bottle production. This study includes an analysis of multiple environmental impact categories, namely, climate change, abiotic depletion, acidification potential and eutrophication potential, while also highlighting the contribution of each life cycle stage of the production system.

The two reviews provide valuable analyses of the state of the art of LCA research in the wine industry. Despite comparisons between the studies, the authors both point out the variability of the results of LCAs conducted in the field, at several levels: LCA-based differences (in system boundaries, in the method used to collect the foreground data inventory, in the background source of data used, in the impact assessment method chosen and in the indicators analysed), variability related to technical practices, also called technical management routes by Renaud-Gentié et al. (2014) (e.g., conventional vs organic wine) and geographical variability.

Building on these reviews and their conclusions, this paper aims extending the analysis of existing studies in the wine sector. An innovative approach is proposed to compare the results of the LCA of wine studies by harmonizing their life cycle inventories, background data and impact assessment methods. We do not aim to redo the work of the PEF category rules for wine, but rather to analyse through the existing literature the methodological and technical sources of variability that can be found in bottled wine LCA results. This approach is similar to that employed by Hsu et al., (2012) and Warner and Heath, (2012), who published approaches for reviewing and harmonizing papers dealing with greenhouse gas (GHG) emissions of photovoltaic electricity and nuclear electricity production, respectively.

The specific objectives of this critical review are multiple:

- To provide a quantitative comparison of the results of the selected case studies based on a harmonization procedure.
- To identify the most contributory life cycle inventory (LCI) elements to the impact in the literature analysed.
- To identify and analyse the sources of variability for each indicator.
- To provide recommendations on the selection of the most significant and relevant indicators for environmental life cycle impact assessment (LCIA) in the wine sector.

2. Materials and method

The materials used for this review are LCA case studies related to wine. The selection of studied papers is described in section 2.1.

The method used to quantitatively compare these papers is a harmonization procedure, as described in sections 2.2, 2.3 and 2.4.

This harmonization procedure aims to decrease and smooth the discrepancies of the different studies related to the LCA methodological considerations, hence enabling comparison of the different production systems and analysis of the source of variability in the results. Variability and uncertainties in LCA have been a research focus in LCA. Huijbregts (1998) proposed the following distinctions: uncertainties can be reduced by additional research and further modelling, while variability corresponds to intrinsic differences related to system studies. Variability therefore covers spatial variability, temporal variability, and source and object-related variability. In agriculture, variability can be important due to the strong dependence of the activity to its local environment. According to Notarnicola et al., (2017), "variability includes different management practices (organic vs conventional for example), soil types and climates, seasonality, the life cycle of perennial crops, and distances (and related transportation modes) between locations of activities in the life cycle of product systems". The proposed harmonization work aims to reduce the LCA-based differences between studies, i.e., in system boundaries, in the foreground and background inventory, in the impact assessment method chosen and in the indicators analysed, therefore harmonizing part of the uncertainties sources to compare the study results and evaluate the sources of variability.

Nonetheless, full harmonization of the studies would require the recollection of data and the use of identical hypothesis for each inventory input of the different studies. Criteria have been chosen to define the outlines of the harmonization. The elements that underwent specific modelling were those identified in LCA studies of wine that contribute significantly to the environmental impact. The remaining data are kept as retrieved.

2.1. Selection of studies

Two steps were required to select the papers reviewed in the study. First, studies were selected among the papers referenced in Rugani et al. (2013) and Ferrara and De Feo, (2018), since their scientific recognition and methods had been scrutinized by the authors. An extended list of papers was obtained with the SCOPUS database, using the following keywords: "Life Cycle Assessment" OR "LCA" OR "Environmental impacts" AND "Wine" OR "Viticulture". Thus, 45 papers related to LCA of wine production were identified. The list is available in Supplementary Information (SI later in the paper - Table S1).

Then, studies providing the foreground life cycle inventory and including, at least in the system boundaries, the steps of viticulture, winemaking and bottling were retained in the review. Thus, the list was reduced to 10 different papers, representing 17 different products. This list of papers is described in Table 1.

Table 1: List of papers selected and reviewed (GW: global warming, OD: ozone depletion, TA: terrestrial acidification, E: eutrophication, FE: freshwater eutrophication, ME: marine eutrophication, IR: ionizing radiation, FET: freshwater ecotoxicity, MET: marine ecotoxicity, TET: terrestrial ecotoxicity, HT: human toxicity, ALO: agricultural land occupation, LC: land competition, AD: abiotic depletion, WD: water depletion: WF: water footprint, PED: primary energy demand, CED: cumulative energy demand, POF: photochemical oxidant formation)

#	Authors	Country	FU & nb of wine studied	Boundaries							Type of exploitation	Year studied	Background data	Foreground data	LCIA method	types of impact
				vine planting	viticulture	vinification	Packaging	Distribution	Use (refrigeration)	end of life (bottle)						
1	(Amienyo et al., 2014)	Australia	0.75 L 1 wine red)		x	x	x	x		x	Conventional	Average year	ecoinvent GaBi CCaLC	On site retrieved data	CML 2001	PED, WD, AD, GW, HT, MET, FET, TET
2	(Benedetto, 2013)	Italy	0.75 L 1 white	x	x	x	x			x	Conventional	2009	GaBi4	On site retrieved data (primary source)	CML 2001	AD, TA, E, GW
3	(Bonamente et al., 2016)	Italy	0.75 L 1 wine red		x	x	x	x		x	Conventional	2012	ecoinvent3,1	On site retrieved data (primary source)	IPCC2013	GWP, WF
4	(Bosco et al., 2011)	Italy	0.75 L 3 Red and 1 white	x		x	x	x		x	Farms & cooperatives (Conventional)	2009	ecoinvent	On site retrieved data (primary source)	CML method 2007	GWP
5	(Meneses et al., 2016)	Spain	0.75 L 1 red	x	x	x	x			x	Conventional (matured)	1998-2005	ecoinvent v3,1	On site retrieved data (primary source)	ReCiPe	GWP, TA, FE, HT, ALO, WD
6	(Neto et al., 2013)	Portugal	0.75 L 1 white		x	x	x	x			Conventional	2009	ecoinvent v2,2	On site retrieved data (primary source)	CML 2001 method	E, LC, OD, TET, FET, MET, HT, AD, AT, POF
7	(Rinaldi et al., 2016)	Italy	0.75 L 1 red and 1 white		x	x	x	x		x	Conventional	2012	ecoinvent	On site retrieved data	IPCC 2013	GWP, WF
8	(Vázquez-Rowe et al., 2012)	Spain	0.75 L 4 white wines		x	x	x				Conventional	2007 to 2010	ecoinvent	On site retrieved data	CML 2 baseline 2000 + USETox	AD, TA, E, GWP, OD, POF, LC, FET

9	(Point et al., 2012)	Canada	0.75 L 1 wine (average of an estate)		x	x	x	x	x	x	conventional	2006	Database not mentioned	Questionnaires + averages from different farm	CML 2 baseline 2000	AD, TA, E, GWP, OD, FET, TET, POF, CED
10	(Fusi et al., 2014)	Italy	0.75 L 1 white wine	x	x	x	x	x		x	Conventional	2012 (considered as average)	ecoinvent	On site retrieved data (primary source)	CML 2000	AD, TA, E, GW, OD, POF

2.2 Goal and scope harmonization

2.2.1 Functional Unit

The studies analyse the environmental impact of the production of a 0.75 L wine bottle. However, the inventory data retrieved from the different studies can be provided using other reference flows, such as the agricultural area for grape growing activities (e.g., one hectare). To compare the environmental impacts of the different studies selected, the first step was to gather inputs for a common reference flow of 1 bottle of 0.75 L of wine.

2.2.2 System boundaries

Each study includes at least the following stages: grape production, wine making and packaging, which is the first selection criterion. These steps constitute the core proficiency of wine estates and are responsible for the most important share of environmental impacts (Ferrari et al., 2017). However, there are discrepancies in the life cycle stages considered, especially in the consideration of end of life of the packaging materials, coproducts and infrastructure elements.

The main difference lies in the consideration of vine planting and the distribution stages in some of the studies. The system boundaries were retained as they are defined in the papers without adding inventory data related to the missing stages (e.g., studies in which no information on distribution is provided).

Consideration of the end of life of materials used in the production of wine varies between studies, from no consideration at all to the inclusion of all packaging materials (glass bottle, paper label, cardboard, cork stopper and metal capsule). Here, only the glass bottle has undergone specific harmonized modelling since it has an important impact on most LCA conducted on wine production (Gazulla et al., 2010.; Pizzigallo et al., 2008). The modelling is described in section 2.2.4. For the other elements, mainly other packaging materials and wastewater, the assumptions of the studies were retained as provided in the papers.

Coproducts from grape production were not considered in all the studies reviewed. Coproducts generated during wine making stage are considered in four out of ten studies with different strategies: Bosco et al. (2011) allocated the burdens through a mass allocation, Meneses and al. (2016) and Vázquez-Rowe et al. (2012) considered no allocation since all by-products and waste from wineries were assumed to be used as fertilizers in a closed loop or to have no economic value, whereas Fusi et al. (2014) devised an allocation on an economic basis. In this last case, the allocation factor for wine was 99.95% (the other 0.05% being grape marc, lees, pomace, stalk and dewatered sludge), which in this case was almost negligible. In the present comparison, 100% of the environmental burdens were allocated to wine.

Consideration of the vineyard and winery infrastructure differed from one paper to another. While vineyard data were available for most of the studies regarding the trellis systems (7 out of 10 studies), the irrigation infrastructure/draining system was not necessarily used and therefore not provided in all the studies (4 out of 10 papers). The construction of farm and winery buildings was never considered. Winery equipment were only considered by Benedetto (2013). Five papers considered the agricultural machineries necessary for the production of grape. The list of infrastructure considerations for each paper is available in SI (Table S2).

Consideration of infrastructures in system boundaries remained similar to the original papers, and no harmonization step was carried out, since (i) it was assumed that they generate a low share of impacts and (ii) many hypotheses would be required to harmonize these LCI elements. We acknowledge that discrepancies in the system boundaries of the studies were thus maintained, which will be considered in the discussion.

Figure 1 summarizes the harmonization procedure for the system boundaries. Each life cycle stage can be split into 3 categories: operations (product and energy used), infrastructure (installations and machineries) and transport related to the purchase of goods and to the distribution. The harmonization procedure focused on the operations-related data since it is available in all the studies and on harmonizing what the other categories would have implied by gathering specific information from each winery of each studied paper.

2.3 Life cycle inventory harmonization

2.3.1 Foreground data inventory

Foreground data consist of data that are directly related to the studied product system. They include direct input & output flows from/to the Technosphere and from/to the Ecosphere.

Input flows from the Technosphere generally relate to the bills of materials (e.g., quantity of fertilizers, pesticides, winery products) bought by the wine maker. This information is generally of good quality since it is derived from financial accounting of the companies and was available in all studies. Therefore, these data were not harmonized but were kept as presented in the papers ("Operation" flows in Figure 1). Output flows to the Technosphere only included the service provided by the product systems under study, i.e., a bottle of wine of 0.75 L. This value has already been harmonized in section 2.2.1.

Input flows from the environment include agricultural land occupation and direct water withdrawal. These values are generally known by wine makers; however, not all LCA studies report agricultural land occupation since they do not consider the impact of land use and transformation. As these data are easily accessible based on the yield of the vineyards and the grape productivity (mass of grape necessary to produce 1 L of wine), this element has been included in all inventories.

Output flows to the environment (emissions) rely on a wide variety of assumptions and models (as shown in Table S3 in SI), which can be explained by different factors: the goal of the study itself and the analysed impacts (some studies only focus on mono criteria such as the carbon footprint, emissions related to pesticide use in those cases are irrelevant), access and quality of the data, and the localization. Therefore, life cycle inventories related to these flows were not comparable between the studies and required to harmonize the following elements: diesel combustion emissions, pesticide emissions and fertilizer emissions, since they usually have a high influence on the results of LCA studies. Diesel combustion, especially related to agricultural machinery usage, is systematically an important contributor to several indicators, while pesticide and fertilizer emissions contribute heavily to toxicity and eutrophication indicators. Furthermore, emissions of pesticides and fertilizers in the environment can be complex to model since they depend on different factors: soil type, climatic conditions and agricultural management practices (Brentrup et al., 2000).

Emissions related to diesel combustion. Emissions related to the combustion of diesel reported in inventory, both for agricultural machineries and road transport, were considered using ecoinvent emission factors retrieved from 'Life Cycle inventories of agricultural Systems'. Table S3 summarizes the emission factors used (in SI).

Emissions related to pesticides. Studies apply different models and assumptions to evaluate the emissions of pesticides into the environment. The issue of pesticide emissions in LCA has been widely studied in the academic field (Rosenbaum et al., 2015). The Glasgow consensus provides recommendations on the construction of the pesticide LCI, on the consideration of the fraction emitted into the environment, and on the life cycle impact assessment method. While application of the recommendations guarantees coherent and representative modelling of the pesticides used in agricultural activities, it requires an important set of data to be applied: specific data related to the field treated (e.g., presence of a buffer zone), specific data on the application (machinery used, climatic conditions when the product is spread, adherence to good agricultural practices, etc.), and specific data on the products (list of active ingredient, formulation, etc.). The amount of field data required is an important limitation for application of the guidelines and can be considered contradictory to the objective of deploying and mainstreaming LCA within the wine sector. Since the studied papers did not provide sufficient data, it was not possible to cope with such recommendations. Therefore, the default approach proposed in the PEF has been applied to model emission: 90% of the applied pesticide is emitted to the agricultural soil compartment, 9% to air and 1% to water (CEEV, 2018).

Another issue is the lack of information on the type of pesticides used. Rinaldi, Bosco, Bonamente, and Amienyo provide only the amount of generic pesticides, with no indication of the typology and active molecules concerned. Based on the European statistics of pesticide consumption in agriculture (Eurostat, 2018), it was assumed that the share of the different categories of pesticides in vine growing was as follows: 52% fungicide, 36% herbicide and

12% insecticide. Scanning of papers that used different types and formulations of pesticide, the following active molecules were considered: Folpet (33%), Tebuconazole (33%), and Cymoxanil (33%) for fungicides, glyphosate (100%) for herbicide, Indoxacarbe (50%) and Flufenoxuron (50%) for insecticide, with an even repartition between the molecules from the same category.

Emissions related to fertilizers. The default approach from the PEF is applied for modelling emissions related to fertilizers. Table S4 (in SI) summarizes the considered elements.

When the nutrient content is not available in the papers, the following assumptions are made: synthetic fertilizer is taken into account with a Nitrate-Phosphate-Potassium (NPK) content of 14-14-14 (corresponding to the nitrate, phosphorus and potassium content of the fertilizer). The nutrient content of manure and compost are retrieved from the ecoinvent 3.4 database (respectively from the processes "nutrient supply from manure, liquid, cattle, GLO" and "nutrient supply from compost, GLO"), as shown in Table S5 (in SI).

Other emissions. As demonstrated by Notarnicola et al. (2003), emissions from biogenic carbon absorption and fermentation are negligible since the amount of CO_2 released into the environment during the fermentation stage is considered to be equivalent to the amount of CO_2 absorbed by the vine during its growth; therefore, it was not been included. Emissions of ethanol during fermentation were considered by Amienyo (2014), Fusi (2014), Point (2012) and Vazquez (2012). For these studies, the amount of ethanol emitted was retained as retrieved. For the other studies, the USEPA (1995) emission factor was used.

2.3.2 Background data selection

The background system supports activities in the foreground system by supplying it with the required goods and services. The background inventory data relate to the indirect input/output flows that occur during these supporting activities (e.g., production of fertilizers, pesticides, energy, etc.). The LCI data related to background processes were harmonized since different databases were used in the selected papers (as shown in Table 2).

The ecoinvent 3.4 database was used for the harmonization procedure since it was considered to be the most recent and comprehensive LCA database available at the time of the review. Taking into account the variety of countries represented in the case studies, the choice of Ecoinvent processes was guided by the following procedure, in order of preference: the country-specific process was chosen if available (this is the case for electricity, for example), and if not the continental process was chosen; for the remainder, the generic process Global (GLO) / Rest of the World (ROW) process was selected. 'Market for' processes were preferred to account for the transport of goods.

An additional challenge relies on the correspondences between the names of foreground input flows found in the literature and background dataset names found in the ecoinvent database, due to the lack of precise information on the material content of the considered input (for example, organic fertilizers have been modelled using the ecoinvent compost dataset). Table S6 in SI summarizes the connections between the inventory data and the ecoinvent datasets. For several elements, specific modelling has been conducted, such as for the glass bottle, bottle capsule, and fertilizers.

The bottling stage, especially glass bottle production, has been often identified as a hotspot of the environmental impact of wine's life cycle (see Gazulla et al., 2010.; Pizzigallo et al., 2008). While trying to adopt a common modelling approach for the consideration of glass bottles in life cycle inventories, the issue of data availability for the recycled content, type of glass used and end of life scenario were encountered. To overcome this issue, the following assumptions were made: a default approach considered that glass bottles were composed of 30% new materials and 70% glass cullet.

Due to the lack of information regarding the material content of the bottle capsule, its consideration required specific modelling. Based on interviews conducted with wine-growing estate managers, the capsules were assumed to be made of polyaminate, which is a combination of aluminium and polyethylene. The mass of each material was retrieved from the specifications of a capsule manufacturer (UnionPack, 2014). The polyaminate capsule process was therefore composed of 68% low density polyethylene and 32% aluminium (including raw aluminium and aluminium working).

Figure 1 summarizes the harmonization process of the LCI.

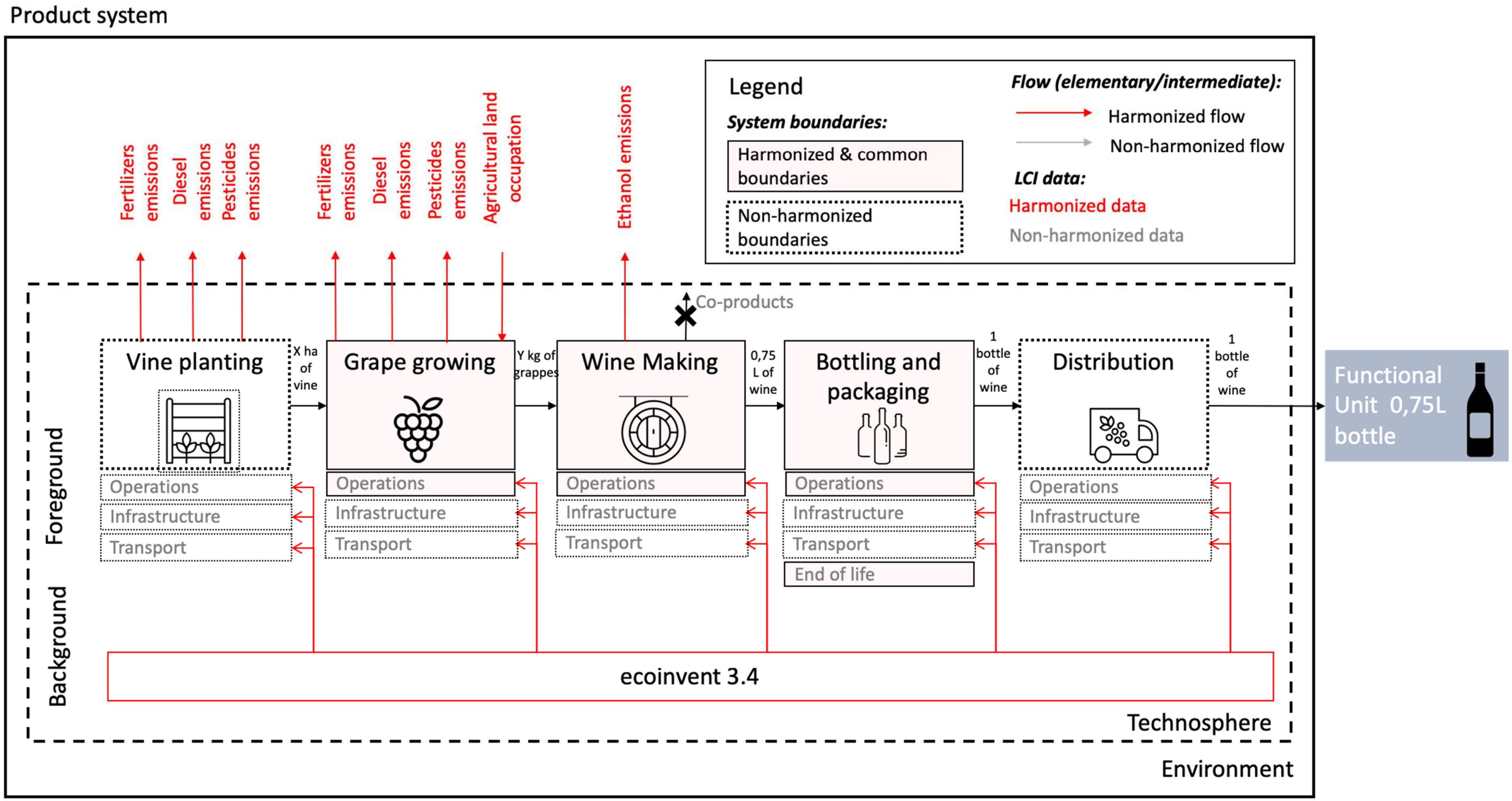

Figure 1. Harmonization procedure

2.4 Life cycle impact assessment method

The procedure described in section 2.2 enabled the construction of the harmonized LCI for the different case studies. The ReCiPe method was chosen as the impact assessment method (Huijbregts et al., 2017a) to convert LCI into LCIA results. ReCiPe is adapted to the European context, while eight out ten studies reviewed were conducted in Europe. Furthermore, ReCiPe enables analysis of the results and their variability at different steps of the effect chain, namely, at the midpoint and endpoint levels. ReCiPe also enables the display of LCA results using a single score indicator, which can be useful for dissemination and communication purposes and which will be considered in this review. Finally, ReCiPe has been developed as the combination and evolution of existing methods, CML for midpoint indicators and EcoIndicator 99 for endpoints. Seven of ten of the reviewed studies used the CML method for impact assessment; thus, using ReCiPe is consistent with the methods employed in the reviewed studies.

3. Results and discussion

3.1 Comparison of results and identification of variability factors at the midpoint level

The first analysis was conducted using ReCiPe midpoint (H) indicators. For clarity, only a limited number of impact categories are presented herein since they were the most screened impacts in past LCA studies. The remaining impact categories (marine ecotoxicity, ionizing radiation, metal depletion, urban land occupation and natural land transformation) are presented in SI.

3.1.1 Climate change

Figure 2 shows the absolute values of the climate change impacts (in kg CO_2 eq) per bottle of wine for the different studies, as well as the contribution analysis related to life cycle steps. The amount of CO_2 eq emissions related to FU was variable depending on the studies (from 0.88 kg CO2 eq to 6.20 kg CO_2 eq). This range of result is in line with the results of Rugani et al., (2013) in a carbon footprint review (2.17 +/- 1.34 kg CO2 eq), with the exception of Bosco et al., (2011) wine 2 demonstrating a high impact due to several factors: the diesel used for the transportation of packaging materials (0.564 kg of diesel per FU), the production and emission of fertilizers and the production of glass bottles.

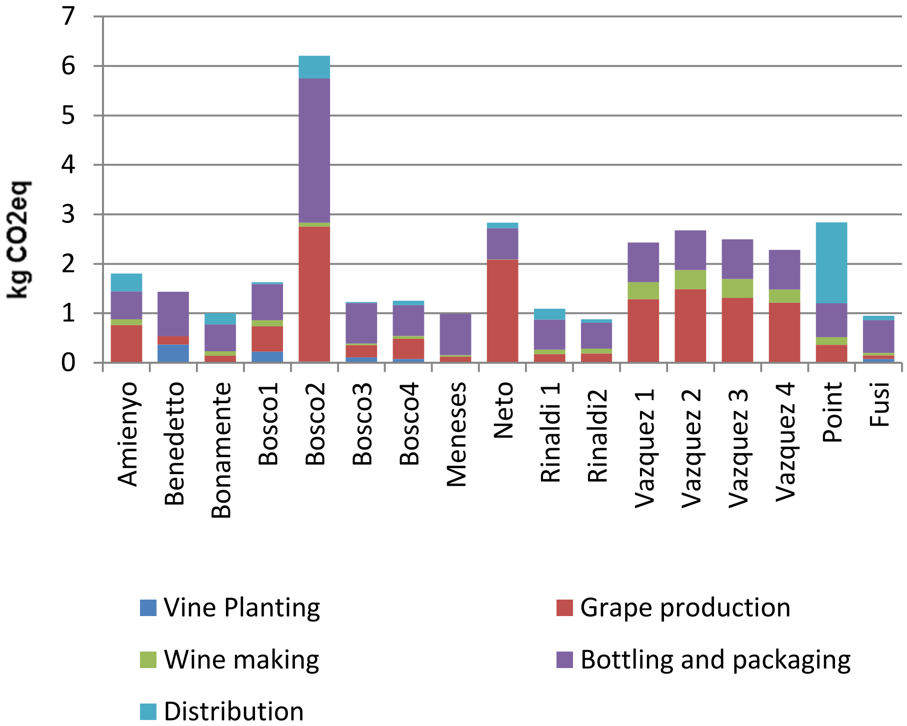

Figure 2. Climate change contribution analysis of each bottle of wine from the reviewed papers

The main contributory stages for climate change were found to be grape production and bottling & packaging, with the exception of the study by Point et al. (2012).

For the grape production stage, the impacts were mainly induced by the manufacture of synthetic fertilizers, pesticides and the emission of diesel used in agricultural machineries. Diesel manufacturing and emissions for field operation contributed from 3% to 42%. The production of fertilizers required the production of nitric acid as an input, which is a source of dinitrogen monoxide emission accounting for 50% of the contributors to climate change among the ‘market for nitrogen fertilizer’ dataset. The manufacture of pesticides requires energy (heat and electricity) and is therefore carbon-intensive.

For the bottling and packaging stage, bottle production and disposal were the highest contributors. The glass bottle contribution ranged between 24% and 70% of the total climate change impact and was mainly caused by the carbon dioxide emitted during production due to energy consumption.

In Point et al. (2012), distribution is the highest contributing phase, due to consideration of the transportation made by the final consumers with a personal car, which represents more than 60% of the climate change impact. Transportation of goods can also be an important contributor to climate change, for example, the transportation of compost represents approximately 30% of the total climate change for the 4 wines studied in Vázquez-Rowe et al. (2012).

Climate change is in general the most scrutinized indicator while assessing environmental impact. The variability of results among the studies is mainly due to the grape production stage and is induced by the synthetic fertilizers and pesticides production, direct N_2O emissions related to their use, combustion of diesel in agricultural machineries and transportation of goods.

3.1.2 Particulate Matter Formation, Photochemical Oxidant Formation, Fossil Depletion and Terrestrial Acidification

The 4 indicators have similar relative contributions as climate change in all studies (as shown in Figure 3 for fossil depletion and Figure S1, S2 and S3 in SI for the 3 other impact categories), because they are all driven by fossil fuels used directly or indirectly during grape production, bottling and distribution. The use of fossil fuels implies the generation of particulates, nitrous oxides and sulphur dioxide (leading to photochemical oxidant formation and acidification) and the depletion of fossil fuels.

Therefore, the sources of variability for these 4 indicators among the studies are similar compared to those found with climate change.

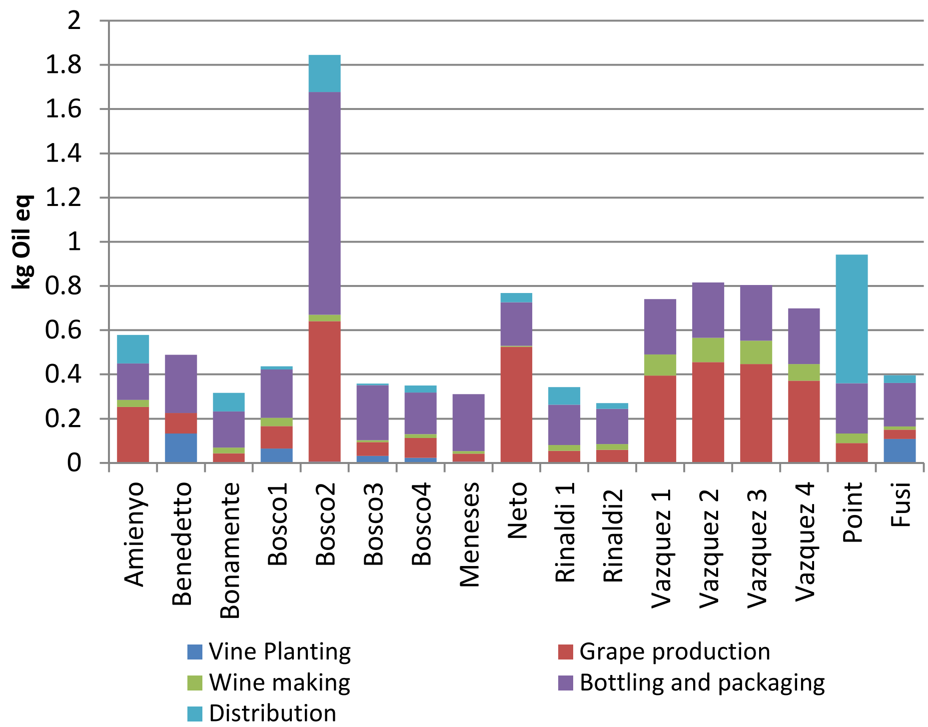

Figure 3. Fossil depletion contribution analysis of each bottle of wine reviewed after the harmonization process

However, specific and minor differences arise for each impact category. The direct emissions of fertilizers include NH_3 and NOx, which are precursor of particulates and induce terrestrial acidification. This was mainly the case in Vázquez-Rowe et al. (2012) and Neto et al., (2013), who used higher amount of fertilizers. Photochemical oxidant formation is driven by the volatile organic compounds and NOx emissions from transportation, direct NOx emissions from fertilizer emissions and ethanol emission during fermentation.

3.1.3 Agricultural land occupation

Agricultural land occupation is mainly driven by the required surface for growing the grapes, ranging from 0.92 to 2.66 m^2.year, as shown in Figure 4. Bottling and packaging generate from 0.2 to 1 m^2.year in all studies, representing the 2nd highest contributor. This generation is driven by wooden products: cardboard, cork, wood for barrel, wood for packaging boxes, wooden posts, etc.

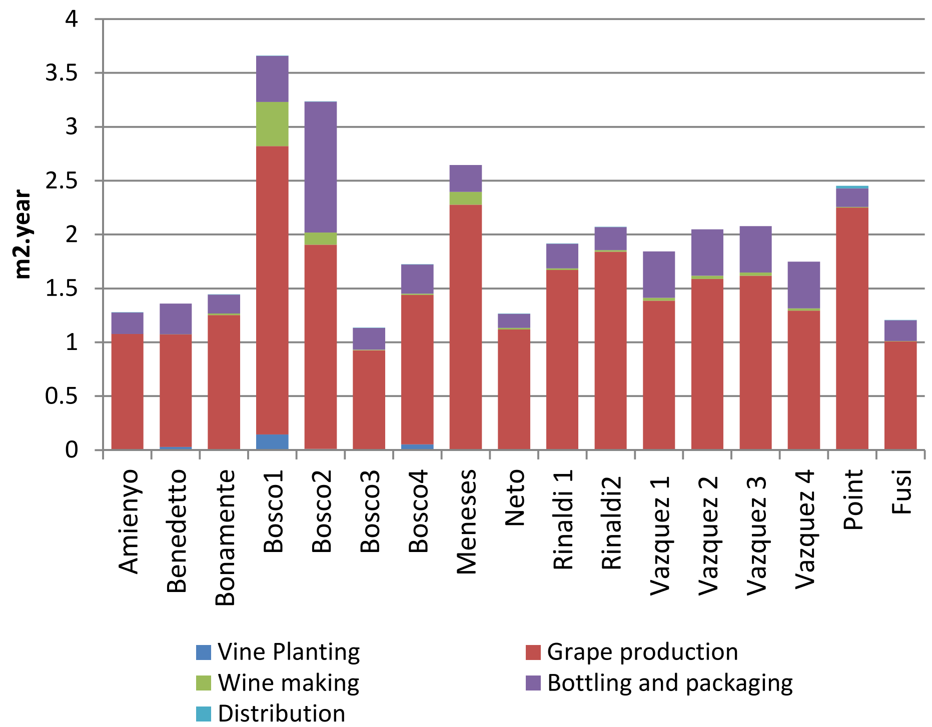

Figure 4. Agricultural land occupation contribution analysis of each bottle of wine reviewed after the harmonization process

The sources of variability among the studies are related to the yield of the vineyards, which has a direct impact on the surface necessary to produce a bottle. Influential sources are the type of grape, climate and year influencing the annual yield, as well as the technical differences in production such as the use of barrels for ageing the wine and the use of wooden boxes for packaging. Finally, the last source is the consideration of the inventory of the wooden post (in the trellis system) used for grape production, which can have a significant contribution, up to 0.3 m^2.year in the case of Point et al. (2012).

3.1.4 Human toxicity

Contributing stages to human toxicity vary among the studies (Figure 5). Human toxicity is related in all studies to emissions of metals in the background system. These emissions mostly occur during the value chains of pesticides and fertilizers (representing respectively 41% and 23% for Bosco et al., (2011) wine 2, 28% and 11% for Neto et al., (2013)), steel (representing 38% for Vázquez-Rowe et al., (2012)), or car and lorry manufacturing (representing respectively 60% for Point et al. (2012) and 18% for Vázquez-Rowe et al., (2012)). These value chains requires tailing treatment activities for mining metals and lead to emissions of manganese and chromium, among others. Such emissions have high human toxicity impacts according to the ReCiPe method. However, the impact of metals might be overestimated in LCIA methods since their lifetime is considered infinite.

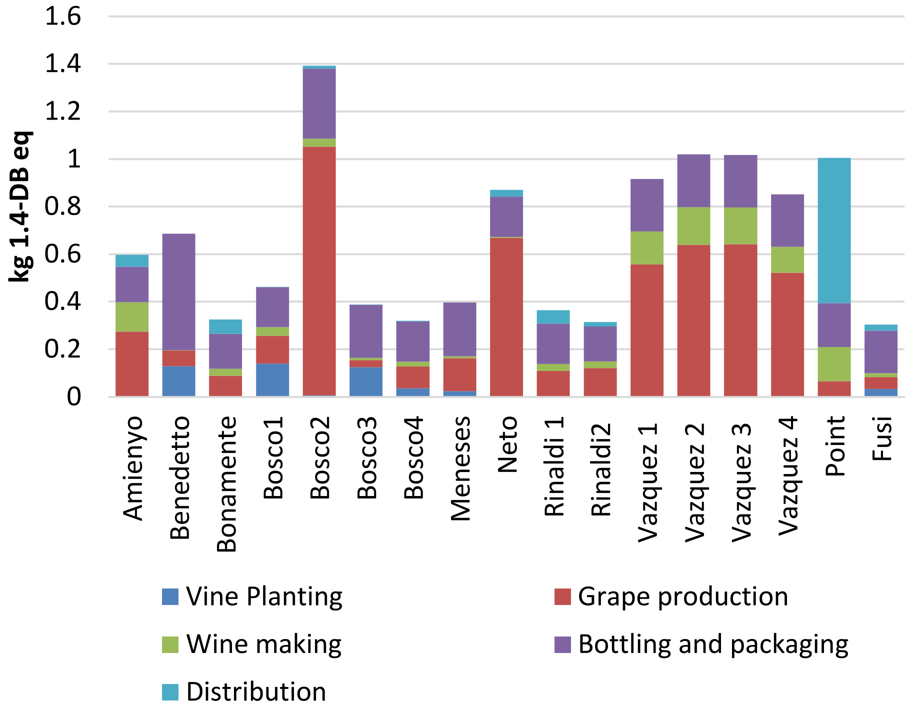

Figure 5. Human toxicity contribution of each bottle of wine reviewed after the harmonization process

3.1.5 Freshwater and terrestrial ecotoxicity

Freshwater ecotoxicity and terrestrial ecotoxicity are mainly induced by the emissions related to pesticide use in the vine planting and grape production stages (Figure 6). In the case of Bosco et al., (2011) wine 2, the impact result was more than 3 times higher than in the other studies, which was explained by the quantity of pesticide per FU retrieved from the inventory (see Table S8 in SI). Sources of variability are therefore related (i) to the different production means, which are reported in the inventory (90 g of pesticide/FU for Bosco et al., (2011) wine 2, 8 g of pesticide/FU on average for the rest), which lead to different results (from 0.01 to 0.7 kg 1,4-DB eq/FU); (ii) to the lack of knowledge on the type of pesticide used and the related active molecule emitted into the environment. Electricity also has a non-negligible contribution to freshwater ecotoxicity in several studies (Bonamente et al., (2016), Bosco et al., (2011) and Rinaldi et al., (2016)), which is related to the metal production and end-of-life treatment for the electricity grid infrastructure.

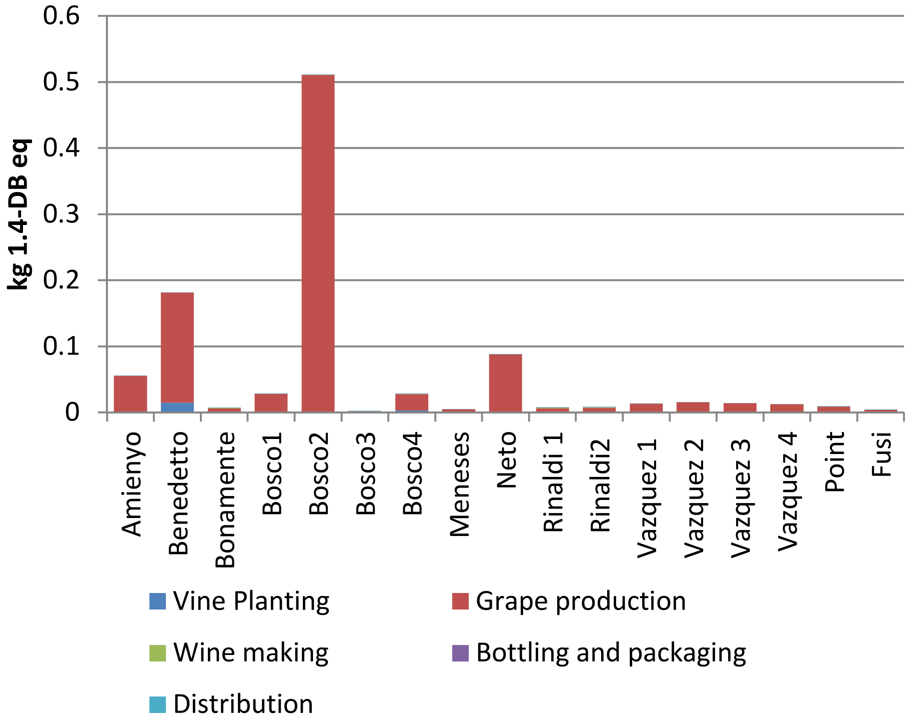

Figure 6 : Terrestrial toxicity contribution analysis of each bottle of wine reviewed after the harmonization process

3.1.6 Freshwater and marine eutrophication

Freshwater and marine eutrophication are mainly caused by P and N-based compounds emitted from fertilizer application during vine planting or grape production (Figure 7).

There is a high variability of the results among the studies for both indicators because of (i) differences in the nutrient quantity applied to the field, which is dependent on the soil quality and on the agricultural practice; (ii) uncertainty related to the quantity of the substances (N, P, etc.) in the fertilizers used; and (iii) uncertainty related to the emission factors that are also variable for the local conditions. The latter source of variability is avoided in the present study by considering the same emission factors based on PEF guidelines.

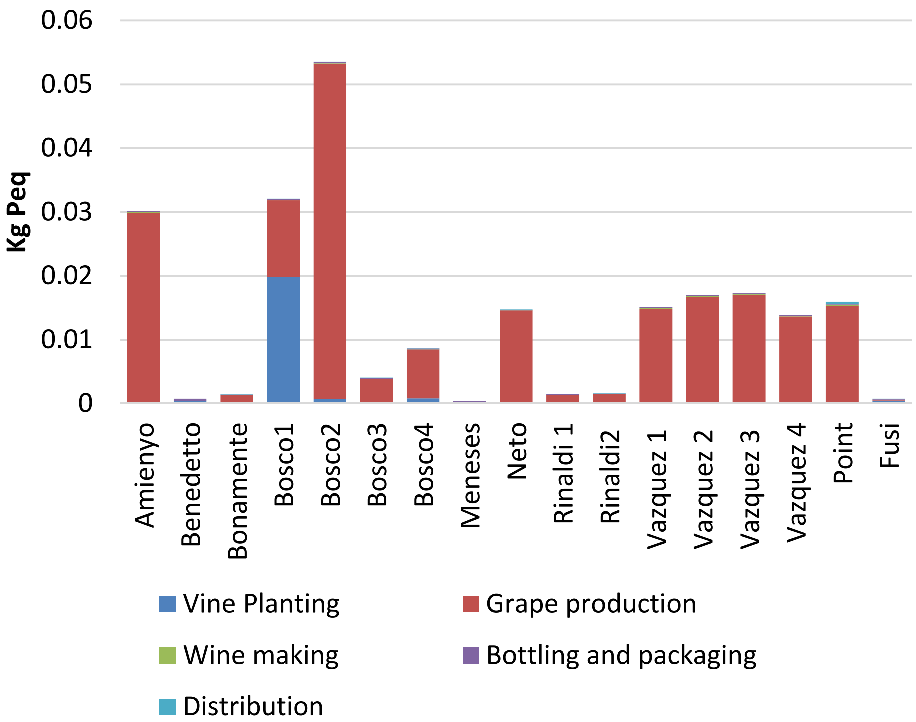

Figure 7 : Freshwater eutrophication contribution analysis of each bottle of wine reviewed after the harmonization process

3.1.7 Water depletion

Geographical location is the main source of variability for water use, since the presence of an irrigation system in the vineyard is responsible for most of the impact (99% in Amienyo et al., (2014) and 93% in Fusi et al., (2014), as shown in Figure 8).

For wine estates that do not irrigate their grapes, the sources of water use are varied: the water used for bottling, for steel production (for machineries), for fertilizer production, cardboard packaging production and for glass bottle production.

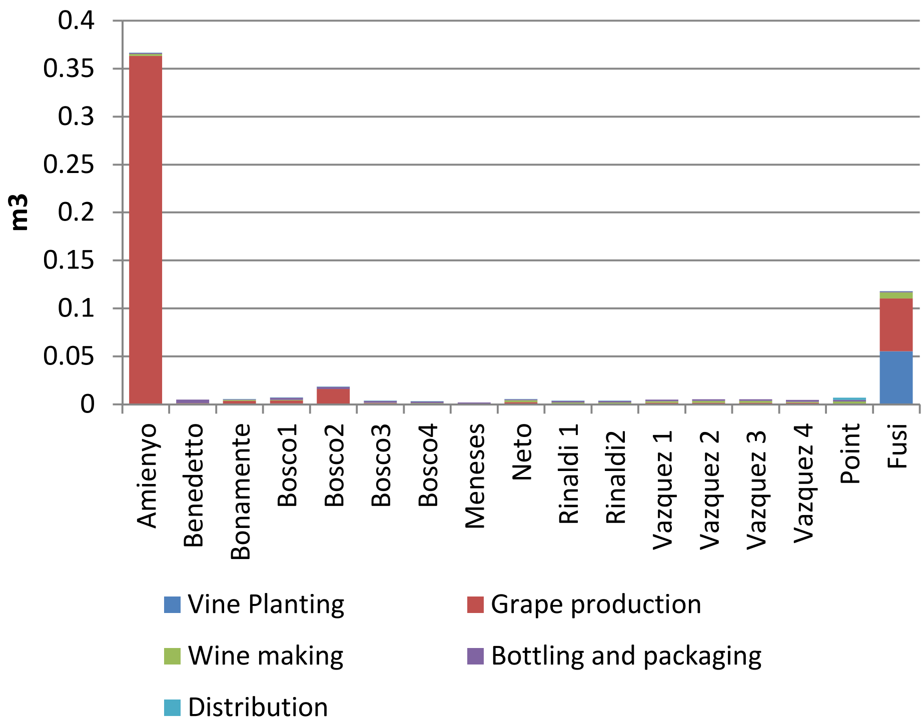

Figure 8 : Water depletion contribution of each bottle of wine reviewed after the harmonization process

3.2 Conclusions for the midpoint results

Analysis of the different midpoint impacts helped us identify the sources of variability, which can reflect technical differences, scope differences, and differences in the precision of the inventories retrieved from the literature.

Common trends were identified between the different studies for several indicators: (i) climate change, fossil depletion, particulate matter, photochemical oxidant formation and terrestrial acidification; (ii) freshwater and marine eutrophication; (iii) freshwater and terrestrial ecotoxicity.

Researchers have studied and proposed sources of variability of the environmental impact of wine bottle. Ponstein et al., (2019), Vázquez-Rowe et al., (2013), Vázquez-Rowe et al., (2012) and Villanueva-Rey et al., (2014) demonstrated the importance of yield with regards to GHG emissions per FU. Ponstein et al., (2019) demonstrated that yield can be responsible for 9% of the reduction in total GHG emissions. The choices made in the agricultural phase and for the glass bottle (weight and recycled content) are also technical choices that have a significant influence on climate change (Aranda et al. 2005, Ardente et al. 2006, Point et al. 2012, Amienyo et al. 2014). Despite valuable results provided by these studies, their focus was on climate change only. The analysis conducted in the review allowed for the identification of each cluster of impact the most contributing elements and drivers of impact, as well as the technical source of variability (Table 2).

Table 2. Impact drivers and sources of variability by cluster of impact

Clusters of impact categories	**LCI element drivers**	**Technical variability**	**Variability related to system boundaries**
Climate change, Fossil depletion, Particulate matter formation, Photochemical oxidant formation, Terrestrial acidification	- combustion of fossil fuels for field operations and transportation - combustion of fossil fuels for energy intensive background processes (manufacture of pesticides, fertilizers and glass bottles)	- fertilization management plan - type of fertilizer and pesticides (synthetic or organic)	- consideration of transportation of goods and distribution
Agricultural land occupation	- agricultural surface required to grow grapes - production of wooden products: barrels, posts, packaging, cork and cardboard	- specific grape yield - use of wooden barrels for wine making - use of wooden packaging	- consideration of infrastructures (trellis system)
Human toxicity	- activities implying mining and tailing treatment: pesticide production, steel parts (machineries and infrastructure), infrastructure for fertilizers and pesticide production	- use of metal-based pesticides	- consideration of transportation of goods and distribution
Freshwater ecotoxicity and terrestrial ecotoxicity	- pesticide emissions into the environment - electricity use during the production process	- quantity of pesticide used	- type of pesticide used and related active molecule emitted into the environment
Freshwater and marine eutrophication	- P and N emissions into the environment - NOx emissions induced by fuel combustion	- fertilization management plan	- uncertainty related to the quantity of substances (N, P, etc.) in fertilizers
Water depletion	- water use for irrigation - water used for bottling	- geographical localization: does the vineyard need to be irrigated	

Pesticides, fertilizers and fuel consumption bear an important share of the different impact categories. A comparison of the different consumption of fuel, pesticides, fertilizers (synthetic and organic) has been performed, and their relative amounts compared with the average of the present sample can be presented (the table is accessible in SI – Table S8). For fuel consumption, a factor of 10 between the smallest and highest consumption has been found. For pesticide synthetic fertilizer consumption, a 400 factor and a 500 factor have been found. These observations show the variability related to agricultural practices reflected in the different studies and the influence on the inventory.

3.1 Comparison of results and identification of variability factors at the midpoint level

In this section, the results obtained using the ReCiPe endpoint (H) are analysed. Endpoint indicators show the environmental damage in three areas of protection: human health, ecosystem quality and resource (Huijbregts et al., 2017b). This aggregation simplifies the interpretation and improves the readability of the results, especially from the perspective of development and use of LCA for decision makers (Kägi et al., 2016).

It also enables identification of the contribution of midpoint impact categories to endpoint damage categories. This identification can highlight the main midpoint impact categories to be considered in an LCA of wine.

The results obtained with the different harmonized LCI will be described by area of protection, and in a second step, the results for a single score will be assessed and explained.

3.3.1 Ecosystem quality

Agricultural land occupation, climate change and terrestrial ecotoxicity emerge as the main contributors of damage to ecosystem quality. Bosco et al., (2011) wine 2 ecosystem quality damage was more than two times higher than in other studies (1.9E-7 species.year for Bosco et al., (2011) and 7.4E-8 species.year for Neto et al., (2013), the second highest) because of the high quantity of pesticides used, generating terrestrial ecotoxicity. Figure 9 reflects the importance and contribution of inventorying the agricultural land occupation required for growing wines and the agricultural practices that are the main source of variability.

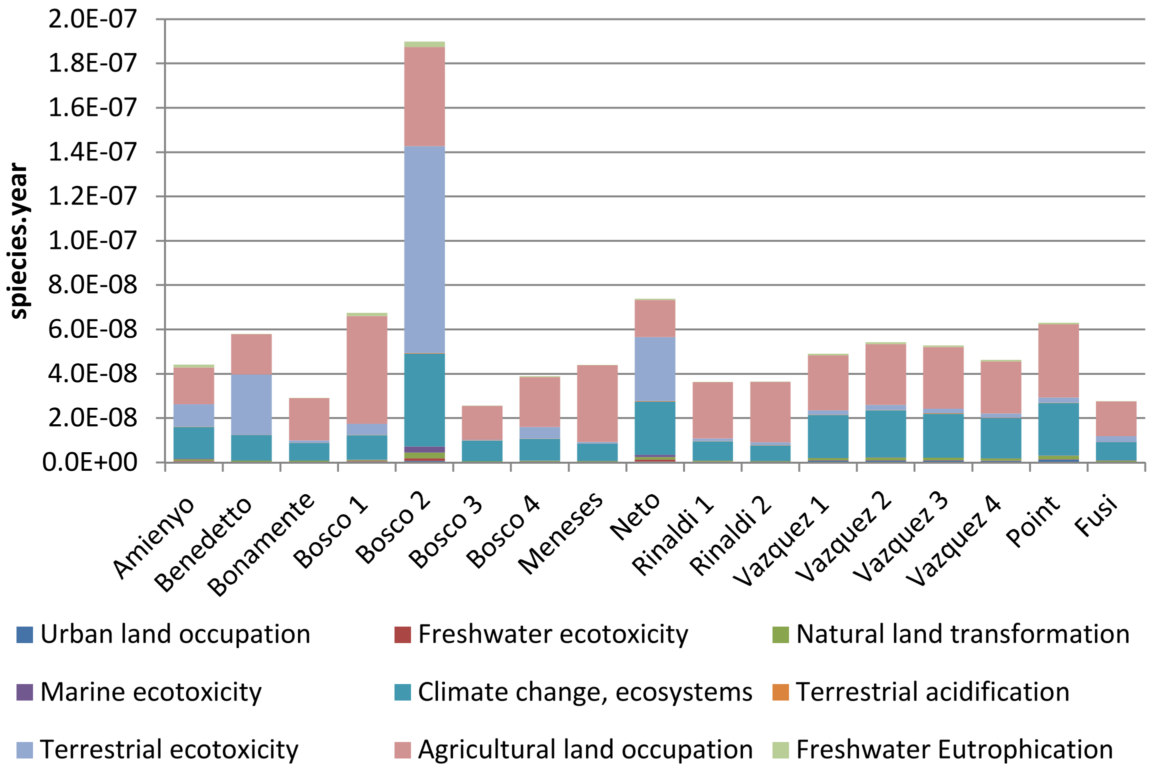

Figure 9. Ecosystem damage of each bottle of wine reviewed after the harmonization process

3.3.2 Human Health

Climate change, particulate matter formation and, to a lesser extent, human toxicity are contributing the most to human health damage (Figure 10). Variability across the studies regarding these contributions is small. The climate change contribution ranges from 49% and 59%, particulate matter contribution from 27 to 40% and human toxicity from 7 to 13%.

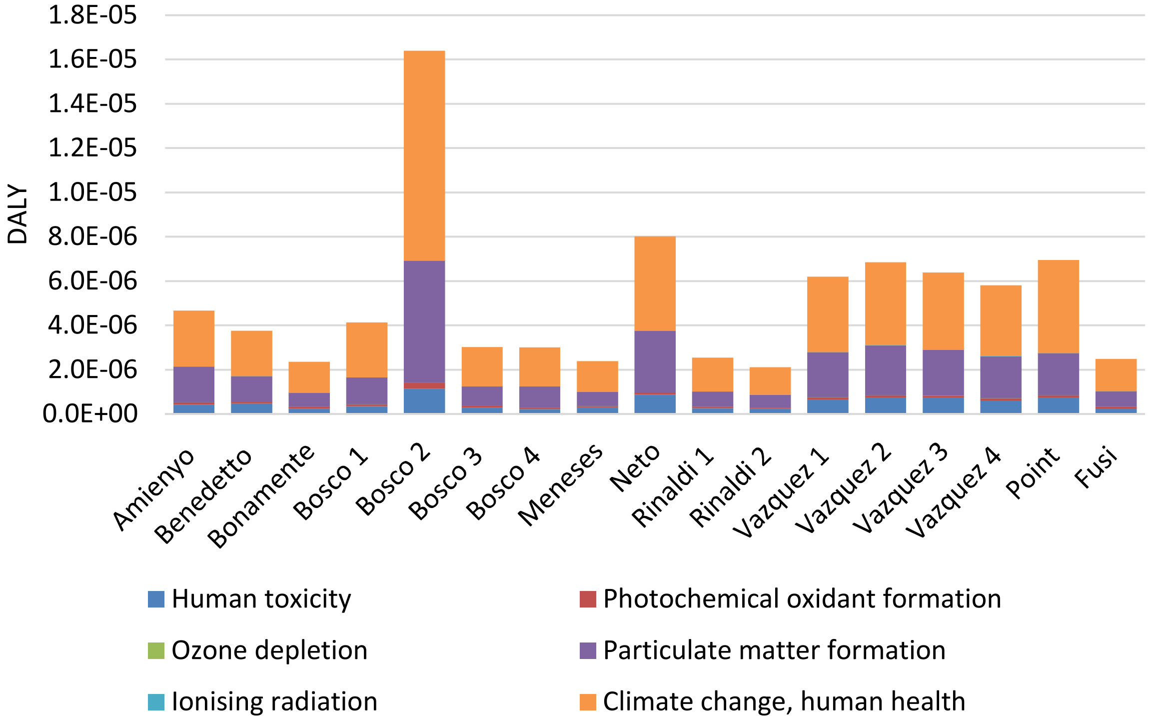

Figure 10. Human health damage of each bottle of wine reviewed after the harmonization process

3.3.3 Resources

Similarly to the human health damage, variability among the studies regarding the contribution of the midpoint indicators is small (Figure 11). Fossil depletion represents the highest share of the impact, ranging from 80% to 95% of the total damage, while metal depletion represents from 5% to 20%.

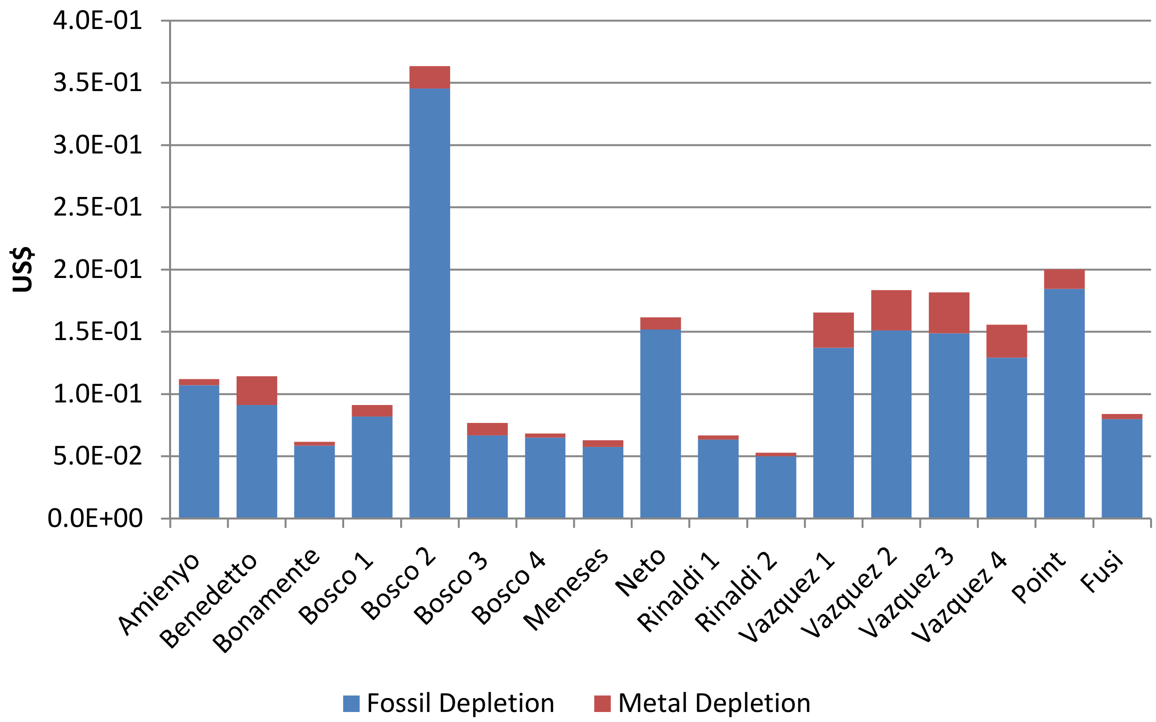

Figure 11. Resource damage of each bottle of wine reviewed after the harmonization process

3.4 Single Score

The single score is achieved through the application of normalization and weighting factors on the endpoint indicators.

3.4.1 Relative and absolute results

The single score can help compare the impacts of the different products (Figure 12). The results range from 0,156 point for Rinaldi et al., (2016) wine 2 to 0.980 point for Bosco et al., (2011) wine 2, with an average of 0.307 points across the 17 bottles compared. Looking at the different production stages, grape production and bottling and packaging are the most contributing stages for all the studies, except for Point et al., (2012), for which distribution represents 49% of the single score.

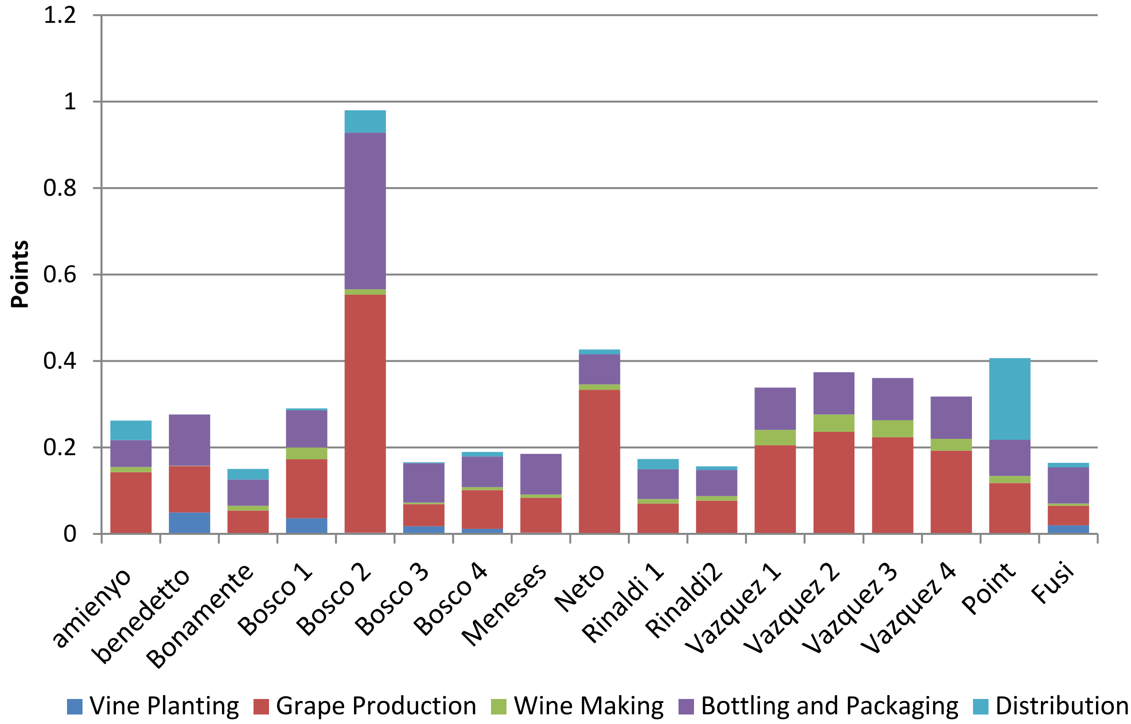

Figure 12. Contribution to the single score of the different life cycle stages

3.4.2 Impact and process contribution to the single score

Each of the three areas of protections contributes significantly to the single score, from 32% to 52% for ecosystem damage, 26% to 36% for human health damage, and 20% to 33% for resources, as shown in Figure 13.

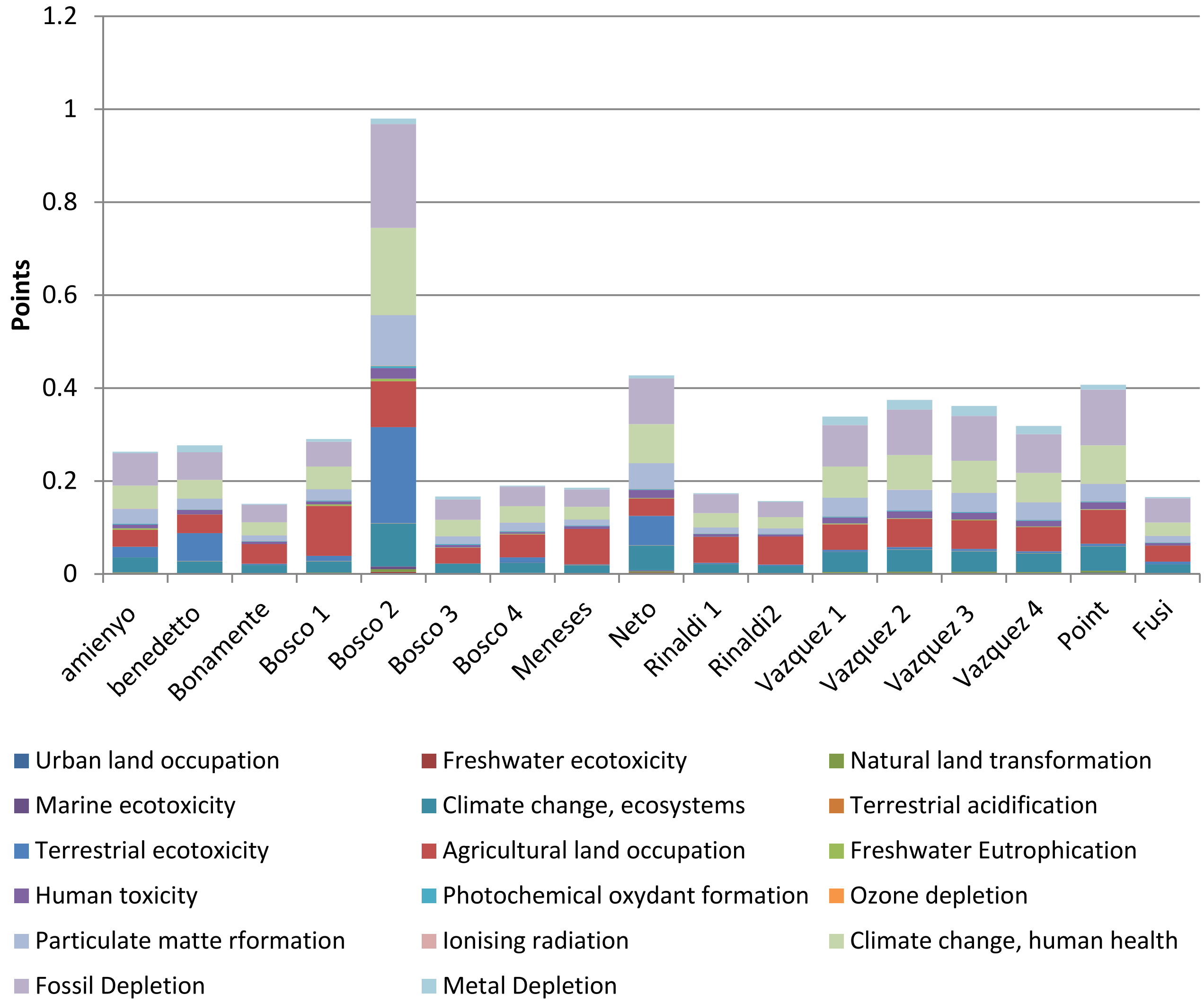

Figure 13. Single score of each bottle of wine reviewed after the harmonization process

Examining the contribution of each indicator in the single score, climate change, terrestrial ecotoxicity, agricultural land occupation, and particulate matter formation fossil depletion represent most of the single score impact (from 87% to 93% of the total score). The highest variability regarding the single score is related to ecosystem damage and, more specifically, to terrestrial ecotoxicity and agricultural land occupation (from 2% to 23% of the single score impact for the first one and from 3% to 41% for the second). For all the studies, 90% of the single score is explained by less than 10 elements of the LCI. Table 7 presents the main contributing elements to the LCI.

Table 3: Contribution of the damage indicators to the single score and related LCI elements that contribute the most to the single score. CC: climate change, ALOP: agricultural land occupation, TET: terrestrial ecotoxicity, PMF: particulate matter formation, FD: fossil depletion

Study	*CC, ecosystems*	*TET*	*ALOP*	*PMF*	*CC, human health*	*FD*	*LCI element contribution to the single score*
Amienyo	12%	9%	14%	12%	19%	26%	glass bottle 22%, transport container ship 16%, land use 13%, pesticide emissions 10%
Benedetto	9%	22%	15%	8%	15%	21%	glass bottle 23%, pesticide emissions 25%, land use 12%, steel machineries bottling 11%
Bonamente	12%	2%	28%	8%	18%	25%	glass bottle 36%, land use 27%, distribution (truck) 10%
Bosco	8%	4%	37%	8%	17%	18%	land use 29%, glass bottle 20%, fertilizer production 10%
Bosco 2	9%	21%	10%	11%	19%	23%	pesticide emissions 25%, pesticide production 11%, diesel emissions 14%, fertilizer production 11%
Bosco 3	12%	0%	20%	10%	21%	26%	glass bottle 44%, land use 18%, steel (vineyard infrastructure) 7%
Bosco 4	11%	6%	26%	10%	18%	22%	glass bottle 26%, land use 23%, pesticide emissions 7%, nitrogen fertilizer production 6%
Meneses	9%	1%	41%	7%	15%	20%	land use 39%, glass bottle 37%, transportation of packaging materials 6%
Neto	12%	15%	9%	13%	20%	23%	pesticide emissions 19%, glass bottle 15%, diesel emissions 13%, fertilizer emissions 11%, land use 8%
Rinaldi 1	11%	2%	32%	8%	17%	24%	glass bottle 31%, land use 31%, distribution (truck) 8%
Rinaldi 2	10%	2%	39%	7%	16%	21%	land use 37%, glass bottle 30%,
Vazquez 1	13%	1%	16%	12%	20%	26%	glass bottle 21%, transport of compost 18%, land use 14%, steel (vineyard) 11%, electricity 10%
Vazquez 2	13%	1%	16%	12%	20%	26%	glass bottle 19%, transport of compost 19%, land use 14%, steel (vineyard infrastructure) 11%, electricity 10%
Vazquez 3	12%	1%	17%	11%	19%	27%	glass bottle 20%, transport of compost 20%, land use 15%, steel (vineyard infrastructure) 12%, electricity 11%
Vazquez 4	13%	1%	16%	12%	20%	26%	glass bottle 23%, transport of compost 18%, land use 13%, steel (vineyard infrastructure) 11%, electricity 8%
Point	13%	1%	18%	9%	20%	29%	passenger car (distribution) 40%, glass bottle 17%, land use 16%
Fusi	11%	4%	21%	8%	17%	31%	glass bottle 41%, land use 19%, diesel emissions 12%

4. Discussion

In this section, we first analyse the present results with regards to the initial objective of the papers (i) to provide a comparison of the results of the study, (ii) to identify and analyse the sources of variability for each indicator (iii) to identify the most contributory process and emissions in the harmonized literature and (iv) to provide recommendations for selection of the most significant and relevant indicators for environmental impact assessment in the wine sector. We then discuss several elements for which the present study has provided insights and that require further research.

4.1 Comparison of the results and source of variability

The harmonization procedure has enabled a comparison of different studies both at midpoint and endpoint levels. We analysed the different bottles of wine and proposed a range of harmonized results for each indicator. Nonetheless, discrepancies remain in the system boundaries and in the inputs that could not be harmonized because of the lack of data. This phenomenon is particularly the case for transport, both for the transportation of goods (fertilizers, etc.) and the distribution of wine bottles. For example, transportation of compost has a high share of impacts in Vázquez-Rowe et al., (2012) for several categories. However, other studies do not include this information in their LCI. Additionally, Point et al., (2012) considered a 5-km trip in a passenger car in the distribution phase, which accounted for an important share of the impacts. Therefore, we were not able to reach a conclusion about the most sustainable life cycle of wine bottles found in the studies. Further information is needed to fully achieve objective (i).

Focusing on agricultural production, all studies provide a common set of data that could help to compare different technical management routes (organic, extensive, intensive, etc.). However, comparisons of results should be made with caution. Indeed, the variability of LCI also depends on other factors that are independent of the technical choices. (i) Climate conditions (and consequent crop yield and vine protection needs) highly depend on the studied year and geographic location. (ii) Several processes such as fertilization are conducted on a multi-year basis, whereas the studies generally focus on a unique year. Consequently, important fertilizer quantities can be used for certain years, while no or little fertilization occurred in subsequent years. In such a case, the quantity of fertilization should be smoothed and averaged over a defined period of time. Therefore, the harmonization procedure, including harmonization of the system boundaries and in the constitution of the life cycle inventory, is a necessary step to compare the different products, assess the different production methods and reduce the sector environmental footprint. From this perspective, the harmonized life cycle inventory proposed in the frame of the PEFwine (CEEV, 2018) can be seen as a major step forward.

4.2 Identification of impact clusters, and drivers of midpoint/endpoint/single score results

The review resulted in the identification of the cluster of impacts (i.e., different categories of impacts that behave similarly across the study and that are driven by the same inventory elements). ReCiPe has the advantage to cover full impact pathways from the midpoint to endpoint and enable the computation of a single score. Building on the results of the single score and analysis in 3.4.2, the impact categories contributing to more than 90% of the single score are climate change, particulate matter, fossil depletion, terrestrial ecotoxicity and agricultural land occupation. The source of variability of the endpoint indicators and the single score is therefore related to the source of variability of the midpoint indicators. However, Table 3 shows that climate change, particulate matter formation and fossil depletion are related and driven by the same LCI data. Most of the impacts are therefore driven by 3 clusters of impacts, with specific drivers for each: (1) “Combustion of fossil fuels for field operations and transportation and for energy-intensive industrial processes related to wine production (pesticides, fertilizers and glass bottle production)” for cluster climate change, particulate matter formation and fossil depletion; (2) “pesticide emissions into the environment” for ecotoxicity; and (3) “agricultural land use and, to a lesser extent, wooden-based products” for agricultural land occupation. Building on this conclusion, a methodology for assessing the environmental impact of wine bottle production could be constructed, requiring a limited amount of inventory data yet representing most of the environmental impact under the form of the single score. This result is in line with the ambition of constructing a tool that would democratize the use of LCA within the wine sector. This perspective is in agreement with a new trend in the life cycle assessment of agricultural systems, which is streamlining the LCI using traceability data. Indeed, Véronique Bellon-Maurel et al., (2014a, 2014b) showed that is it possible to partially generate the LCI of vineyards when it is equipped with information and communication technologies. Targeting only the most contributory elements that have been promoted in this research can further simplify the data collection. Going further in the projection, this technique, combined with the development of artificial intelligence to predict the environmental impact of an agricultural systems (Kaab et al., 2019; Nabavi-Pelesaraei et al., 2018), can facilitate the mainstream use of LCA, reducing the need for the intervention of an LCA expert and provision of solutions that include data collection and treatment.

Comparing the contribution to the total impact of the different impact categories in the PEFwine and in the present review, the results are similar for climate change fossil depletion and particulate matter (see Table 4). Agricultural land occupation has a significantly higher contribution in the present review than in PEF, because of the different (i) characterization models used in ReCiPe and PEF (Guinee, (2002) for ReCiPe and LANCA (Beck et al. 2010) for PEF) and (ii) weighting schemes: ReCiPe weights the different categories according to the endpoint damage, whereas PEF weights them according to expert judgement (Serenella Sala, Alessandro Kim Cerutti, 2017). The main difference lies in the consideration of the toxicity impact, which in the present case has a significant impact (with a high variability between studies), and the choice of the European commission to exclude this impact in the normalization and weighting procedure. In the technical evaluation of the environmental footprint pilot phase, the reporters justify the exclusion of toxicity impacts since “USEtox was perceived as not robust enough for benchmarking and communication purposes” (ECOFYS; PRé Consultants; RDC Environment, 2017). The authors nonetheless specify that the decision to exclude toxicity impacts will be revised in 2020, “after the finalization of the ongoing work performed in collaboration between the Commission and ECHA agency in Helsinki on developing the new CF based on REACH data”. This work has recently been published by the European commission (Saouter et al., 2018).

Table 4: Impact contribution to the total impact in the PEFwine recommendations and in the present review

PEF		Present findings	
Impact category	**Contribution to the total impact (single score)**	**Impact category**	**Contribution to the total impact (single score)**
climate change	29%	climate change	30%
resource use, fossils	17%	fossil depletion	24%
resource use, minerals and metals	14%	Agricultural land occupation	22%
particulate matter	9%	particulate matter formation	10%
Acidification, terrestrial and freshwater	7%	terrestrial ecotoxicity	5%
land use	7%		

4.3 Research needs to improve LCA in the wine sector

As stated in the previous section, agricultural land occupation and toxicity-related impacts appear to have a large contribution in endpoint damage and single score results. However, these two categories lack consensus in the LCA community, and a better consideration of these impacts is required to increase the robustness of LCA in the wine sector.

4.3.1 Agricultural land occupation contribution

Modelling of agricultural land occupation does not differentiate soil and land management practices, which can have a significant impact on biodiversity and ecosystems. De Baan et al., (2013) mentioned that biodiversity damage potential, which is used in the ReCiPe damage assessment methodology, “can approximate land use impacts on biodiversity in LCA studies that are not intended to directly support decision-making on land management practices. […] For LCA studies aiming to support decisions of specific land management, a more detailed, site-dependent assessment, including additional region- or site-specific data, is indispensable“. Further research should be conducted to examine the impact of soil management on biodiversity, especially for perennial crops such as vines and its integration in LCA.

4.3.2 Pesticide emission impact on human health

While emissions of pesticides have a direct impact on the terrestrial ecotoxicity impact and on ecosystem quality damage indicators, pesticide emissions have a small contribution to human toxicity impacts and human health damage indicators. This phenomenon is in opposition to the civil society perspective, for which the impact of pesticide emissions on field workers and neighbour's health (who are exposed to pesticide spraying) is one of the most scrutinized environmental issue related to wine production. However, the human toxicity indicator fails to reflect the occupational exposure to the phytosanitary products, and therefore, the impact can be underestimated. The complexity of assessing the impact on human health is related to the wide variety of active molecules, the heterogeneity of the agricultural practices, the change in products over the years and the simultaneous use of different products (Baldi I and Lebailly P, 2013). LCA is not dedicated to evaluating site-specific impacts to overcome the issue of underestimation of pesticide impacts on human health; the combination of LCA with risk assessment approaches should be investigated in that field.

4.3.3 Supply chain improvement requirements: the example of pesticide production consideration

Additionally, the upstream pesticide strategies in LCI production should be improved. Only the active molecule of the product is taken into account for pesticide modelling in LCA, which leads to potential imprecision: the rest of the formulation is not considered in the inventory, or the quantity of the product used is considered the active molecule, which would significantly increase the impact. Furthermore, the active molecule is not always known when the data are collected, or the molecule cannot be found in the ecoinvent database. In this case, the dataset "Pesticide unspecified" has been used, which has been calculated from the arithmetic mean of all inputs and outputs of all 78 pesticides included in the ecoinvent database. The use of this mean value can provide an approximation of the impact of pesticide production since there is high impact variability depending on the active molecule considered. The problem is similar in terms of the impact of direct emission of products in the environment.

The same issue occurs with fertilizers when precision regarding the nutrient content and type of fertilizer used is not known.

5. Conclusion

This paper aims to provide a quantitative comparison of LCA case studies on wine production through a harmonization procedure, which is an innovative approach for a critical review.

It provides a range of results for different impact categories using a unique method (the ReCiPe method in the present case). Having the same impact categories and evaluating the endpoint damage also enables the identification of the most contributory categories for the sector. From the inventory perspective, the most contributory elements could be identified, and the dissimilarity between studies was proposed. While the harmonization procedure has its methodological limits, especially regarding the harmonization of system boundaries, it provides useful results for comparison of different wine products and for dissemination of the results to consumers. The Product Environmental Footprint ambitions are in line with these perspectives; nonetheless, the present review provides different conclusions than the PEF recommendations. Indeed, the dissemination of LCA results implies a need to improve their readability, therefore synthesis of the amount of information that needs to be analysed. While the PEF proposes a weighting scheme based on expert opinion, excluding the toxicity-related categories, the ReCiPe impact pathways was used in the review, keeping the toxicity indicators in the single score, which can represent a high share of impact (up to 22% of the total impact score). This difference should be further investigated since LCI elements that have a significant impact in the present cases could be less important using the PEF recommendations.

Finally, the procedure highlights the need for further research to increase the robustness of LCA in the sector, namely, improving the consideration of different land management, improving the consideration and impact of pesticide use in agricultural fields, and strengthening the LCA database to improve understanding of the impact related to the supply chains.

Acknowledgements

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