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Greenhouse gas emissions in the agricultural phase of wine production in the Maremma rural district in Tuscany, Italy

Simona Bosco,[1] Claudia Di Bene,[1] Mariassunta Galli,[1] Damiano Remorini,[1,2] Rossano Massai,[2] Enrico Bonari[1]

[1]Land Lab, Scuola Superiore Sant'Anna, Pisa; [2]Dipartimento di Coltivazione e Difesa delle Specie Legnose G. Scaramuzzi, Università di Pisa, Italy

Abstract

In recent years, there has been an increasing interest from retailers, industries and environmental associations in estimating the life cycle of greenhouse gases emitted in the atmosphere from everyday products and services, also known as carbon footprint (CF). Life cycle assessment (LCA) is the most common methodology used to evaluate the environmental impact of a product. This approach was largely used in many industrial sectors and was also recently applied to quantify the environmental impact of the agri-food chain. Within agri-food products, wine is one of the most analysed, both for its importance in economic production and in the world distribution market. The present study is a part of the *Carbon Label Project* carried out in the wine production chain in the Maremma rural district (Tuscany, Italy). The project assessed the greenhouse gas (GHG) emissions from wine production for labelling purposes. Here, we evaluated the environmental performances of four high quality wines for carbon labelling. The international standards ISO 14040, ISO 14044, and the Product Category Rules (PCR) *Wine from Fresh Grapes (except sparkling wine) and Grape Must* for the Environmental Product Declaration (EPD) certification, specifically for Climate Declaration, were used in order to carry out our analyses. The functional unit (FU) used here was one 0.75 L bottle of wine. The system boundaries were set from the vineyard planting to the distribution and waste disposal. The global warming potential (GWP) of four investigated wines was found to lie between 0.6 and 1.3 kg CO_2-eq./bottle, showing a value comparable with literature. With all the four wines analysed, the agricultural phase covered, on average, 22% of the total GWP/bottle, while the main impact was in the production of the glass bottle. The results showed that the vineyard-planting phase has a significant impact on the wine CF, thus it has to be considered in the life cycle, while in literature it is frequently omitted. On the contrary, the pre-production phase did not present a relevant impact. The use of nitrogen fertilisers, the grapes' yield and N_2O emissions were the parameters that mostly affected the carbon footprint in the agricultural phase, as underlined by the sensitivity analysis.

Correspondence: Dr. Simona Bosco, Land Lab, Scuola Superiore Sant'Anna, p.zza Martiri della Libertà 33, 56127 Pisa, Italy.
Tel. +39.050.883503 - Fax: +39.050.883526.
E-mail: s.bosco@sssup.it

Key words: agri-food chain, carbon footprint, global warming potential, life cycle assessment, vineyard management, wine-growing farm.

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Introduction

In the global warming and climate protection debate, there is an increasing interest from retailers, industry and environmental regulators to declare the environmental impact of their products by assessing the life cycle of greenhouse gas (GHG) emission per unit of product (Boumann and Tillman, 2004; Weidema *et al*., 2008; Bala *et al*., 2010). Life cycle assessment (LCA), defined in ISO standards 14040 and 14044 (ISO, 2006 a, b), is an internationally recognised environmental accounting tool which offers a standardised framework and methodology for quantifying the environmental impacts of a product or a production system throughout its life cycle, which is known as a *from cradle to grave* analysis. The environmental impact of a particular product or service during its lifetime, assessed only in terms of GHG emissions, is called carbon footprint (CF) (Weidema *et al*., 2008; Finkbeiner, 2009; Schmidt, 2009). One of the first definitions of carbon footprint was given by Wiedmann and Minx (2008): *CF is a measure of the total exclusive amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product*. This definition refers only to carbon dioxide, being well aware that there are other substances with greenhouse warming potential. However, today the carbon footprint analysis is typically expressed in kg CO_2-equivalent (CO_2-eq.) and including emissions of GHG, monitored under the Kyoto Protocol, and especially of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In recent years, the carbon footprint has gained recognition as a tool able to identify a good or service's contribution to climate change.

So far, different approaches and guidelines were developed for accounting GHG emissions in order to monitor and mitigate the long-term effects. Besides, methodologies for the territorial scale developed by the Intergovernmental Panel on Climate Change (IPCC) for GHG emissions, national inventories and for the quantification of GHG emissions in organization as the ISO 14064 (ISO, 2006c), many guidelines have been elaborated for the GHG life cycle of goods and services. The best known are the Publicly Available Specification PAS2050, developed by the British Standard Institute and the Carbon Trust (BSI, 2008; Carbon Trust, 2010), the French Bilan Carbone (ADEME, 2010), the GHG Protocol drew up by the World Resources Institute and the World Business Council for Sustainable Development (WBCSD/WRI, 2009). A specific ISO standard on product carbon footprint, ISO 14067 (ISO, 2010) is under preparation.

The use of a single indicator compared to a complete LCA raises the prospect of burden shifting – solving one problem while creating another. This can unfairly promote products that do not necessarily have a better overall environmental performance, or environmental footprint (Weidema, 2008). However, there is much interest from non-governmental organizations and retail chains with regard to this indicator due to its easiness in understanding and communicating the impact of climate change from everyday products. Moreover, this indicator could be a meaningful tool for mitigating global warming (Finkbeiner, 2009).

In the last few years, many specific labels were created, such as the procedures for evaluating the environmental performances of products or services during the lifetime, and many authors and organizations tried to standardize the methodology to measure the GHG and CF of a product (SETAC, 2008). One of most used labels in Europe is the Climate Declaration developed in the Environmental Product Declaration (EPD) system and devised by the Swedish Environmental Research Institute in 2007 (Schau and Fet, 2008).

The LCA and CF approach was largely used in many industrial sectors and was also recently applied to quantify the environmental impact of the agri-food chain (Milà i Canals *et al*., 2006; Avraamides and Fatta, 2008; Meisterling *et al*., 2009; Roy *et al*., 2009). It is well known that the LCA for food products is more difficult to assess in comparison with the one of the industrial products, since for the agricultural phase such methodology is not well established and the process cannot be easily standardised (Cowell and Clift, 1997; Haas *et al*., 2000; Mourad *et al*., 2007). Hence, said phase is associated with the uncertainty due to the variability of natural processes (Ardente *et al*., 2006; Röös *et al*., 2010).

Within agri-food products, the wine chain is one of the most analysed, both for its importance in the economic production and in the world distribution market (Ardente *et al*., 2006; Point, 2008; Barber *et al*., 2009; Petti *et al*., 2010). Considering the whole wine chain, several studies reported that the major environmental impacts of wine production are the use of pesticides and fertilisers in the agricultural phase, and the production of glass bottles in the industrial phase (Notarnicola *et al*., 2003; Aranda *et al*., 2005; Ardente *et al*., 2006; Point, 2008; Gazulla *et al*., 2010).

Moreover, wine distribution may also contribute to the overall environmental impact of such chain (Cholette and Venkat, 2009), although the impact of distribution can widely vary due to distance, means of transportation and the efficiency of the logistics management (Point, 2008).

In that regard, in 2008 the *Carbon Label Project* was founded by the National Institute for Foreign Trade in collaboration with the Administration of the Grosseto Province (Tuscany, Italy). This project was set up in the Maremma rural district in order to evaluate the environmental performances of wine, olive oil and fruit productions, which represent the main food chains of that area. The aim of the project was to identify the suitable label on GHG emissions and to carry out the CF study for the wine producers to label that product. CF analysis was applied to the entire line of selected wines.

This paper presents the results of the CF analysis of four high quality wines produced in Maremma rural district, including all the products' life cycle stages, namely vineyard planting, pre-production and production phase, vinification, bottling and packaging, distribution and waste management phases, with special interest on the agricultural phase.

Materials and Methods

Site description and farms monitored

The present study is a part of the *Carbon Label Project* carried out on wine production chains in the Maremma rural district. This area, the largest agricultural area in the Tuscany region, is very suitable for the production of high quality wine due to the specific characteristics of the terroir (soil, climate and vineyard-environment interaction). Such suitability is confirmed by the occurrence of three wine routes, known as *Routes of Wine and Taste*, and several quality trademarks, such as eight, controlled denomination of origin (DOC), two typical geographical indications (IGT) and one controlled and guaranteed denomination of origin (DOGC). In that regard, there are many small to medium winery enterprises and five cooperative wineries. Such cooperatives account for about 28% of the total wine making sector (more than 1400 members) and cover an area of 2150 ha, which is one third of the total area of all the vineyards (Montaldo *et al*., 2007).

In order to obtain a representative sample, in this study four wines have been selected and analysed; two produced by closed cycle farms, with medium to large vineyards and small to medium wineries (wine 1, W1 and wine 2, W2) and two wines produced by cooperative wineries (wine 3, W3 and wine 4, W4), composed by several members who deliver grapes to a common winery. The cooperative wineries suggested one or more farms in order to collect data on the agricultural phase. The characteristics of the wines and farms analysed are shown in Table 1.

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Table 1. The four wines investigated in the Maremma rural district.

	Wine 1	Wine 2	Wine 3	Wine 4
Wine Company	Closed cycle farm	Closed cycle farm	One farm and one cooperative winery	Nine farm and one cooperative winery
Municipality	Massa Marittima	Grosseto	Pitigliano	Scansano
DOC Area	DOC Monteregio di Massa Marittima	DOCG Morellino di Scansano	DOC Bianco di Pitigliano	DOCG Morellino di Scansano
Wine	IGT Maremma Toscana (red wine)	IGT Maremma Toscana (red wine)	Bianco di Pitigliano DOC (white wine)	Morellino di Scansano DOCG (red wine)
Bottle	0.75 L green glass	0.75 L green glass	0.75 L white glass	0.75 L green glass
Number of bottles	39,000	23,000	132,000	250,000
Aging	18 months	24 months	No	No
Average platform distance	130 km	1600 km	60 km	350 km

DOC, controlled denomination of origin; IGT, typical geographical indication; DOGC, controlled and guaranteed denomination of origin.

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Methodological choices for life cycle assessment

Goal definition

The purposes of this study were i) to evaluate the CF of the entire life cycle of four high quality wines from Maremma rural district, two DOC and two IGT (Table 1), following the specific PCR for EPD certification and to identify the most critical hotspots; and ii) to investigate the specific impact of the agricultural phase.

Functional unit, system boundaries and assumptions

The definition of system boundaries is affected by the goal of the study that complies with an existing label. Here, we followed the international standards (ISO 14040 and ISO 14044) and the product category rules (PCR) *Wine from Fresh Grapes (except sparkling wine) and Grape Must* for the *Environmental Product Declaration* certification, specifically for the Climate Declaration, in order to carry out our analyses (EPD, 2008).

The functional unit (FU) used here was one 0.75 L bottle of wine, instead of a 1 L bottle of packaged wine, specifically in the PCR, since all four wines are sold in the same format of 0.75 L.

The system boundaries were set from vineyard planting to distribution and waste disposal. The system boundaries were followed, as described in the PCR, for the up stream process including vineyard planting, the pre-production phase, grape production, wine production, bottling and packaging, transportation from final production site to an average distribution platform and recycling or handling of packaging materials after use. The generation of energy and production of input material, external transportation of raw material and production of primary and secondary packaging materials are considered. Figure 1 reports the flowchart of the whole wine production chain, divided into two main phases, the agricultural and industrial ones, and seven sub-phases. In particular, the agricultural phase has been divided into three sub-phases: vineyard planting, pre-production and production. Concerning the agricultural stage, few studies deal with vineyard planting (Pizzigallo *et al*., 2008), while others start the life cycle from the cultivation phase (Notarnicola *et al*., 2003; Point, 2008; Gazulla *et al*., 2010). The industrial phase has been organised into 4 sub-phases: vinification, bottling, packaging, distribution and waste management.

The analysis was performed with the GaBi4 software package, developed by PE International (GaBi4, 2007a) and the bundled professional database and the Ecoinvent database (GaBi, 2007b; Ecoinvent, 2009). The GWP impact category was analysed with the comparison of life cycle assessment (CML) method, version 2007 (Guinée *et al*., 2002).

Here, the assumption to evaluate the GWP impact was to consider the emissions of CO_2, CH_4 and N_2O generated by the energy and material input production in each chain phase. The Italian energetic mix, included in the GaBi4 database, was used for energy production impact. As the PCR document does not give specific rules for the calculation of soil GHG emissions from fertilisers, direct and indirect N_2O emissions from soil were calculated using the IPCC methodology and emissions factors (IPCC, 2006). The CO_2 emissions/removal generated by the carbon stock changes in biomass and soil were not included, due to difficulties obtaining a specific spatial estimate without a sampling campaign or validated models (Koerber *et al*., 2009). The CO_2 biogenic emissions, such CO_2 derived from grape fermentation, has not been included. A sensitivity analysis was performed in order to validate the robustness of the LCA model and identify the key parameters.

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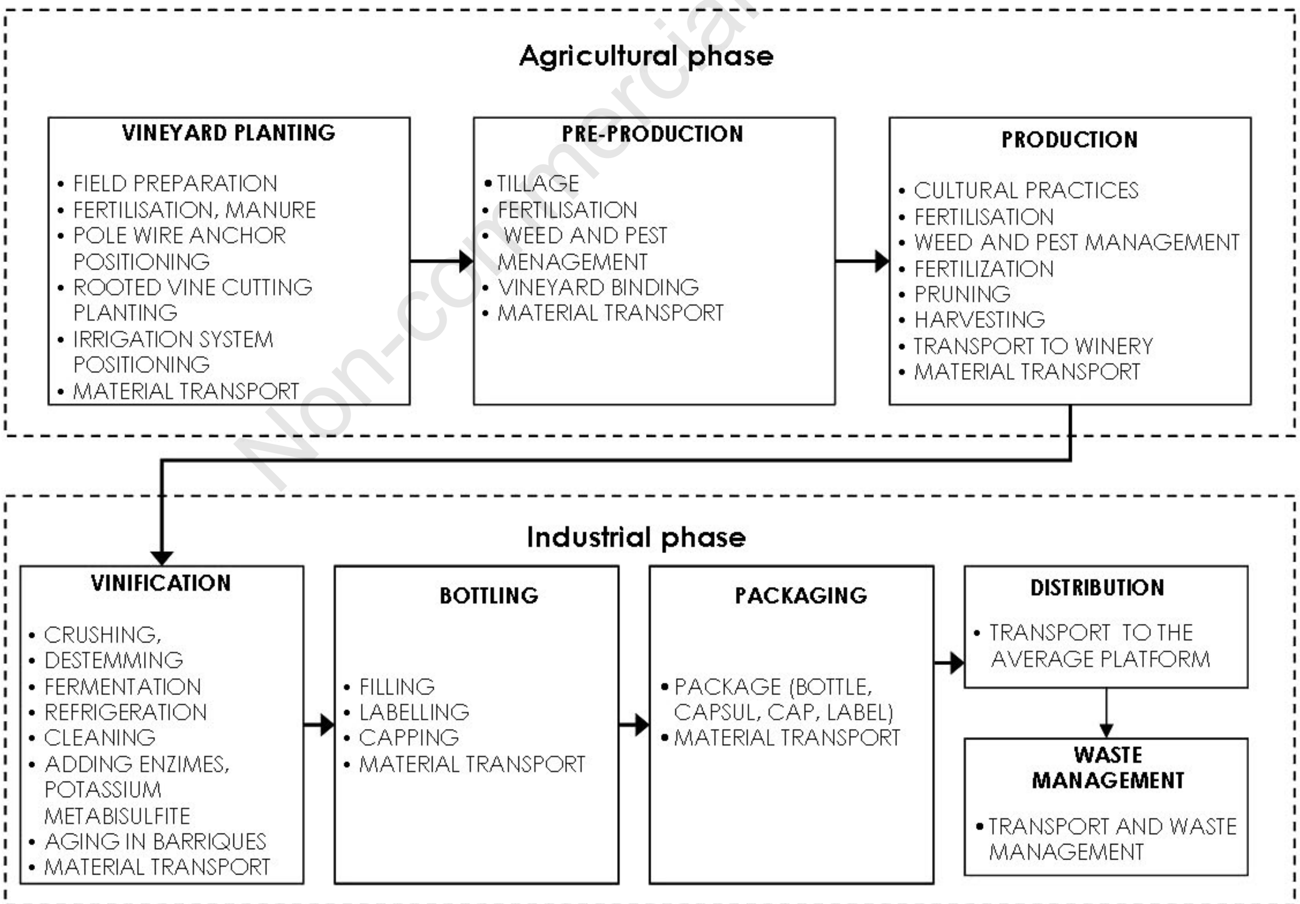

Figure 1. Block diagram of the life-cycle of Maremma rural district wines.

Data collection and life cycle inventory

The most effort-consuming step of the LCA studies implementation is the collection of data in order to build the life cycle inventory. Furthermore, data for agricultural processes are limited in literature and in LCA database, compared to industrial processes. Questionnaires were elaborated for specific data collection for each phase of the wine chain production and were fulfilled by personal interviews with farmers and oenologists during 2009. Thus, the data collected can be considered to be of very high quality, according to the criteria of reliability, completeness, and temporal and spatial representation.

For each unit process within the system boundary, qualitative (vine training systems, presence of irrigation systems) and quantitative data inputs (energy and material) and outputs (wastes, GHG emissions and co-products) were collected.

Data collected on the agricultural phases of vineyard planting were: the diesel consumption for soil preparation, pole, wire and irrigation system positioning and material consumption, depending on the number of plants per hectare, said poles, anchors, manure or fertilisers. In Table 2, the energy and material inputs for the agricultural phase are presented per hectare for each wine. The production of the irrigation system has been included where it was present. The disciplinary plan for the DOC or IGT area allowed irrigation only during specific periods of year for emergency purposes. Only the W1 Company used the irrigation system. The energy and material inputs for the vineyard-planting phase have been partitioned by the lifetime of each kind of grape variety. The vineyard pre-production phase (3 years long in all wine companies) generally required a simpler management in comparison with the production phase, with rare pesticide treatment. The only operations performed on all farms were weed management and vine binding. Also included in the production phase are pruning, grassing (if performed), harvesting and transport to the winery. The main differences in the production phase were due to the rate, products and application of fertilisers to the harvest, and to the wood residue management. About 300 kg of triple soil fertiliser (NPK) were applied to Wine 1 (W1), Wine 2 (W2) and Wine 3 (W3), while in Wine 4 (W4), a very low quantity of nitrogen (N) fertiliser was applied, in order to limit the vegetative growth, since the soil showed high N levels.

The grape yield, established in the disciplinary of the wine specific for each IGT or DOC area, did not depend on potential field productivity (Table 2). The grapes were harvested both by machinery and manually, with no differences between closed-cycle farms and cooperatives.

For the wine production phase, all the energy consumption for crushing grapes, fermentation, refrigeration filtration and bottling were included. W1 and W2 had a refining process in barriques for 12 and 18 months, respectively, before bottling. The packaging phase included the primary and secondary package. The wine was bottled in green 0.75 L glass bottles with a weight of 0.5, 0.6, 0.4 kg, respectively, for W1, W2 and W4, and a clear glass bottle of 0.6 kg for W3. The secondary package was a six-bottle cardboard box for W1, W3, W4 and a six-bottle wood box for W2, and then sent out by truck in standard European pallets.

In the distribution phase, the transport from the winery gate to the average platform of distribution has been considered (Table 1). The impact for the phase of wine bottle usage is not relevant and not considered in PCR, whereas the waste management of the bottle, the bottle cap, and the sticky label have been considered. The glass bottles were assumed to be 100% recycled in the end, while the label and the stopper were assumed to be deposited in a landfill. Only the transport to the waste collection station was considered for the wastes produced in the other chain phases. Table 3 lists the main energy and direct material input to the product systems under the study of a 0.75 L bottle of wine.

Data on the eco-profile of input material was obtained from GaBi4

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Table 2. Vineyard management in the four wine companies (data showed per hectare).

	Wine 1	Wine 2	Wine 3	Wine 4
		Vineyard planting		
Vineyard lifetime (years)	30	37	20	25-30
Vine plant (n)	4400	4000	3333	3333-4200
Diesel total consumption (L)	1834	1451	451	300-1300
Diesel consumption for deep tillage (L)	377	351	180	250-400
Pole (material)	Wood (head) and steel (within row)	Wood	Iron and steel	Cement, wood, iron
Anchor, wire positioning	Machinery	Machinery	Manual	Machinery and manual
Vineyard removal consumption (L)	139	360	85.9	80-600
Irrigation system	no	yes	no	no
Manure	yes	yes	yes	both
		Pre-production phase		
Diesel consumption (L)	161	133	53	89-208
Fertilisation	yes	no	yes	both
Pest management	yes	no	yes	both
Weed management	yes	yes	yes	yes
Irrigation	no	yes	no	no
		Production phase		
Diesel consumption (L)	212	576	218	190-450
Fertilisation (kg)	300 NPK	300 NPK + foliar	300 NPK	200 K2SO4 + foliar
Pruning	Machinery	Machinery	Machinery	Machinery
Pest treatment (n)	7-8	7-8	7	7-8
Grassing	Natural	Natural	Natural	Natural
Grapevine residue management	Removed	Cut + incorporated into soil	Cut + incorporated into soil	Cut + incorporated into soil
Weed treatment	yes	yes	no	yes
Harvesting	Machinery	Manual	Manual	Machinery and manual
Grape yield (t)	5	6	11	9

Table 3. Life cycle inventory of the main inputs for the four wines investigated.

Agricultural phase	Input	Unit	Wine 1	Wine 2	Wine 3	Wine 4
Vineyard planting	Diesel (field operation)	kg	1.50E-02	1.41E-03	2.23E-03	3.65E-03
	Wood pole	kg	3.03E-02	2.33E-03		1.11E-02
	Cement pole					1.06E-02
	Manure	kg	3.55E-01	8.57E-01	1.44E-01	5.83E-02
	Iron part	kg	2.62E-02	2.58E-03	8.19E-03	1.36E-02
	Steel part	kg	1.70E-02		3.97E-02	2.02E-04
	Aluminium part	kg	1.33E-04			2.73E-06
	P fertiliser	kg	1.72E-02			
	Irrigation systems	kg		5.56E-03		6.11E-04
	Diesel (transport)	kg	7.43E-04	2.08E-05	2.45E-03	6.03E-04
Pre-production	Diesel (field operation)	kg	3.09E-03	4.77E-04	7.69E-04	3.30E-03
	Pesticides	kg	5.32E-05		1.15E-04	5.80E-04
	Binding tube (PVC)	kg	2.40E-04			1.13E-04
	NPK fertiliser	kg	7.99E-03			9.55E-04
	N fertiliser					1.64E-04
	P foliar fertiliser					5.77E-04
	Water	m^3		1.74E-04		
	Diesel (transport)	kg	1.41E-05		7.71E-04	2.47E-06
Production	Diesel (field operation)	kg	3.08E-02	8.82E-02	1.78E-02	3.58E-02
	Electricity	MJ			2.77E-02	6.30E-03
	Binding tube (PVC)					6.72E-04
	Ternary fertiliser	kg	7.99E-02	3.34E-01	2.45E-02	2.67E-04
	NPK fertiliser			9.57E-04		3.49E-03
	N fertiliser					1.11E-02
	P foliar fertiliser			1.82E-03		6.62E-03
	Calcium foliar					6.53E-03
	Pesticides	kg	4.79E-03	9.01E-02	1.45E-04	4.38E-03
	Diesel (transport)	kg			1.78E-02	8.93E-05
Industrial phase	**Input**	**Unit**	**Wine1**	**Wine2**	**Wine3**	**Wine4**
Vinification	Electricity	MJ	9.41E-01	1.76E-01	2.52E-01	4.40E-01
	Diesel (transport)	kg	2.73E-03	4.84E-04	3.46E-05	1.61E-06
	Grapes	kg	1.33E+00	1.08E+00	1.01E+00	1.24E+00
	Potassium metabisulfite	kg	2.78E-04	8.57E-05	1.88E-04	1.07E-04
	Barrel	kg	1.66E-01	4.46E-02		
	Detergents	kg	1.25E-03	4.91E-02	1.41E-04	3.71E-04
	Paper package	kg	6.13E-05	1.97E-05		
	Plastic package	kg	1.18E-05	1.56E-05		4.12E-05
	Pectolytic enzymes	m^3			9.38E-09	1.24E-05
	Yeast	kg	6.96E-04	1.54E-04	1.13E-03	3.21E-04
	Output	*Unit*	*Wine1*	*Wine2*	*Wine3*	*Wine4*
	Pomace	kg	4.73E-02	4.29E-02	6.09E-02	6.18E-02
	Stalk	kg	3.08E-02	5.14E-02	5.05E-02	2.06E-02
	Pips, skins	kg	1.60E-01	1.29E-01	1.31E-01	2.88E-01
	Wine	m^3	7.50E-04	7.50E-04	7.50E-04	7.50E-04
	Plastic package	kg	6.13E-05	1.56E-05	9.38E-06	
	Paper package	kg		1.97E-05	2.02E-05	
Bottling	Electricity	MJ	1.37E-02	5.63E-01	1.97E-01	1.05E-01
	Diesel (transport)	kg	3.18E-06	5.63E-01	5.22E-05	9.54E-06
	Wine	m^3	9.32E-04	7.50E-04	7.50E-04	7.50E-04
	Cardboard package				3.04E-04	
	Plastic package	kg	1.11E-03	4.29E-06		1.99E-04
	Output	*Unit*	*Wine1*	*Wine2*	*Wine3*	*Wine4*
	Bottle of 0,75 l	m^3	7.50E-04	7.50E-04	7.50E-04	7.50E-04
Packaging	Electricity	MJ	1.12E-02	1.22E-01	1.49E-01	1.66E-02
	Diesel (transport)	kg	3.94E-03	1.31E-03	4.58E-03	7.39E-03
	Glass bottle	kg	5.00E-01	6.00E-01	5.91E-01	4.10E-01
	Cork	kg	1.30E-02	7.00E-03		6.00E-03
	Silicon stopper				6.90E-03	
	Capsule	kg	2.00E-03	7.70E-04		2.00E-03
	Label	kg	3.00E-03		5.57E-04	5.00E-03
	Wood box	kg		1.67E-01		
	Cardboard package	kg	8.33E-02		4.77E-02	5.48E-02
Distribution	Diesel (transport)	kg	1.07E-02	1.24E-01	5.62E-03	2.45E-02
Waste management	Glass bottle	kg	5.00E-01	6.00E-01	5.91E-01	4.10E-01
	Capsule	kg	2.00E-03	7.70E-04	7.70E-04	2.00E-03
	Label	kg	7.24E-03	5.60E-04	5.60E-04	5.00E-03
	Cap	kg	1.30E-02	7.24E-03	6.90E-03	6.00E-03

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and Ecoinvent databases and from literature. Among the wine-related products, data on yeast, fermentation starter and pectolytic enzymes were included in the inventory but were not included in the impact assessment due to lack of information.

Allocation problems arise when the process under study generates co-products, or a main product and by-products, and allocations cannot be avoided. It is therefore necessary to decide how to allocate the environmental burdens of the process among the co-products and/or by-products (Ekvall and Finnveden, 2001). In the wine chain, the problem of how to allocate the different co-products of wine-making (skins, pips and stalks) is solved in literature allocating the environmental burden on mass or economic value. In this study, the allocation on mass has been used to distribute the impact between the co-products of vinification. The stalks were reused in farms as organic fertiliser; the pips and skins were send to the distillery for spirits production in the case of all four of the wines. The transport to the distillery and the distillation process has not been included.

Results and Discussions

Impact assessment and interpretation

The GWP of the four investigated wines was found to lie between 0.6 and 1.3 kg CO_2-eq./bottle (Table 4), showing a comparable value with literature (Notarnicola *et al*., 2003; Ardente *et al*., 2006; Point, 2008; Gazulla *et al*., 2010). The aged red wines (W1 and W2) showed the higher GWP/bottle results, followed by the white wine (W3) and then by the other red (W4). The agricultural phase covered on average 22% of the total GWP/bottle, while the industrial phase was the relevant stage, covering more than 80% of the total GWP/bottle, mainly due to vinification and packaging sub-phases (Figure 2).

Consistent with our data, Notarnicola *et al*. (2003) and Point (2008) observed that the agricultural phase accounted for 20%, while Gazulla *et al*. (2010) reported that it was the most relevant life cycle stage, covering almost the 50% of the GHG emissions associated with the whole life cycle of wine production. On the contrary, Ardente *et al*. (2006) reported for one bottle of wine, a GWP of 1.4% on the overall impact, probably due to the accounting of the CO_2 biogenic emissions for tartaric stabilisation.

The vinification and bottling phases are particularly important for aged wines (W1 and W2), where the consumption for refrigeration systems increased the electricity consumption.

The packaging phase was the most relevant phase, with an impact ranging from 41% (W1) to 63% (W3) and the main impact was due to

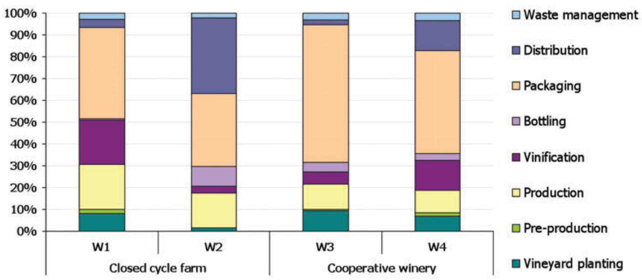

Figure 2. Relative contribution (%) to GWP for each phase of the four wines analysed.

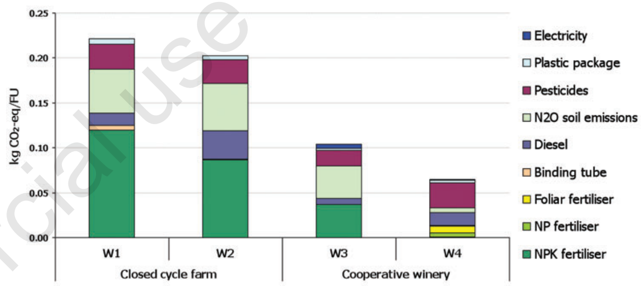

Figure 3. GWP of main processes occurring in the production phase (kg of CO_2-eq./FU).

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Table 4. Greenhouse gas emissions in the wine chain for functional unit (kg CO_2-eq./0.75 L packed wine).

	Vineyard planting	Pre-production	Production	Vinification	Bottling	Packaging	Distribution	Waste management	Total
Wine 1	0.09	0.02	0.22	0.22	0.01	0.45	0.04	0.03	1.07
Wine 2	0.02	0.00	0.20	0.04	0.11	0.43	0.44	0.03	1.28
Wine 3	0.08	0.01	0.10	0.05	0.04	0.57	0.02	0.03	0.91
Wine 4	0.04	0.01	0.07	0.09	0.02	0.30	0.09	0.02	0.63

Table 5. Sensitivity analysis of individual parameters, for the four wines investigated, change in carbon footprint.

Parameter	Wine 1		Wine 2		Wine 3		Wine 4	
Head weight (cement, steel or wood)	-0.5%	0.5%	0.0%	0.0%	-1.4%	1.4%	-0.3%	0.3%
Fuel consumption for field operation at vineyard planting	-0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%	0.1%
Inter row pole weight	-0.6%	0.6%	-0.1%	0.1%	-0.3%	0.3%	-0.7%	0.7%
Fertiliser in production	-2.2%	2.2%	-1.3%	1.3%	-0.8%	0.8%	-0.4%	0.6%
Grape yield	7.7%	-5.1%	5.5%	-3.5%	5.2%	-3.5%	4.5%	-3.0%
N_2O emissions in production	-3.2%	3.2%	-2.9%	2.9%	-2.7%	2.7%	-0.6%	0.6%
Electricity for vinification	-3.5%	3.5%	-0.5%	0.5%	-1.1%	1.1%	-2.6%	2.6%
Bottle weight	-5.6%	5.6%	-5.6%	5.6%	-10.1%	10.1%	-7.5%	7.5%
Average platform of distribution distance	-0.7%	0.7%	-6.9%	6.9%	-0.4%	0.4%	-0.8%	0.8%

the glass bottle production. The variability in packaging results is explained mainly by the weight of the bottle, the glass type and the secondary packaging.

The distribution of the packaged wine became relevant for W2 and W4, where there was an international distribution market.

Impact of agricultural phase and discussion

The variability among the agricultural phases of the four wines was analysed (Figure 3). There are differences in the GWP of agricultural phases between the four wines, that cover 30.7%, 17.4%, 21.6%, 18.6% for W1, W2, W3 and W4, respectively.

The impact of the planting phase was mainly affected by the input material production, such as steel, iron and cement poles, and diesel consumption. The GWP impact ranged from 2% to 10% of total GWP in W2 and in W3, respectively (Figure 2). The vineyard lifetime plays an important role in partitioning the impact, thus the white wine (W3) is particularly unfavoured, 20 years lifetime, in comparison with the red wines that have a lifetime of 30-37 years.

In the vineyard-planting phase, diesel consumption for the deep tillage operation done before planting was massive. The diesel consumption for the field operation varies together with the different levels of mechanization of the cultural practices (Table 2).

The pre-production phase did not show any relevant impact in the overall assessment, since it covered less than 2% of GWP impact in all the four wines investigated.

Within the agricultural phase, the production phase is the most impacting, with an average GWP impact of 15% of the total GWP, ranging from 10-21%, in W4 and W1, respectively (Figure 2). The main processes affecting the GWP impact at this stage were represented by the fertilisers and pesticides production, N_2O emissions from fertiliser distribution and diesel consumption, as shown in Figure 3. These four inputs explain in each case more than 80% of the impact results for the production phase. On average in this phase, the pesticides and fertilisers' production cover 35% and 23%, respectively, of the GWP impact, while diesel consumption, N_2O emissions from soil and other flows cover 20%, 13% and 9%, respectively.

The N_2O emissions from soil are caused by nitrogen fertiliser distribution and the emissions are proportional to the N content in the fertiliser. This is important in the results obtained for the farm associated with W4, where the foliar fertilisation application was utilised instead of soil fertilisation and nitrogen content was very low. On the contrary, when NPK fertilisers were applied (W1, W2 and W3), N_2O emissions rose to 20-30% of the GWP of the agricultural phase.

The analysis of the four wine companies pointed out that the agricultural phase differs between the closed-cycle company and the cooperative (Table 4). The main difference between closed-cycle and associated companies was due to size and management organization. Individual companies had large vineyard cultivated area, means of production and greater economic possibilities, while associated farms were generally small (few hectares), were family-run with low means of production and high use of manual operations. Such differences influenced economic aspects and the investment in machinery and mechanization, which might affect diesel consumption.

The result showed that the vineyard-planting phase has a significant impact on the wine carbon footprint, so it has to be considered in the life cycle, while in literature it is frequently omitted. On the contrary, the pre-production phase did not present a relevant impact.

A sensitivity analysis was carried out with Gabi4 software in order to find the most impacting parameters. The results of the analysis are reported in Table 5. A standard deviation of 20% was applied to the main parameters that affect the carbon footprint, while a standard deviation of 70% was applied to the N_2O emissions, following the uncertain values reported in the IPCC methodology (IPCC, 2006). The sensitivity analysis showed that the most sensitive parameters were the grape yield and glass bottle weight in the case of all four of the wines. Hence, the impact of the inputs per hectare is affected by the yield obtained, as reported also by Röös *et al*. (2010). Fertilisers distribution is a relevant factor in W1 and W2, where a larger quantity was used. The distance of the average platform for distribution, considerably affected the carbon footprint of W2 that had an international market, while it was not a key parameter in other wines.

Therefore, some effective mitigating actions for the GHG emissions reduction in the agricultural phase of the wine chain could be the reduction of fertilisers distribution, especially nitrogen, the reduction of the number of tractor transits through the vineyards and finally the use of fuel-saving engines.

Conclusions

The attention of researchers, non-governmental associations and companies is now focused on the carbon footprint as the first major environmental impacts associated with the production of goods, due to the urgency of climate change mitigation. High-quality products, such as wine, distributed in an international market, more frequently look toward an innovative approach for environmental assessment, such as the LCA and CF. Here, a detailed carbon footprint analysis of four wines from the Maremma rural district has been performed and the results pointed out a range from 0.7 to 1.3 kg CO_2-eq. for a 0.75 L bottle, showing a higher impact for aged white wines than not aged ones. The agricultural phase plays an important but minor role, with a mean value of 22% total GWP, compared with the industrial phase (78%). The production of the glass bottle covers a great part of CF, ranging from 40% to 60% of the total GWP, thus the weight of the glass bottle could be a significant difference in comparing two CF wine bottles. Distribution became important only when the market of distribution is international. On the other hand, as underlined by the sensitivity analysis, some parameters of the agricultural phase play an important role, such as the use of fertilisers, the grapes' yield and N_2O emissions. These findings have noteworthy implications in identifying the effective mitigating actions for the GHG emissions reduction in the agricultural phase of the wine chain at product level. Large-scale results in greenhouse gases mitigation in the wine production chain in Maremma rural district could be achieved by adopting a territorial analysis approach.

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