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Greenhouse gas emissions and mitigation options for German wine production

Helena J. Ponstein [a, b, c, *], Andreas Meyer-Aurich [a, b], Annette Prochnow [a, b]

[a] Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany
[b] Faculty of Life Sciences, Humboldt Universität zu Berlin, Invalidenstr. 42, 10115 Berlin, Germany
[c] German Institute for Sustainable Development (DINE) at Heilbronn University, Max-Planck-Str. 39, 74081 Heilbronn, Germany

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ABSTRACT

In the light of a dire need to reduce greenhouse gas emissions (GHG) from food value chains, this paper analyses GHG emissions from wine production based on primary data from 5 wineries, one wine cellar and 9 grape producers in Germany and explores main emission sources based on their contributions to variance. Considering system boundaries from cradle to gate we found a 90% confidence interval for results between 0.753 and 1.069 kg CO_2e per bottle of wine. Main contributors to variance were bottle weight (31%), electricity usage (18%), heat (11%), yield (−9%), and diesel use in vineyards (9%). Looking at production process phases, 19% of emissions resulted from the production of wine grapes, while 81% were attributable to the winery phase, mainly to the packaging materials (57%). Exploring the mitigation potential of a reduction in bottle weight, reuse of glass bottles, increase in packaging volume and renewable energies, we found that the reuse of glass bottles deserves close attention from wine producers, consumers, and policy makers who strive for an effective decarbonization of the wine value chain. The mitigation potential of the reuse of an average bottle exceeds the mitigation potential from a reduction in bottle weight by more than threefold. A combination of the replacement of grid electricity by renewable energies, bottle weight reduction and reuse can curb GHG emissions per bottle of wine by 47%.

1. Introduction

Germany's long history of wine production dates back to the Roman era. As the world's tenth largest wine producer, with an annual volume of 8.9 million hectolitres from approximately 102,000 hectares of planted vineyards in 2016, Germany is amongst the most important markets in terms of wine consumption. Its consumption volume of 20.5 million hectoliters (hl) the country is exceeded only by Italy (22.5 million hl), France (27.0 million hl) and the USA (31.8 million hl) (OIV, 2017). With a market volume of €8.9 billion, wine plays an important economic role (Deutsches Weininstitut, 2017).

A lot of attention has been paid to the environmental impacts of the wine value chain (Christ and Burrit, 2013). A focus on greenhouse gas emissions (GHG) can be observed in the literature, referred to as a proxy for environmental impacts (Rugani et al., 2013). An estimate of the contributions of wine to global anthropogenic greenhouse gas emissions revealed that this value chain cannot be overlooked, contributing approximately 0.3% of annual global GHG emissions (Rugani et al., 2013). Amienyo et al. (2014) demonstrated the significance of the wine sector on the national level for a country with a high wine consumption per capita, estimating that the annual wine consumption in the UK caused 0.6% of the national GHG emissions. This demonstrates that while the wine industry is highly affected by climate change (Hannah et al., 2012; Galbreath, 2012), it also is a relevant driver of global warming.

Internationally, wine producers regard the inventory of the greenhouse gas emissions related to their activities, commonly referred to as carbon footprint (CF), as an incremental element of environmental sustainability (Szolnoki, 2013), and a driver for eco-innovation (Navarro et al., 2017a). The communication of low GHG emissions to customers provided a competitive edge for food items in Germany, as the consumer's willingness to pay was positively associated with lower carbon emissions (Grebitus et al., 2016). This

* Corresponding author. German Institute for Sustainable Development at Heilbronn University, Max-Planck-Str. 39, 74081 Heilbronn, Germany.
E-mail addresses: ponstein@dine-heilbronn.de (H.J. Ponstein), ameyeraurich@atb-potsdam.de (A. Meyer-Aurich), aprochnow@atb-potsdam.de (A. Prochnow).

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tendency was confirmed for wine by Schäufele and Hamm (2017), who found a higher willingness to pay for wine with sustainability characteristics. Consequently, the assessment, communication and effective reduction of the carbon footprint directly benefits the market position of a winery while contributing to the much-needed mitigation of climate change.

CF studies on wine typically refer to a production area or country, with several studies focussing on Spain (e.g. Navarro et al., 2017a; Gazulla et al., 2010; Vázquez-Rowe et al., 2012a; Vázquez-Rowe et al., 2012b; Villanueva-Rey et al., 2014) and Italy (e.g. Ardente et al., 2006; Pizzigallo et al., 2008; Benedetto, 2013; Chichelli et al., 2016). Further, wine production in France (Jradi et al., 2018), Portugal (Neto et al., 2013), Canada (Point et al., 2012), and California in the USA (Steenwerth et al., 2015) was assessed. Wine producers from several countries such as France and Spain (Navarro et al., 2017a,b) and Italy, Luxembourg and Spain (Vázquez-Rowe et al., 2013) were analysed based on the same methodological assumptions. Villanueva-Rey et al. (2014) compared conventional and biodynamic wine grape production systems, attributing lower GHG emissions to biodynamic wine grapes. Several authors often refer to only one winery or vineyard (e.g. Neto et al., 2013; Fusi et al., 2014; Benedetto, 2013; Vázquez-Rowe et al., 2012b, Marras et al., 2015). Despite high variations in annual yield and the subsequent effects on a carbon footprint calculation, the assessment of more than one harvest year is rare (Villanueva-Rey et al., 2014; Vázquez-Rowe et al., 2013, 2012b).

The inherently high degree of variability of agricultural systems compared to other economic sectors is embedded in a farmer's preferences and know how, soil types, or climates (Notarnicola et al., 2017), and is particularly pronounced for the wine value chain. In their extensive review on GHG emission from wine production, Rugani et al. (2013) reported an average of 2.2 (+- 1.34) kg CO_2e per 0.75 L bottle of wine from 'cradle to grave', considering the full life cycle from vineyard establishment to waste disposal. If limiting the focus to the production of one bottle of wine from cradle to gate, the reported average results were 0.79 (+- 0.30) kg CO_2e for organic wine, and 1.06 (+-0.73) kg CO_2e for conventional wine. The high standard deviations were explained by substantial differences in production methods and material use at vineyard or winery level (Vazquez-Rowe et al., 2013) but also by methodological differences between studies, such as the choice of system boundaries, allocation, and source of emission factors (Rugani et al., 2013). Yield fluctuations were pointed out as a main influencing factor by Vázquez-Rowe et al. (2012b) and Bosco et al. (2011). Combined, these influencing factors limit the comparability between study results and the transferability thereof to other wine-growing areas.

Because of the consistently dominating impact of the production of glass bottles, reducing the GHG emissions of the glass bottle via a reduction of bottle weight is widely recognized as the key mitigation option for the wine value chain (Navarro et al., 2017a; Point et al., 2012; Amienyo et al., 2014). A particularity of the German beverage market is the reuse of glass bottles, common for mineral water, juice and beer distributed in PET and glass bottles, and for wine sold by wineries and cellars for local consumption. We argue that in light of the dire need for GHG emission reductions in our food systems, the mitigation potential from the reuse of glass bottles deserves closer attention.

This study seeks to contribute to a better understanding of GHG emissions from wine production in Germany through assessing the range and variability of GHG emissions based on primary data from 5 wineries and one wine cellar with 9 grape producing members. To support wine producers, wine consumers, and policy makers in their aspirations for low carbon production and consumption strategies, based on primary data we explore the mitigation potential of (1) the reduction in bottle weight, (2) the reuse (washing) of wine bottles, (3) an increased bottle volume, and (4) the replacement of grid electricity by renewable energy.

2. Material and methods

2.1. Methods

This article is based on the standardized life cycle assessment (LCA) methodology (ISO 14040, 2006) while the focus is on GHG emissions. Following the GHG Protocol (WRI, WBCSD, 2004; 2011) data were gathered on company level and allocated to the final product. This top-down approach is feasible for wine CF studies, but does not display a product carbon footprint (Navarro et al., 2017b).

Following the GHG protocol (WRI, WBCSD, 2004; 2011), the emission sources were structured into three spheres of influence (Table 1): direct emissions that occur directly in the vineyard or on premises of the winery ('scope 1'), indirect emissions from electricity production ('scope 2'), and other indirect emissions ('scope 3') that occur upstream or downstream of the core activities. Scope 1-emissions include the combustion of diesel by tractors, and direct field emissions such as N_2O from the application of Nitrogen and CO_2 from liming. At the winery stage, direct emissions include the use of diesel and petrol by the company car fleet, the use of fossil fuels to produce heat and steam and leakages of cooling agents. Indirect emissions (scope 2) cover purchased electricity. Other indirect emissions (scope 3) at the viticulture stage include the material of the trellis systems for the establishment of the vineyards, the production of fertilizer and phytosanitary products. At the winery stage, emission sources encompass additives and cleaning chemicals, as well as packaging material (glass bottles, closures, labels and secondary packaging material such as cardboard boxes and plastic foil), and the provision of fossil fuels. The contribution of Human Labour (HL) is an integral part of all process stages of wine production, and related GHG emissions from the commuting of staff to the vineyard and the winery were included.

The calculation of GHG emissions was performed with MS Excel, while the statistical modelling was carried out using the @risk 5.5 software (Palisade Corp., Ithaca, NY).

2.2. System description

The wine production system can be subdivided into A) establishment of the vineyard B) grape production, C) vinification, D) bottling and packaging, E) transport to the point of sale, F) purchase and consumption. The system boundaries of this study encompass phases A+B and C+D (Fig. 1), referred to as 'viticulture' and 'winery'.

Emission sources from subsequent process steps, and the transportation and treatment of non-organic waste were excluded. The vast majority of vineyards in this study were not irrigated. There was no data on irrigation water and the energy requirements for the pumps for vineyards under irrigation, therefore these emission sources were neglected. Cooling agents can have a powerful global warming potential and leakages have to be reported as direct emissions in scope 1 under the GHG Protocol (2004, 2011). There were no leakages of cooling agents reported by the wineries, which mainly used water and dried ice for cooling.

The functional unit was 0.75 L wine. GHG emission sources were reported separately for the viticulture and the winery stage. For viticulture, GHG emissions were reported per hectare of vineyard and FU, following Navarro et al. (2017a), Steenwerth et al. (2015), Vázquez-Rowe et al. (2013), and Bosco et al. (2011).

The allocation of inventory data and results per hectare of vineyard to FU was done based on grape yield and wine yield (kg

Table 1
Information retrieved by questionnaires per scope.

Viticulture stage	Winery stage
Scope 1 – direct emission sources	
Diesel use by tractor (L)	Diesel and gasoline used in vehicles (L)
N_2O from fertilizer applications (kg N-fertilizer)	Heat production, natural gas and heating oil (kWh)
CO_2 from liming (kg $CaCO_3$)	Fugitive emissions from losses of cooling agents (kg)
Scope 2 – indirect emission sources	
n.a.	Electricity (kWh)
Scope 3 – other indirect emission sources	
Trellis system material[a] (kg) and lifespan (years)	Additives and cleaning agents (kg)
Production of fertilizer (kg synthetic N, P_2O_5, K_2O)	Reusable and single use glass bottles (0.75 L, 1.0 L) (kg)
Production of phytosanitary products (kg)	Labels and stoppers (kg)
Commuting of staff (pkm[b])	Secondary packaging (boxes, foil) (kg)
	Provision of fossil fuels (kWh, L)
	Commuting of staff (pkm)

[a] The vine training system typical for the assessed wine-growing areas consisted of wood poles, metal poles, and wire.
[b] Passenger kilometre.

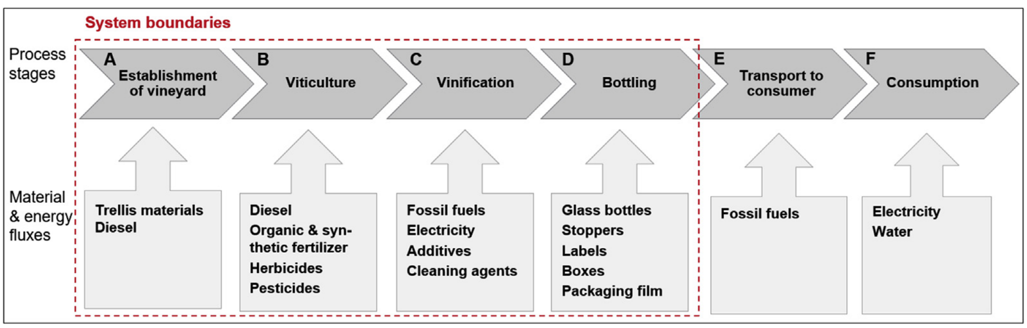

Fig. 1. System boundaries.

grapes to L wine), which was assumed to be 0.75. The range found in literature varied from 0.65 (Bonamente et al., 2016) to 0.78 (WeinV, 1995).

The inventory was based on primary data of material and energy fluxes from 5 wineries, one wine cellar and 9 wine grape producers located in the wine-growing areas Baden (1), Wuerttemberg (2), Palatinate (11), and Rhinehessen (1), surveyed between 2010 and 2016. Quality wine ("Qualitätswein bestimmter Anbaugebiete, Q.b.A.") was produced from red and white wine grapes. The production systems encompass 5 wineries with a certified sustainable farming approach (FairChoice®), of which one produced organic wine grapes, and 9 grape producers with conventional production. The data cover 220 hectares of vineyard and a yield of 2206 tons of grapes. The inventory was compiled by a questionnaire, which was checked and clarified where necessary. It covers one calendar year (1st of January until 31st of December).

2.3. Data modeling and assumptions

Emission factors were retrieved from the ecoinvent database V.3.4 (ecoinvent, 2017). Here, the characterization factor employed was the GWP 100 based on IPCC 2013, with allocation at the point of substitution (ecoinvent, 2017) (Table 2). Emission factors for fossil fuels were retrieved from Defra (2016). For the production of packaging glass, we relied on the Bundesverband Glas (BV Glas 2013), the association of glass manufacturers in Germany, because this emission factor was based on a recent carbon footprint of several glass producers, considering the actual energy consumption, transport distances and the current recycling rate (0.743 kg CO_2e/kg glass). This emission factor exceeds the one supplied by ecoinvent by 0.123 kg CO_2e/kg glass.

Pre-chains of fossil fuels were included. Emissions from grid electricity were based on Icha and Kuhns (2018). GHG emissions related to the use of synthetic N fertilizers occur during the production and transportation, and in the form of N_2O emissions from application. N_2O-N emissions from the application of N to soil were estimated based on IPCC methodology (IPCC, 2006), using the default emission factor of 1% of N_2O-N per kg N applied. Indirect emissions from N losses in temperate zones were included following Cherubini et al. (2009), therefore a factor of 1.35% of N_2O-N was assumed, which were converted into N_2O based on molecular mass (44/28). Based on the global warming potential of N_2O of 265 (Myhre et al., 2013) GHG emissions from the application of fertilizer were assumed to be 5.62 kg CO_2e per kg N. Regarding the production and transportation of N-fertilizer, we assumed the lower range of Lal (2004) who reported a range of 3.3–6.6 kg CO_2e/kg N fertilizer.

Organic fertilizers such as grape marc and yeasts were categorized as waste streams from processes within the wine cellar, and no GHG emissions were allocated to their production. Direct and indirect GHG emissions from the application were calculated based on the N content (KTBL, 2013). Following the methodology of IPCC (2006) and Cherubini et al. (2009), 1.35% of N_2O per kg N was assumed.

The emission factors for the production of sulphur and copper compounds and canola oil were used, while GHG emissions from other fungicides were approximated with a generic emission factor for pesticides. For herbicides we assumed the emission factor of glyphosate. Emissions from the production of pheromones were neglected due to the lack of an emission factor.

The contribution of Human Labour (HL) is an integral part of all process stages of wine production. As Rugani et al. (2012)

Table 2
Inventories of main emission sources retrieved from the ecoinvent database.

Input into pro-duction system	Inventories retrieved from ecoinvent V.3.4
Viticulture	
P_2O_5 fertilizer	market for phosphate fertilizer, as P_2O_5, GLO
K_2O fertilizer	market for potassium fertilizer, as K_2O, GLO
CaO	market for quick lime, GLO
$CaCo^3$	limestone, milled, packed, RoW
Copper compounds	copper sulfate production, GLO
Potassium hydroxide	market for potassium hydroxide, GLO
Sulfur	market for sulfur, GLO
Pesticide, other	pesticide production, unspecified, RER
Herbicide	glyphosate production, RER
Wood pole	beam, softwood, raw, air drying to u = 20%, RoW; assuming a wood density of 510 kg/m^3
Metal pole	market for steel, low alloyed, GLO & market for zinc coating, pieces, GLO & market for impact extrusion of steel, GLO
Metal wires, zinc coated	market for steel, low alloyed, GLO & zinc coating, coils, RER & market for wire drawing, steel, GLO
Plastic cover for young vines	HDPE granular, RER & extrusion, plastic pipes, RER
Bottling/packaging	
Aluminium closure	aluminium production, primary, ingot, IAI Area, EU27 & EFTA & market for sheet rolling, aluminium, GLO
Packaging film	market for packaging film, low density polyethylene, GLO
Cardboard box	corrugated board box production, RER
Label	market for printed paper, offset, GLO

highlighted, the recognition of HL in life cycle inventories is relevant as no product would exist without HL, and contributes to a more accurate result. Related GHG emissions of HL in wine production were approximated based on the commuting of staff (pkm, passenger kilometre) per means of transportation. Data were available for the wineries only.

The type and amount of wine additives, including wood barrels, and cleaning agents was considered. In absence of emission data from barrel production we estimated the emissions based on weight, life-span transport distance, and mode of transport from the production site to the wine cellar.

The materials for the poles encompassed wood and coated iron or steel, with life spans ranging from 20 to 50 years. An average lifespan of 30 years was assumed.

2.4. Sensitivity analysis

To illustrate the effect of the range provided by the LCI on the final result, we carried out a sensitivity analysis based on a Monte Carlo simulation (Meneses et al., 2016; Wei et al., 2015). The simulation considers the variability in the inventory data only, thereby exploring the natural variability (Björklund, 2002) of the wine value chain.

We determined a confidence interval of results of 90% based on 10,000 simulations, assuming a uniform distribution based on the range of GHG emissions displayed in the result section. Parameters for viticulture encompass trellis system material, diesel, fertilizer, phytosanitory products, and commuting of staff to vineyards. For the winery phase the parameters include electricity, heat, fuel used in company cars, commuting of staff to the winery, additives and cleaning agents, and packaging material. For the viticulture phase those correlations with statistical significance were included, which was limited to the correlation between trellis system and phytosanitory products ($r = 0.660$) and the production of fertilizer and direct field emissions ($r = 0.822$).

2.5. Scenario modelling

The reduction of bottle weight is a key mitigation option identified by many previous authors (e.g. Navarro et al., 2017a; Amienyo et al., 2014; Point et al., 2012). In addition to weight reduction, we explore mitigation potentials related to the reuse of glass bottles, which is common for wine distributed by wineries and cellars for local consumption within the wine-growing areas. However, this bottle type is not common for wine distributed nationwide, exported, and for wine sold in supermarkets. While single-use glass bottles were recycled after their disposal in glass containers, reusable bottles had to be returned to a winery that takes back reusable bottles, or another collection point from which the used bottles can be transported to a washing facility. In these facilities, the bottles were cleaned, disinfected, and returned to the wineries. It was assumed that the distance (return) between winery and washing facility was 50 km, covered by an average van. Process flows are illustrated in Fig. 2. While glass bottles for water or beer are reused up to 50 times (Schonert et al., 2002), the optical requirement for a wine glass bottle is an unscathed appearance,

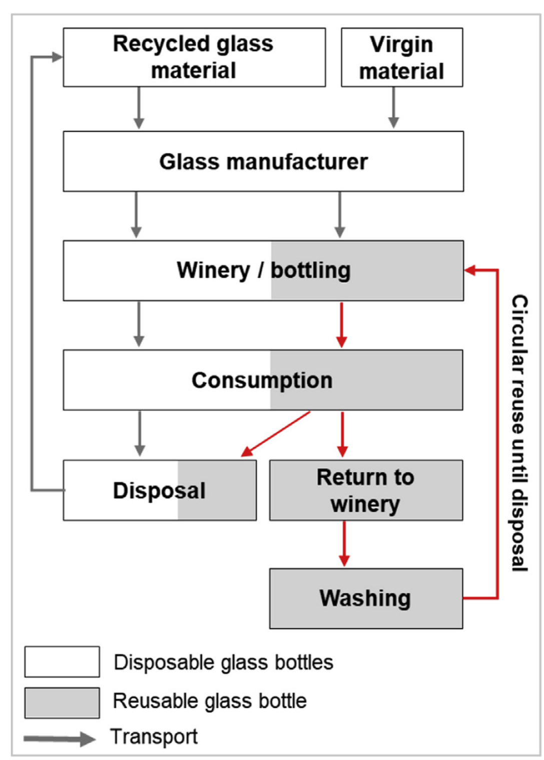

Fig. 2. Process flow diagram of single use and reusable glass bottles.

which severely limits the use cycles. In the absence of data, we assumed a reuse rate of 5 and the recycling thereafter in the same way as single use glass bottles once disposed of in a glass container. The reuse rate served as an allocation factor for the production of a new glass bottle to the production phase of a reusable glass bottle, with reference to the respective bottle weight. GHG emissions attributed to the transport and washing were calculated based on primary data of a bottle washing facility (Table 3). The scenario considers the mean and the range of the bottle weight reported by the wineries and the cellar, which was considered when computing the GHG emissions from glass production for reusable glass bottles.

As an alternative to the 0.75 L glass bottle, the 1 L glass bottle is a packaging type mainly used for entry-level wines, available for single use or reuse. We considered the empirical mean bottle weight of 0.510 kg.

Electricity from renewable energies is a recognized mitigation option. Wine producers could produce electricity from renewable energy sources on own premises or purchase it from a power provider. While direct emissions from the production of renewable energy are zero (WRI, WBCSD, 2004), this is not the case when following a life cycle approach due to upstream (scope 3) processes. We assumed renewable energy generation with photovoltaic and applied a regional emission factor (0.068 kg CO_2eq/kWh, Memmler et al., 2017).

Following the goal of the study we quantified the mitigation potential from weight reduction, comparing it to the reuse of bottle and the use of a larger bottle volume. Therefore, we developed six scenarios: (1) the reduction of weight of an average 0.527 kg bottle, (2) the reuse of an average bottle, (3) the combination of a reduction of weight from average to light weight and reuse. Regarding the increase in bottle volume we assumed the use of a (4) 1.0 L disposable and (5) 1.0 L reusable glass bottle. In addition, we modelled (6) the replacement of grid electricity by renewable energy.

2.6. Inventory

2.6.1. Viticulture

The inventory is presented in detail in Table 4. The range of weight displayed for trellis can be explained by deviations in slope of the vineyards, row spacing and number of vines per hectare (KTBL, 2013), and the differences in the weight of wood and metal poles.

Diesel use was subject to several factors such as the distances between vineyards and the winery, the tractor type, as well as type and amount of viticultural activities. The establishment of new vineyards can also be a cause for high diesel usage. The comparatively high diesel consumption of grape producer 3 can be explained by the prevalence of steep slopes and relatively high demands for phytosanitation due to a particularly moist microclimate.

The types and amounts of herbicides and pesticides were highly farm-specific. The application of a herbicide band underneath the vines and the establishment of a cover crop was common for the assessed conventional vineyards, which results in lower amounts of herbicides used compared to vineyards with a broad herbicide band or full-surface treatments. The organic vineyard did not use herbicides. Insect pests were controlled with pheromone traps, insecticides were not used.

The amount and type of fertilizer supply varied substantially between the producers, which reflects the recommended range of N of 0–80 kg N/ha (DLR RLP, 2018). One grape producer did not add fertilizer, 4 relied entirely on organic sources of N, and 4 supplied 30–60% of N with organic fertilizer (Table 4). The amount and type of fertilizer typically depends on the soil type, humus content, management, vigour of vines, and the outtake of nutrients by the harvest of grapes and the type of cover crop, which may supply the N required by a vineyard partially or even totally (DLR RLP, 2018).

Grape yield per hectare varied but was not explained explicitly. Influencing factors include grape variety, quality management regime, age of vineyard, climate, and seasonal weather events. The average wine grape yield was 10.75 tons per hectare (t/ha) (min 7.22, max 13.90), which is below the national average (12.4 t/ha) reported by Anderson et al (2017), but at the upper end of the range referred to by other studies, such as 10 t/ha (Amienyo et al., 2014), 6 to 12 t/ha (Notarnicola et al., 2003), 5 to 11 t/ha (Bosco et al., 2011), and 3.7 to 11.4 t/ha (Navarro et al., 2017a).

2.6.2. Winery phase

The electricity use covered the operation of machinery, electronic equipment in the winery and attached office spaces, and lighting (Table 5). It was impossible to allocate the electricity use to single processes, therefore we assumed that the main share was required for the wine making process and allocated the electricity use to this process step only (Bosco et al., 2011; Vázquez-Rowe et al., 2012b).

Heat was generated by various energy carriers, mainly natural gas (winery 1,3,5,6), heating oil (winery 4,6), diesel (winery 4) and electricity-powered heaters (winery 2). For winery 5 it was not possible to allocate the use of natural gas to the wine cellar, therefore the mean use of natural gas from wineries 1, 3 and 6 was assumed. The fuel use (diesel and petrol) for vehicles was provided and covered trips made by company vehicles (Table 5).

Table 6 presents the values found for packaging materials. The average weight of a 0.75 L glass bottle used by the sample of this study was 0.527 kg, ranging from 0.400 to 0.650 kg, which represents a wide range of bottle types. Ten percent of the bottles could be categorized as light weight (0.450 kg and less), the weight of 32% was between 0.460 and 0.500 kg, 38% were between 0.510 and 0.550 kg, 14% were between 0.560 and 0.600 kg while the remaining 6% had a weight of 0.610–0.650 kg.

Four types of closures were used by the wineries, namely long-cap aluminium closure (82%) natural cork (7%), synthetic cork (6%), and a glass closure (5%). Both corks and the glass closure are covered with a PE film, which we considered in our model. For natural cork we assumed emissions based on Rives et al. (2013), for synthetic cork the only available information source was a producer Normacorc (2017). The GHG emissions for the aluminium closure were modelled based on the manufacturing and processing of aluminium (ecoinvent 3.4). The emissions for the glass closure were approximated based on the emission factor for glass (BV Glas, 2013).

The observed range of the weight of labels per bottle of wine can be explained by differences in packaging design, such as front and back labels and the size and thickness of labels. The range in packaging film can be explained by distribution channels of the wine producers, with direct sales requiring less packaging film than distribution via other parties.

Table 3
Primary data from the bottle washing facility.

Process inputs for one bottle	Unit	Value
Glass bottle[a]	kg	0.527
Heating oil	kWh	0.032
Electricty	kWh	0.008
Water	L	0.650
Transport 50 km	tkm	0.025

[a] Mean weight of a 0.75 L bottle based on inventory data.

Table 4
Inventory data per hectare for wine grape production (viticulture phase).

Inputs from the technosphere	unit	winery/grape producer 1	2	3	4	5	6	7	8	9	10	11	12	13	14	mean	min	max
Trellis system[a]	kg	n.a.	183.2	304.0	228.8	190.4	173.8	111.8	147.2	152.5	143.7	145.2	112.5	90.1	136.8	163.1	90.1	304.0
Diesel	L	246.4	293.2	369.2	89.4	43.5	156.6	193.1	139.8	173.7	159.5	193.3	156.7	127.7	159.1	178.6	43.5	369.2
Fertilizer																		
Synthetic N	kg	0.1	35.7	37.2	–	67.0	27.3	–	–	30.6	27.9	–	14.7	42.6	31.2	22.4	–	67.0
Organic N	kg	39.5	11.6	24.9	22.6	11.2	15.3	–	14.0	5.6	19.1	25.5	22.1	–	7.3	15.6	–	39.5
% Organic N	%	100%	25%	40%	100%	14%	36%	n.a.	100%	15%	41%	100%	60%	0%	19%	50%	0%	100%
P_2O_5	kg	11.6	4.6	–	–	24.0	–	–	–	8.3	20.7	–	26.7	12.8	8.5	8.4	–	26.7
K_2O	kg	7.4	18.1	12.3	–	34.0	58.0	–	–	41.7	43.1	–	36.9	63.9	42.6	25.6	–	63.9
MgO	kg	3.6	4.6	–	57.4	4.0	29.0	–	–	16.7	16.6	–	8.3	25.5	17.0	13.1	–	57.4
CaO	kg	–	–	62.0	–	–	–	–	–	–	–	–	–	–	–	4.4	–	62.0
$CaCO_3$	kg	–	–	–	–	–	–	–	–	–	79.7	–	46.1	–	–	9.0	–	79.7
Phytosanitory products																		
Copper compounds	kg	–	22.0	3.9	1.1	6.4	–	–	–	–	–	–	–	–	–	2.4	–	22.0
Potassium hydroxide	kg	5.0	–	–	–	–	–	–	–	–	–	–	–	–	–	0.4	–	5.0
Canola oil	kg	–	15.4	–	–	–	–	–	–	–	–	–	–	–	–	1.1	–	15.4
Sulfur	kg	9.6	2.9	14.5	13.1	–	4.6	6.2	3.7	6.1	3.8	2.7	4.4	6.8	2.7	5.8	–	14.5
Pesticides, other	kg	2.4	6.4	10.5	11.6	2.7	5.2	6.4	4.4	5.9	4.8	5.9	4.6	5.3	4.5	5.8	2.4	11.6
Herbicide	kg	1.0	0.4	1.4	–	2.2	1.4	0.9	1.7	1.3	1.5	2.4	1.8	0.8	1.1	1.3	–	2.4
Commuting of staff	pkm	560.6	340.4	1.393.8	555.8	582.6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	686.7	340.4	1.393.8
Outputs																		
Wine grapes	t	10.1	9.9	9.1	9.8	9.2	12.3	7.7	13.9	13.9	10.4	11.1	9.1	13.6	10.3	10.7	7.7	13.9

[a] Per ha and year assuming a lifespan of 30 years.

Table 5
Summary of inventory data per FU (0.75L wine), winery phase.

Inputs from the technosphere	unit	winery/cellar 1	2	3	4	5	6	mean	min	max
Electricity	kWh	0.069	0.189	0.126	0.158	0.334	0.086	0.160	0.069	0.334
Heat	kWh	0.132	0.207	0.489	0.017	0.144	0.123	0.179	0.017	0.489
Diesel	L	0.006	0.012	0.014	0.003	0.018	0.020	0.012	0.003	0.020
Petrol	L	0.005	0.025	–	0.001	–	–	0.005	–	0.025
Wine additives	kg	0.018	0.048	0.015	0.012	0.008	0.018	0.020	0.008	0.048
Cleaning agents	g	0.066	0.789	0.784	2.177	1.000	0.709	0.066	0.789	0.784
Commuting	pkm	–	0.118	0.026	0.076	0.017	0.024	0.043	–	0.118
Wine grapes	kg	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Outputs										
Bottled wine	L	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750

Table 6
Inventory of packaging materials.

Packaging	Unit	mean	min	max
Glass bottles	g	526.88	400.00	650.00
Closures	g	4.89	4.73	6.30
Labels	g	2.08	0.94	3.50
Boxes	g	34.72	31.67	36.67
Packaging film	g	3.90	0.08	18.25

3. Results

3.1. General results

The production of one bottle of wine from cradle to winery gate caused 0.829 kg CO_2e on average, based on the empirical data. Employing a Monte Carlo simulation, we derived a 90% confidence interval of 0.753–1.069 (Fig. 3). This is within the range of results reported by previous studies (e.g. Navarro et al., 2017a; Vázquez-Rowe et al., 2013).

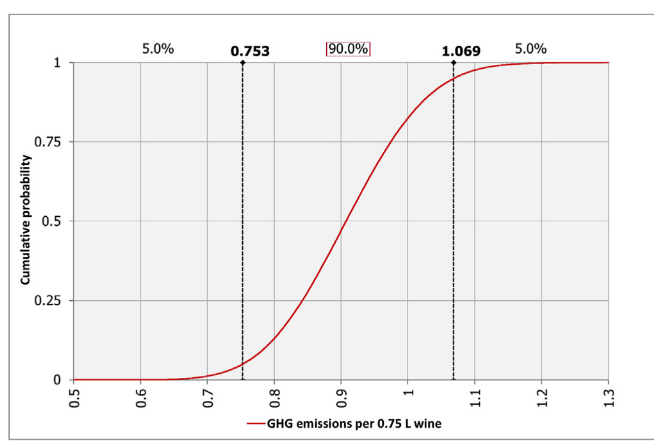

Fig. 3. Monte Carlo simulation of GHG emissions per FU.

Looking at the two process phases, emissions from viticulture activities accounted for 19%, mainly caused by diesel used by tractors, trellis, fertilizer application and production, and to a minor extent by the production of phytosanitory products and the commuting of staff to vineyards (Table 7). GHG emissions from the application of fertilizer exceeded those from pre-chains, also because of the prevalent use of organic sources of N, as explained in the inventory.

Table 7
GHG emission from wine grape production.

Emission source	kg CO_2e per hectare				kg CO_2e per FU			
	% per ha	mean	min	max	% FU	mean	min	max
Trellising system	32%	545.02	237.49	767.48	6%	0.051	0.022	0.071
Diesel	33%	565.59	137.65	1168.85	6%	0.053	0.013	0.109
Fertilizer production	9%	155.86	–	350.95	2%	0.014	–	0.031
Direct field emissions	13%	220.9	–	439.20	2%	0.021	–	0.041
Phytosanitory products	5%	84.53	57.07	184.09	1%	0.008	0.005	0.017
Commuting of staff	8%	128.37	63.64	260.57	1%	0.012	0.006	0.024
Sum	100%	1700.27	495.86	3171.14	19%	0.158	0.046	0.295

At the winery stage 81% of the emissions occurred, the main share being attributable to packaging materials (57% of total emissions, including secondary packaging), with glass bottles being the dominant source (47%). Another main contributor was the electricity used in the winery (10%). Fuel use by the car park of the winery, closures, and boxes amounted to 4% respectively, commuting of staff to the cellar, labels, packaging film, wine additives and cleaning agents each caused 3% or less of the emission budget (Table 8).

The contribution to variance was used as a predictor for the expected effectiveness of a mitigation option, assuming that a high contribution to variance correlates with a high potential impact of efforts to mitigate GHG emissions. The main contributors to variance were the bottle weight (31%), electricity usage (18%), heat used in the winery (11%), and diesel use in vineyards (9%). Yield was negatively associated with the result (−9%), meaning that an increase in yield reduced the GHG emissions per FU (Fig. 4). Based on this indicator, mitigation options can be assumed to be most effective when optimizing the parameters listed above. Fuel used by winery vehicles contributed 8%, and direct field emissions 4% to variance, while all other emission sources contributed less than 3%. Consequently, efforts to reduce GHG emissions that focus on secondary packaging, fertilizer use, trellis, additives, cleaning agents, commuting of staff, and phytosanitory products will have a limited effect on the carbon footprint per bottle of wine.

3.2. Scenario results

A weight reduction of the glass bottle by 24% (Scenario 1) could avoid 11% of the average GHG emissions per bottle of wine (Table 9). Both reuse scenarios clearly outperformed the weight-reduction scenario, with a reuse of an average bottle (Scenario 2) mitigating 36% and in combination with the reduction in weight (Scenario 3) mitigating 38% of the average GHG emissions. The limited increase in mitigation potential of weight reduction in combination with reuse (Scenario 3) can be explained by the GHG emissions attributable to the energy requirements from washing process and transportation associated with the reuse of the wine bottles, as explained in section 2.3. The use of a larger bottle volume (Scenario 4) could avoid 13% of GHG emissions, only slightly exceeding the mitigation potential of the "Weight reduction" scenario (Scenario 1). The reusable larger bottle (1.0 L) provided the highest abatement potential (39%, Scenario 5). Yet, this hardly differs from that of the light-weight reusable 0.75 L bottle (38%, Scenario 3).

Table 8
GHG emissions from vinification and bottling.

Materials and fuels	kg CO_2e per FU			
	% FU	mean	min	max
Electricity	10%	0.085	0.036	0.176
Heat	6%	0.051	0.005	0.120
Fuel (company cars)	4%	0.033	0.002	0.094
Commuting of staff to winery	1%	0.008	–	0.022
Additives + cleaning	3%	0.022	0.013	0.035
Glass bottles	47%	0.390	0.296	0.481
Closures	4%	0.031	0.008	0.046
Labels	1%	0.007	0.003	0.012
Boxes	4%	0.032	0.029	0.034
Packaging film	1%	0.012	0.000	0.055
Sum	81%	0.671	0.393	1.075

With a mitigation potential of 9% the use of electricity from renewable energy presents itself as a valuable stand-alone option (Scenario 6), or as an addition to the other mitigation options discussed above. In combination with a weight reduction and reuse of the bottle (Scenario 3), the abatement of 47% of the GHG emissions per standard bottle of wine would be possible. More detailed scenario assumptions and respective mitigation potentials are presented in Table 9.

4. Discussion

Mitigation strategies focused on energy management and water use in the vineyard and the cellar, fertilization of vines and, most importantly, packaging material (Navarro et al., 2017a; Aranda et al., 2005; Benedetto, 2013; Ardente et al., 2006; Point et al., 2012; Amienyo et al., 2014).

Based on the results from the Monte Carlo simulation and the analysis of the contribution of the single emission sources to the variance of the result showed that the top 5 management options with the highest potential impact on GHG reductions are related to glass bottles, electricity consumption in the winery, diesel use in vineyards, heat used in the winery, and an increase in yield. Management options related to other inputs such as fertilizer and pesticides use, labels, closures and boxes, or commuting had minor effects on overall GHG emissions from wine production. Previous wine CF studies also claim the reduction of glass weight to be the key strategy to reduce GHG emissions from the wine value chain (e.g. Navarro et al., 2017a; Point et al., 2012). This is undoubted for bottles with a weight clearly exceeding 0.400 kg, and the potential reduction in GHG emissions is the more pronounced the heavier the bottle. However, there are two limitations. First, for bottles that are already light the potential to reduce the weight further is very limited or not existent for technical reasons as the stability of the glass bottle can be reduced (Hartley, 2008). Second, if consumers do not perceive wine in light-weight bottles as equally valuable to wine in heavy bottles, this has to be acknowledged as an important implementation barrier resulting from consumer behaviour. In this respect, in their extensive review on consumer behaviour for wine Lokshin and Corsi (2012) point towards a small segment of the population that values wine with sustainability characteristics.

We found a GHG emission abatement of 11% for the reduction in weight of an average bottle to 0.400 kg (−24%). This finding is in

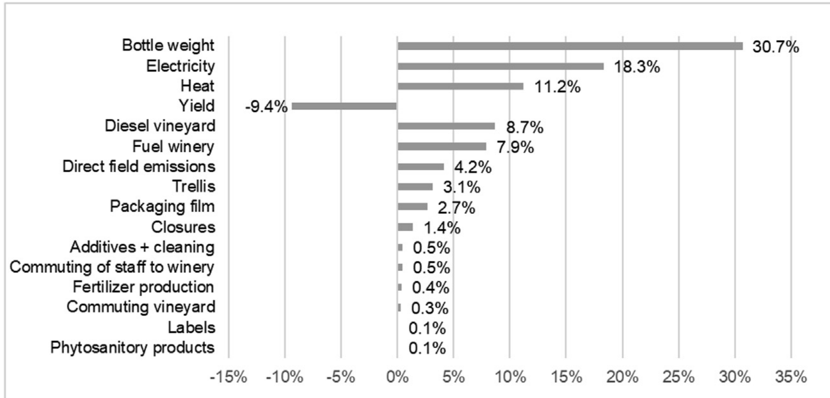

Fig. 4. Contribution to variance of GHG emission sources.

Table 9
Mitigation potential of selected scenarios.

#	Scenario	Description	kg CO_2e sce-nario, per FU	Mitigation (kg CO_2e)	Mitigation (% result)
1	Weight reduction, average weight	Reduction of glass bottle weight from 0.527 kg to 0.400 kg (0.75 L)	0.297	0.094	11%
2	Reuse, average weight	Reuse of average 0.527 kg bottle (0.75 L)	0.093	0.298	36%
3	Reuse light-weight	Weight reduction to 0.400 kg and reuse (0.75 L)	0.074	0.317	38%
4	1.0 L bottle volume	FU in average disposable 1.0 L glass bottle, 0.510 kg	0.285	0.107	13%
5	1.0 L bottle volume reuse	FU in average reusable 1.0 L glass bottle, 0.510 kg	0.068	0.323	39%
6	Renewable energy	Electricity consumption: replacement of grid electricity with renewable energy (PV)	0.011	0.074	9%

line with Amienyo et al. (2014) who found a reduction in GHG emissions of 11% following a reduction in bottle weight by 30%. However, these authors based their assumed bottle weight reduction on a light-weight 0.465 kg glass bottle, not acknowledging practical limitations highlighted by Hartley (2008). Point et al. (2012), reported a reduction in GHG emissions of only 5.3% for a bottle weight decreased by 30% to 0.380 kg. This lower relative reduction can be explained by the larger system boundaries (cradle to grave) of their study, which lead to a lower share of GHG emissions from the glass bottle production compared to the total result (11.5%). The authors include the mitigative effects in process stages subsequent to bottling, such as transportation to retail, consumer shopping trip, and recycling. This exemplifies the importance of a reduced bottle weight as it not only mitigates GHG emissions attributable to packaging but also to downstream processes such as transportation.

Exploring various scenarios for a reduction of GHG emissions from glass bottles we found that the reuse of an average 0.527 kg glass bottle exceeded the mitigation potential of a weight reduction to a light weight 0.400 kg bottle by more than threefold, avoiding 36% as opposed to 11%. Further, our scenario analysis points towards the mitigative effect of a combination of bottle weight reduction and reuse (−38%) and the increase in bottle volume to 1.0 l and reuse (−39%). In light of these new findings, we argue that the reuse of glass bottles has to be at the core of any strategy that aims at an effective decarbonization of the wine value chain. The reuse of bottles can be complemented with a reduction in bottle weight. Moreover, this option can overcome undesired environmental effects related to consumer behaviour related to the acceptance of light-weight bottles for premium wines. Given the large reduction in GHG emissions, the reuse of glass bottles is a viable mitigation option where longer transport distances between wine producer, consumer, and washing facility are required.

Practical limitations of the reuse of wine glass bottles cannot be ignored and include a lack of infrastructure if the access to a washing facility is difficult or prohibitive due to high transport cost and associated carbon emissions for long distances, and possible additional cost for reusable bottles. Further, aside from wine producers, specialised retailers, supermarkets, discounters which distribute approximately 87% of the wine consumed (Deutsches Weininstitut, 2017) would need to limit themselves to a variety of bottle types that can be circulated amongst them, which in turn limits the individuality of packaging design. Last but not least, wine consumers would need to make the effort to return glass bottles to a collection point instead of disposing of them into a glass container.

While the increase of recycling content may be a relevant option in Spain, France (Navarro et al., 2017a), or England (Amienyo et al., 2014), this is not feasible in Germany as the recycling share for wine glass bottles is already very high (87%). Therefore, GHG emissions from glass production could only be reduced by increasing the share of renewable energy and natural gas (BV Glas, 2013).

The scenario analysis presented the use of renewable energies as a viable mitigation strategy, avoiding 9% of GHG emissions. We argue that this is an attractive strategy as implementation barriers are low, merely requiring a change in the electricity supply, unless renewable energy was generated on own premises. The implementation barrier to a decarbonization of the heating system would be significantly higher, requiring investments into a change of existing infrastructure.

Considering the categorization of emission sources based on the GHG Protocol (Table 1) the most important mitigation options occur in scope 3 – other indirect emissions, meaning they arise from processes external to the wine producer and are within the scope of influence of stakeholders. Consequently, wine producers and stakeholders share the responsibility for the decarbonisation of the wine value chain.

Yield was named as a main driver of variability by other authors (e.g. Vázquez-Rowe et al., 2013, 2012b; Villanueva-Rey et al., 2014), which we confirm based on the high negative contribution to variance (−9%). Being the allocation factor of GHG emissions from viticulture to the final product, yield has a high impact on the GHG emissions per FU because an increase in yield leads to a reduction in GHG emissions per hectare of FU, if the agri-inputs are kept stable or increase at a lower rate. However, limits to increase yield can arise from legal (BMJV, 2016), geological and climatological factors, while an induced increase in yield can counteract the quality regime, and therefore the market positioning, of a wine producer. Considering international yield patterns, there are clear differences between wine-growing nations. While Germany had an average wine grape yield of 12.4 tons, other "Old World" wine-growing nations report lower levels (France 8.1, Italy 9.9, Portugal 4.6, Spain 6.7 tons), and "New World" wine destinations may have higher average levels of yield (e.g. USA 17.1, Chile 17.9, China 15.8 tons of grape per hectare) (Anderson et al (2017)). While single vineyards may deviate greatly from these averages, these general differences should be acknowledged when comparing wine CF studies.

5. Conclusions

GHG emissions due to wine production can vary substantially according to management and selection of inputs and materials. We found a 90% confidence interval for 0.753–1.069 kg CO_2e per bottle of wine. The main contributors to the variance of GHG emissions were glass bottle weight (31%), electricity use at the winery stage (18%), heat used in the winery phase (11%), yield (−9%), and diesel used in vineyards (9%). The trellis system, production and use of fertilizer, and secondary packaging were minor contributors to the final result, but it should be acknowledged that out of 14 grape production entities one did not add any fertilizer, 4 relied entirely on organic sources of N, and another 4 covered 30–60% of added N with organic fertilizer. The production of phytosanitory products, commuting of staff, and wine additives and cleaning agents were negligible sources of GHG emissions.

We found that the reuse of glass bottles deserves close attention from wine producers, consumers, and policy makers who strive for an effective decarbonization of the wine value chain. The mitigation potential of the reuse of an average bottle exceeds the mitigation potential from a reduction in bottle weight by more than threefold. A combination of the replacement of grid electricity by renewable energies, the reduction in weight and reuse of a lightweight glass bottle can curb GHG emissions per bottle of wine by 47%.

While recommendations on emission reduction in the winery phase are straight forward and transferrable to other wine producers, this is not the case for the viticulture stage. Here, main options for GHG reductions were the reduction in fuel use, the increase in the life span of the trellis system, and the increase in yield. Factors such as differences in the topography, microclimate, the age and layout of existing vineyards, as well as quality aspirations, impose limits to the validity of generalized recommendations on vineyard level.

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References

Amienyo, D., Camilleri, C., Azapagic, A., 2014. Environmental impacts of consumption of Australian red wine in the UK. J. Clean. Prod. 72, 110–119.
Anderson, K., Nelgen, S., Pinilla, V., 2017. Global Wine Markets, 1860 to 2016: a Statistical Compendium. University of Adelaide Press, Adelaide.
Ardente, F., Beccali, G., Cellura, M., Marvuglia, A., 2006. POEMS: a case study of an Italian wine-producing firm. Environ. Manag. 38, 350–364.
Benedetto, G., 2013. The environmental impact of a Sardinian wine by partial life cycle assessment. Wine Econ. Policy 2, 33–41.
Björklund, A.E., 2002. Survey of approaches to improve reliability in lca. Int. J. Life Cycle Assess. 7 (2), 64–72.
BMJV (2016). Bundesministeriums der Justiz und für Verbraucherschutz. Weingesetz in der Fassung der Bekanntmachung vom 18. Januar 2011 (BGBl. I S. 66), das durch Artikel 3 des Gesetzes vom 16. Januar 2016 (BGBl. I S. 52) geändert worden ist: Weingesetz. WeinG 1994; Bundesministeriums der Justiz und für Verbraucherschutz: Berlin, Germany, 2016.
Bonamente, E., Scrucca, F., Rinaldi, S., Merico, M.C., Asdrubali, F., Lamastra, L., 2016. Environmental impact of an Italian wine bottle: carbon and water footprint assessment. Sci. Total Environ. 560–561, 274–283.
Bosco, S., Di Bene, C., Galli, M., Remorini, D., Massai, R., Bonari, E., 2011. Greenhouse gas emissions in the agricultural phase of wine production in the Maremma rural district in Tuscany. Italy. Ital. J. Agron. 6, 93–100.
Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S., 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges, and recommendations. Ressour. Conserv. Recy. 53, 434–447.
Chichelli, A., Pattara, C., Petrella, A., 2016. Sustainability in mountain viticulture. The case of the Valle Peligna. Agric. Agric. Sci. Proc. 8, 65–72.
Christ, K.L., Burrit, R.L., 2013. Critical environmental concerns in wine production: an integrative review. J. Clean. Prod. 53, 232–242.
Defra, 2016. Conversion Factors 2016 - Full Set (For Advanced Users). Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016. (Accessed 28 May 2018).
Deutsches Weininstitut, 2017. Deutscher Wein Statistik 2016/2017. Bodenheim, Germany.
DLR RLP (Dienstleistungszentren Ländlicher Raum Rheinland-Pfalz), 2018. Stickstoff-Düngemittelbedarfsermittlung im Weinbau. Available at: http://www.dlr.rlp.de/Internet/global/themen.nsf/71d722c50f66ecc3c12581210042df58/f8a073bd5ff13380c1258138004274d3/$FILE/N-D%C3%BCngebedarfsermittlungWEINBAU_Merkblatt+Formular_D%C3%BCV2017_RLP_14.05.18.pdf. (Accessed 29 May 2018).
Ecoinvent, 2017. Ecoinvent Database V.3.4. Swiss Centre for Life Cycle Inventory, CH. Available at: http://www.ecoinvent.org/database. (Accessed 1 December 2017).
Fusi, A., Guidetti, R., Benedetto, G., 2014. Delving into the environmental aspect of a Sardinian white wine: from partial to total life cycle assessment. Sci. Total Environ. 472, 989–1000.
Galbreath, J., 2012. On the Relevancy of Climate Change to Business: Evidence from the Margaret River Wineregion of Australia. AAWE. Working Paper No. 107.
Gazulla, C., Raugei, M., Fullana-i-Palmer, P., 2010. Taking a life cycle look at Crianza wine production in Spain: where are the bottlenecks? Int. J. Life Cycle Assess. 15, 330–337.
Glas, B.V., 2013. BV Glas Nachhaltigkeitsstudie. Zusammenfassung. January 2013, Düsseldorf, Germany.
Grebitus, C., Steiner, B., Veeman, M., 2016. The roles of human values and generalized trust on stated preferences when food is labeled with environmental footprints: insights from Germany. Food Pol. 52, 84–91.
Hannah, L., Roehrdanz, P.R., Ikegami, M., Shepard, A.V., Shaw, M.R., Tabor, G., Zhi, L., Marquet, P.A., Hijmans, R.J., 2012. Climate change, wine, and conservation. Proc. Natl. Acad. Sci. Unit. States Am. 17, 6907–6912.
Hartley, A., 2008. Lightweight Wine Bottles: Strength as an Issue in the Manufacture of Lightweight Wine Bottles. Final Report: GlassRite: Wine. ISBN: 1-84405-388-1, Banbury, Oxon, May 2008, Available at: http://www.wrap.org.uk/sites/files/wrap/Wine%20bottle%20strength%20May'08.pdf. (Accessed 28 May 2018).
Icha, P., Kuhns, G., 2018. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 – 2017. Umweltbundesamt. Dessau-Roßlau, Germany.
IPCC, 2006. Guidelines for national greenhouse gas inventories, vol. 4. Agriculture, Forestry and Other Land Use, Intergovernmental Panel of Climate Change.
ISO 14040, 2006. Environmental Management-life Cycle Assessment-principles and Framework. International Organization for Standardization, Geneva, Switzerland.
Jradi, S., Chameeva, T.B., Delhomme, B., Jaegler, A., 2018. Tracking carbon footprint in French vineyards: A DEA performance assessment. J. Clean. Prod 192, 43–54.
KTBL, 2013. Weinbau und Kellerwirtschaft, fifteenth ed. Darmstadt, Germany.
Lal, R., 2004. Carbon emissions from farm operations. Environ. Int. 30, 981–990.

Lockshin, L., Corsi, A.M., 2012. Consumer behaviour for wine 2.0: a review since 2003 and future directions. Wine Econ. Pol. 1, 2–23.
Marras, S., Masia, S., Duce, P., Spano, D., Sirca, C., 2015. Carbon footprint assessment on a mature vineyard. Agric. For. Meteorol. 214–215, 350–356.
Memmler, M., Lauf, T., Wolf, K., Schneider, S., 2017. Emissionsbilanz Erneuerbarer Energieträger, Umweltbundesamt. Dessau-Rosslau, Germany.
Meneses, M., Torres, C.M., Castells, F., 2016. Sensitivity analysis in a life cycle assessment of an aged red wine production from Catalonia, Spain. Sci. Total Environ. 562, 571–579.
Myhre, G., Shindel, D. l., Breon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013. Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Navarro, A., Puig, R., Kiliç, E., Penavayre, S., Fullana-i-Palmer, P., 2017a. Eco-innovation and benchmarking of carbon footprint data for vineyards and wineries in Spain and France. J. Clean. Prod. 142, 1661–1671.
Navarro, A., Puig, R., Fullana-i-Palmer, P., 2017b. Product vs. Carbon Footprint: some Methodological Issues. A case study and review on the wine sector. Sci. Total Environ. 581–582, 722–733.
Neto, B., Dias, A.C., Machado, M., 2013. Life cycle assessment of the supply chain of a Portuguese wine: from viticulture to distribution. Int. J. Life Cycle Assess. 18, 590–602.
Normacorc, 2017. Environmental footprint. Available at: www.normacorc.com/environmental-footprint/. Accessed May 2018.
Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of Life Cycle Assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140 (2), 399–409.
OIV, April 2017. State of the Vitiviniculture World Market. Available at: http://www.oiv.int/public/medias/5287/oiv-noteconjmars2017-en.pdf. Accessed October 2018.
Pizzigallo, A.C.I., Granai, C., Borsa, C., 2008. The joint use of LCA and emergy evaluation for the analysis of two Italian wine farms. J. Environ. Manag. 86, 396–406.
Point, E., Tyedmers, P., Naugler, C., 2012. Life cycle environmental impacts of wine production and consumption in Nova Scotia, Canada. J. Clean. Prod. 27, 11–20.
Rives, J., Fernandez-Rodriguez, I., Rieradevall, J., Gabarrell, X., 2013. Integrated environmental analysis of the main cork products in southern Europe (Catalonia – Spain). J. Clean. Prod. 51, 289–298.
Rugani, B., Panasiuk, D., Benetto, E., 2012. An input-output based framework to evaluate human labour in life cycle assessment. Int. J. Life Cycle Assess. 17 (6), 795–812.
Rugani, B., Vázquez-Rowe, I., Benedetto, G., Benetto, E., 2013. A comprehensive review of carbon footprint analysis as an extended environmental indicator in the wine sector. J. Clean. Prod. 54, 61–77.
Schäufele, I., Hamm, U., 2017. Consumers' perceptions, preferences and willingness-to-pay for wine with sustainability characteristics: a review. J. Clean. Prod. 147, 379–394.
Schonert, M., Motz, G., Meckel, H., Detzel, A., Giegrich, J., Ostermaxer, A., Schorb, A., Schmitz, S., 2002. In: Ökobilanz für Getränkeverpackungen II/Phase 2. Forschungsbericht 103 50 504, UBA-FB 000363. German Environment Agency, Berlin, Germany.
Steenwerth, K., Strong, E.B., Greenhut, R.F., Williams, L., Kendall, A., 2015. Life cycle greenhouse gas, energy, and water assessment of wine grape production in California. Int. J. Life Cycle Assess. 20, 1243–1253.
Szolnoki, G., 2013. A cross-national comparison of sustainability in the wine industry. J. Clean. Prod. 53, 243–251.
Vázquez-Rowe, I., Villanueva-Rey, P., Iribarren, D., Teresa Moreira, M., Feijoo, G., 2012a. Joint life cycle assessment and data envelopment analysis of grape production for vinification in the Rías Baixas appellation (NW Spain). J. Clean. Prod. 27, 92–102.
Vázquez-Rowe, I., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2012b. Environmental analysis of Ribeiro wine from a timeline perspective: harvest year matters when reporting environmental impacts. J. Environ. Manag. 98, 73–83.
Vázquez-Rowe, I., Rugani, B., Benetto, E., 2013. Tapping carbon footprint variations in the European wine sector. J. Clean. Prod. 43, 146–155.
Villanueva-Rey, P., Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2014. Comparative life cycle assessment in the wine sector: biodynamic vs. conventional viticulture activities in NW Spain. J. Clean. Prod. 65, 330–341.
Wei, W., Larrey-Lassalle, P., Faure, T., Dumoulin, N., Roux, P., Mathias, J.-D., 2015. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. Environ. Sci. Technol. 49 (1), 377–385.
WeinV (1995). Weinverordnung in der Fassung der Bekanntmachung vom 21. April 2009 (BGBl. I S. 827), die durch Artikel 16 der Verordnung vom 05. Juli 2017 (BGBl. I S. 2272) geändert worden ist.
WRI, WBCSD, 2004. The Greenhouse Gas Protocol. A Corporate Accounting and Reporting Standard. World Resources Institute, Washington DC (USA).
WRI, WBCSD, 2011. Greenhouse Gas Protocol. Corporate Value Chain (Scope 3) Accounting and Reporting Standard. World Resources Institute, Washington DC (USA).