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Comparative life cycle assessment in the wine sector: biodynamic vs. conventional viticulture activities in NW Spain

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ABSTRACT

Viticulture is currently experiencing a gradual shift to more sustainable production practices. Many producers see in this shift an opportunity to increase their sales, especially in a context which is greatly influenced by the reduction in wine sales due to the world economic crisis. Hence, both organic and biodynamic viticulture have begun to be applied in many vineyards as alternative attractive agricultural techniques. Nevertheless, it remains unclear which are the exact environmental benefits (or drawbacks) of applying these techniques for numerous environmental impacts, such as climate change or toxicity. Therefore, the main goal of this study is to perform an environmental evaluation using Life Cycle Assessment (LCA) for three different viticulture techniques within a single appellation (*Ribeiro*, NW Spain): biodynamic cultivation sites, conventional vineyards and an intermediate biodynamic-conventional wine-growing plantation (i.e. biodynamic site lacking certification). Moreover, two methodological improvements in the field of wine LCA studies are suggested and developed in terms of land use impact categories and labour inclusion in life-cycle thinking. Results demonstrate that biodynamic production implies the lowest environmental burdens, and the highest environmental impacts were linked to conventional agricultural practices. The main reasons for this strong decrease in environmental impacts for the biodynamic site is related to an 80% decrease in diesel inputs, due to a lower application of plant protection products and fertilisers, and the introduction of manual work rather than mechanised activities in the vineyards. Nevertheless, a series of preliminary assessments suggest that the impacts linked to land use and human labour, two under-analysed issues in wine LCA, may show different trends to those obtained for the other environmental dimensions, adding complexity to the integrated interpretation of the results.

1. Introduction

Historically the production of wine has concentrated in Europe. However, the so called "New World" wines have experienced a strong development in recent decades in countries such as United States, Argentina, Chile, Australia or South Africa. Ever since year 2000, the surface dedicated to viticulture has decreased on a worldwide level, while the production of wine has remained constant (OIV, 2012). Nowadays, Europe still represents roughly 60% of the global surface area used for wine-growing. More specifically, Spain is the country with the highest surface area destined for grape production, representing 18.3% of the world's vineyards (OIV, 2012). However, in terms of wine production, Spain is the third world producer, after France and Italy, with 33 million hectolitres in 2011 (OIV, 2012). Galicia (NW Spain) only represents 1% of the Spanish vineyard surface (INE, 2012). However, the five appellations in this region, *Monterrei*, *Rías Baixas*, *Ribeira Sacra*, *Ribeiro* and *Valdeorras*, have acquired international recognition for their quality (Decanter, 2012).

Currently, viticulture is experiencing a gradual shift to more sustainable production patterns (Gabzdylova et al., 2009). In fact, many producers see in this shift an opportunity to increase their sales, especially in a context which is greatly influenced by the reduction in wine sales due to the world economic crisis (OIV, 2011). Therefore, many producers have initiated or have already accomplished the conversion towards field operations that improve the environmental profile of wine production. Hence, both organic

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and biodynamic viticulture have begun to be applied in many vineyards as novel and attractive agricultural techniques. On the one hand, organic viticulture is characterised by the avoidance of mineral fertilisers and plant protection substances of synthetic origin. Organic products, including those related to the viticulture and vinification sector, are regulated by Member States in the European Union (EU) based on a common legislation (European Commission, 2007, 2008, 2012), which covers the supervision of techniques, compliance with standards and labelling. On the other hand, biodynamic viticulture can be seen as a specific type of organic viticulture that is based on a radical consideration of the two postulates that characterize organic viticulture, as explained in more detail in Section 1.1. Moreover, these techniques seek a higher independence from the use of machinery, and consequently, fossil fuels, by implementing artisanal field operation strategies. However, it is important to point out that despite the attractive gains in terms of input minimisation when organic or biodynamic practices are applied to viticulture, there is also an important reduction in the harvest yield of these vineyards (White, 1995; Hassall et al., 2005; Badgley et al., 2007; Seufert et al., 2012).

Nevertheless, the wines obtained when these methods are used are characterised by an exceptional quality concerning the organoleptic characteristics, with higher doses of polyphenols and lower concentrations of sulphites. Currently, Spain is the European leader regarding organic agriculture, with 1.08 million hectares used for this purpose; 9.5% of this surface area corresponds to viticulture (Eurostat, 2012; INE, 2012).

In recent years a set of different studies have evaluated the environmental profile of grape and wine production from a life-cycle perspective. Hence, an internationally standardised environmental tool, named Life Cycle Assessment (LCA), has proven to be an appropriate assessment tool for analysis of agri-food products (Brentrup et al., 2004a,b; Roy et al., 2009), as well as products from the wine sector (Petti et al., 2010), with the objective of determining the most relevant environmental burdens linked to the life-cycle of the system (ISO, 2006a,b). Hence, LCA studies have been developed for "Old World" wines in Spain (Aranda et al., 2005; Gazulla et al., 2010; Vázquez-Rowe et al., 2012a,b), Italy (Notarnicola et al., 2003; Pizzigallo et al., 2008; Bosco et al., 2011), France (Renaud et al., 2010) or Portugal (Neto et al., 2013), and for "New World" wines in Canada (Point et al., 2012), Australia (WFA, 2011) and Chile (Cárdenas-Rodríguez, 2008). In fact, most of these studies have not only examined the environmental profile of grape for wine production, but also other stages of the wine sector, such as vinification, bottling or distribution (Petti et al., 2010; Rugani et al., 2013). In addition, some studies have focussed on specific life-cycle indicators, such as water footprint (Ene et al., 2013; Herath et al., 2013) or carbon footprint – CF (Pattara et al., 2012; Vázquez-Rowe et al., 2013).

1.1. Biodynamic viticulture

Biodynamic agriculture was developed in the 1920s based on a set of conferences performed by the philosopher Rudolf Steiner (Steiner and Gardner, 1993). This type of agriculture considers a holistic approach concerning the exploitation of the natural resources, taking into consideration the sustainability of different elements, such as the crops themselves, animal life preservation or the maintenance of a high quality soil, in order to recover, preserve or improve ecological harmony (Lotter, 2003). This perspective is achieved through a sharp reduction of external inputs into the production system, the use of a set of preparations to apply on their crops to aid fertilisation and the application of other homoeopathic treatments based on infusions or plant extracts (Table 1).

Table 1
List of the main biodynamic preparations.

Number of preparation	Main ingredient
500	• Cow manure
500P	• Preparation 500 with 502–507
501	• Silica
502	• Yarrow flowers (*Achillea millefolium*)
503	• Camomile flowers (*Matricaria recutia*)
504	• Stinging nettle shoots (*Urtica dioica*)
505	• Oak bark (*Quercus robur*)
506	• Dandelion flowers (*Taraxacum officinale*)
507	• Valerian extract (*Valeriana officinalis*)
Compost	• Cow manure with preparation 502 to 507

Source: Masson (2009).

Cultivation sites that are certified as being biodynamic need to be previously certified as organic agriculture production sites (European Commission, 2007, 2008, 2012; Demeter, 2012; CRAEGA, 2012) and have to go through a three year conversion period. Currently, there is on-going debate regarding the positive effects of applying biodynamic farming practices to different crops (Turinek et al., 2009), especially regarding the influence and appropriateness of using biodynamic preparations. Some studies have demonstrated substantial benefits of using biodynamic preparations in terms of soil structure and microorganisms, improving the fertility of the soil or the microbial biodiversity (Reganold et al., 1993; Mäder et al., 2002; Probst et al., 2008; Reeve et al., 2010), whereas other studies have highlighted the lame benefits that biodynamic agriculture can render under certain conditions (Carpenter-Boggs et al., 2000; Tassoni et al., 2013). There are several theories regarding the way in which the preparations may interact with the crops, including hormonal stimulation, enhancing crop growth, especially at a root level (Stearn, 1976; Goldstein and Koepf, 1992; Deffune and Scofield, 1995; Fritz and Köpke, 2005). Other studies, however, suggest that biodynamic preparations act as regulators of bacterial activity (Miller and Bassler, 2001).

2. Materials and methods

2.1. Goal and scope

Despite the strong increase in wine LCA studies in past years, a recent review by Rugani et al. (2013) points out a series of gaps that remain unexplored when life cycle thinking is applied to the wine sector. One of these gaps is directly connected to an in-depth analysis of the different viticulture techniques that may be used (i.e. organic, biodynamic, conventional…), since some authors have suggested that organic practices may not be linked with lower environmental impacts (Venkat, 2012). Therefore, the main goal of this study is to perform a life-cycle environmental assessment for three different viticulture techniques within a single appellation (*Ribeiro*, NW Spain): a biodynamic cultivation site (BD), a conventional grape production site (CV) and an intermediate biodynamic-conventional wine-growing plantation (BD-CV).[1]

Moreover, this novel approach is combined with three methodological improvements suggested and developed in this case study. In the first place, a comparison between land use impact categories is provided. Secondly, a repeatedly underrepresented activity in environmental management is the role of human labour in environmental impacts (Rugani et al., 2013). Finally, a third issue, in line with the work developed by Vázquez-Rowe et al. (2012a), is

[1] The intermediate biodynamic-conventional site considers biodynamic protocols for viticulture activities, but does not consider crop diversity or livestock farming. In addition, it has no type of organic or biodynamic certifications.

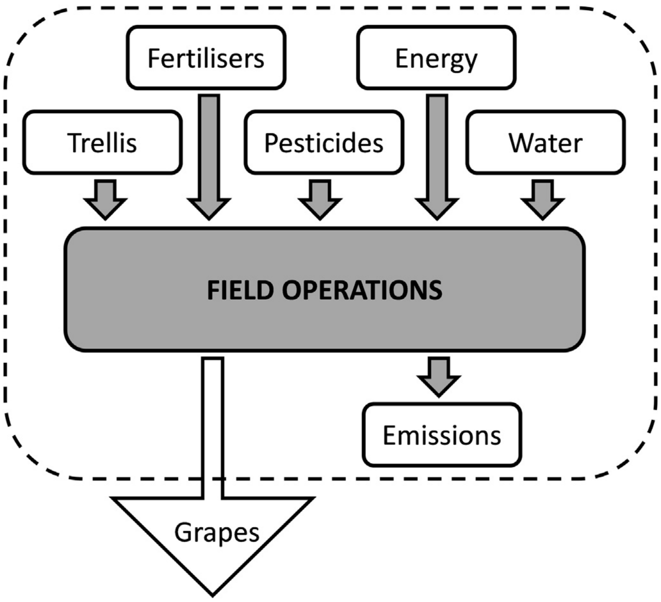

Fig. 1. Graphical representation of the assessed production system.

the use of updated assessment methods for results computation, as described in Section 2.6.

The selected functional unit (FU), which is the reference unit to which the results are referred to (ISO, 2006b), was 1.1 kg of collected grape, which was the amount of grape necessary to produce one bottle of *Ribeiro* wine (i.e. 750 mL of wine) in two consecutive harvest years: 2010 and 2011. Furthermore, the FU is in accordance with prior wine LCA and carbon footprint studies available in literature (Petti et al., 2010; Hayashi, 2013; Pattara et al., 2012; Rugani et al., 2013).

2.2. System boundaries

System boundaries in this study were limited to the gate of the winery (i.e. agricultural phase of wine production) in order to provide a direct comparison between the different viticulture techniques, disregarding post-agricultural stages of the life-cycle. More specifically, while substantial differences can be observed in post-agricultural stages of winemaking, these are not attributable to the implementation of different viticulture techniques. All the processes and field operations needed for grape production, including the production and use of the major inputs, such as fossil fuels, pesticides, water and the trellis of the vineyard (Fig. 1) were included within the systems' boundaries. Excluded processes include the vine nursery stage, due to the lack of data. Moreover, it should be highlighted that the number of vines that are replaced on an annual basis is very low, which minimises the effect of this exclusion (Bosco et al., 2011; Vázquez-Rowe et al., 2012a). The greater part of the substances used in the biodynamic preparations were also excluded from the inventory, since most of these corresponded to the collection of minimal amounts of wild plants in the neighbouring areas of the cultivation sites, such as nettles (*Urtica dioica*), horsetails (*Equisetum* spp.) or camomile (*Chamaemelum nobile*). These plants are applied to the preparations in homoeopathic doses; therefore, the assumed impact of these inputs would be close to zero. In contrast, other substances used in biodynamic preparations, such as powdered quartz, salt or soy, were included within the system boundaries. Finally, concerning fertiliser use, the production of compost was excluded due to the fact that it was assumed to be a residue from ovine farming. Hence, only its transport and spreading on the vineyards was considered (Martínez-Blanco et al., 2007; Vázquez-Rowe et al., 2012a).

2.3. Data acquisition

Primary data were retrieved through a set of questionnaires that were distributed between the wine-growers of the exploitations inventoried in the study. The cultivation sites were located in Leiro and San Amaro (*Ourense* province), therefore, belonging to the *Ribeiro* appellation (NW Spain) – (Table 2; Fig. 2). These surveys embraced a wide range of inputs for the cultivation sites, such as fuel use, pesticides, field operations, machinery or trellis. Moreover, specific labour data, regarding working hours of employees, were included in order to include human labour activities in life-cycle thinking – see Section 4.2 (Rugani et al., 2012).

Direct emissions from field operations, such as those derived from fossil fuel consumption by agricultural machinery, were estimated based on the characterisation factors proposed by EMEP-Corinair Emissions Handbook 2006 (EMEP-Corinair, 2006). Nitrogen emissions linked to fertiliser spreading on the vineyards were calculated following the methodology proposed by Brentrup et al. (2000). Nevertheless, as mentioned in Section 2.2, only on field emissions were considered for compost, since the compost processing stage was excluded from the system boundaries. Finally, phosphorus and phosphate emissions associated with fertiliser spreading were obtained from the bibliography (Cowell, 1998; Cowell and Clift, 1997).

The emissions linked to the use of plant protection substances (pesticides), shown in Table S1 in the Supplementary Material (SM), were estimated based on the PestLCI dispersion method (Birkved and Hauschild, 2006), which was adapted to the climatic and soil characteristics of the area (Vázquez-Rowe et al., 2012a). Emissions related to the use of sulphur- and copper-based pesticides were not taken into consideration for two main reasons. On the one hand, their emissions cannot be computed with the current PestLCI methodology. On the other hand, the retention rate of the soil for these pesticides is very high (Fernández-Calviño et al., 2008), limiting their importance in terms of air and water emissions. Additionally, the complex reactions and interactions occurring between Cu and the soil hinder the capacity to establish the endpoint of this substance (Kiaune and Singhasemanon, 2011). Finally, electricity inclusion in the study was integrated by adapting the electricity grid available for Spain in the ecoinvent® database, for the two years under analysis, based on official statistics (Frischknecht et al., 2007; REE, 2010, 2011).

Secondary data referred to the production of plant protection products, trellis or diesel were obtained from the ecoinvent®

Table 2
Selected sample for the assessed period 2010–2011.

	Surface area (ha)	Plots	Grape production (tonnes/year)		Annual yield (tonnes/ha)	
			2010	2011	2010	2011
Biodynamic farm (BD)	4	1	15	15	3.75	3.75
Biodynamic-conventional farm (BD-CV)	27.6	42	124	162	4.49	5.87
Conventional farm (CV)	14	7	120	152	8.57	10.86

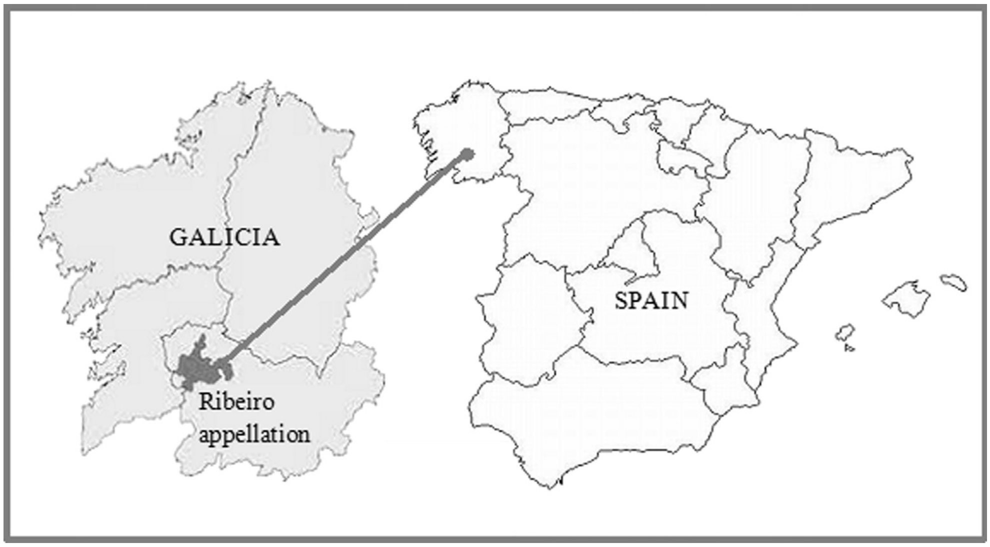

Fig. 2. Geographical location of the *Ribeiro* appellation in Galicia and Spain.

database (Frischknecht et al., 2007). The synthetic pesticides used in conventional viticulture were grouped in compound families (e.g. thiocarbamates, triazines…); while for the copper- and sulphur-based pesticides specific processes were used for disaggregating these substances from an inventory perspective. For instance, sulphur was assumed to be obtained as a sub-product in the oil refining industry, and copper from the extractive mining sector (Manuel Montaño, Afepasa SA, April 2013, personal communication). For the biodynamic treatments and due to the lack of inventory data for certain products, only quartz, soy and salt were included in the inventory.

Data regarding the trellis of the vineyards were retrieved by contacting a specialised company that delivers this type of materials to the inventoried wineries – e.g. iron, steel or wood (Pedro Mosteiro, Viniequip SL, April 2013, personal communication). Consequently, detailed data regarding the specific types of materials used in each cultivation site, as well as the transportation, were available. Whenever the vineyards showed a wooden trellis, the specific inventory process chosen in ecoinvent® was the wood whose density was the closest to the wood used in this area (*Acacia dealbata*). This species is selected for vine support in this area for two main reasons: on the one hand, it constitutes an invasive species in the *Ribeiro* region; therefore, its availability is guaranteed and the need to control its expansion is augmenting; on the other hand, its resistance allows its use without any type of pretreatment (e.g. copper salts, arsenic or chromium), reducing its toxicity potential (Point et al., 2012). Steel and iron trellis background processes were extracted and modified from ecoinvent®, in order to include the wire characteristics of the product, and in the case of iron, to include the galvanisation process. The non-woody materials used for the trellis were allocated to a total of 50 years of usage on the vineyards, in order to compute the proportional environmental impact per harvest year, while woody materials were considered to be replaced on an annual basis.

2.4. Life cycle inventory (LCI)

2.4.1. Biodynamic farm (BD)

This cultivation site is completely adapted to biodynamic viticulture, including the certification process as an organic agricultural producer. The specific certificate for biodynamic production was under revision when this study was developed. Furthermore, it is important to note that the yield of the vineyards is relatively constant, due to the strict controls regarding the productivity of each vine (Table 2). In fact, the clarification of the grape clusters is conducted to ensure grape quality and their correct ripening.

Table 3 shows the LCI for grape production in this wine farm for the 2010 and 2011 harvest years. Most inputs remained constant when the two harvest years are compared, due to the strict quality controls. However, copper-based pesticides and diesel showed important variations between the two years, since year 2011 was characterised by a low proliferation of fungi, such as downy mildew (*Plasmopara viticola*) or powdery mildew (*Uncinola necator*). This led to a lower dose of copper applied in the fields. Moreover, in this particular wine farm it is important to note the absence of fertiliser spreading on the vineyards. Despite the fact that organic fertilisers may be used in this type of grape cultivation, the soil analyses performed concluded that no fertiliser spreading was necessary in these two years of assessment. In fact, one of the reasons for this may be the fact that the previous land use was pasture land for livestock. Furthermore, as part of the holistic biodynamic approach, currently sheep and poultry pasture is on-going within the vineyards (Petherick, 2010), enhancing not only fertilisation activities, but also helping in terms of weed control, reducing the number of interventions and, therefore, the use of machinery and labour.

2.4.2. Biodynamic-conventional farm (BD-CV)

This winery does not present the entire range of biodynamic cultivation elements, since it does not consider crop diversity or livestock farming, but it follows biodynamic protocols for vineyard activities. Additionally, it lacks the certificates for organic agriculture or biodynamic farming. Therefore, it can be stated that this farm combines conventional and biodynamic operations in a hybrid manner. For instance, synthetic pesticides are not applied on the vineyards, using exclusively biodynamic preparations, copper- and sulphur-based pesticides and quartz powder. As shown in Table 3, there is a considerable interannual variation in harvest yields, due to the high productivity in 2011. Furthermore, diesel and pesticide use variation is notable between the two harvest years, due to the good climatic conditions for the non-proliferation of vine pathogens in 2011, which reduced the amount of field operations. Finally, this winery did not include within its operations the

Table 3
Inventory data for the three viticulture sites for the period 2010–2011 (Data per FU: 1.1 kg of grapes).

Inputs	Units	BD site		BD-CV site		CV site	
		2010	2011	2010	2011	2010	2011
From the technosphere							
Energy							
Diesel	g	16.58	10.16	29.39	16.98	73.33	55.00
Electricity	kWh	–	–	0.33	0.25	4.60E-2	3.70E-2
Fertilisers							
Sheep manure	g	–	–	–	–	275.0	217.1
Transport (compost)	tkm	–	–	–	–	2.80E-2	2.20E-2
Pesticides							
Copper-based compounds	g	0.20	0.15	0.58	0.22	1.16	0.76
Soybean	g	0.88	0.88	–	–	–	–
Silica dust	g	5.9E-03	5.9E-03	14.69	5.62	–	–
Sulphur	g	–	–	14.40	3.67	1.36	1.07
Sodium chloride	g	–	–	0.00	0.07	–	–
Thiocarbamates	mg	–	–	–	–	57.37	36.25
Acetamide-anillide	mg	–	–	–	–	9.24	7.29
Dithiocarbamate	mg	–	–	–	–	385.4	228.2
Nitriles	mg	–	–	–	–	60.16	47.49
Cyclic-N-compounds	mg	–	–	–	–	15.26	12.04
Fosetyl-Al	mg	–	–	–	–	644.3	410.0
Gliphosate	mg	–	–	–	–	316.0	249.5
Phtalamide-compounds	mg	–	–	–	–	149.2	117.8
Triazine	mg	–	–	–	–	305.2	241.1
Trellis							
Iron (wire)	g	5.66	5.66	4.16	3.18	–	–
Steel (cables and tubes)	g	–	–	–	–	9.71	7.67
Wood	g	614.1	614.1	42.70	32.69	–	–
Water (tap)	g	586.7	440.0	979.4	524.7	1110	720.0
Machinery							
Field sprayer user	m^2	2.93	2.93	2.45	1.87	1.28	1.01
Fertilising, by broadcaster	m^2	–	–	–	–	0.18	0.14
Tillage, rotary cultivator	m^2	–	–	–	–	0.28	0.22
Rotary mower	m^2	2.93	2.93	2.45	1.87	0.18	0.14
Hoeing	m^2	–	–	2.45	1.87	0.18	0.14
From the environment							
Energy, gross calorific value, in biomass	MJ	20.35	20.35	20.35	20.35	20.35	20.35
Transformation, from pasture and meadow	m^2	2.93	2.93	2.45	1.87	1.28	1.01
Transformation, to arable, non-irrigated	m^2	2.93	2.93	2.45	1.87	1.28	1.01
Occupation, arable, non-irrigated	m^2a	2.7E-04	2.7E-04	2.24	1.72	1.18	0.93

Outputs	Units	BD site		BD-CV site		CV site	
		2010	2011	2010	2011	2010	2011
To the technosphere							
Products							
Grapes	kg	1.1	1.1	1.1	1.1	1.1	1.1
To the environment							
Emissions to the atmosphere							
CO_2 (diesel)	g	52.02	31.88	92.21	53.26	230.1	172.6
SO_2 (diesel)	mg	33.16	20.32	58.77	33.95	146.7	110.0
VOC (diesel)	mg	120.5	73.87	213.7	123.4	533.1	399.9
NO_x (diesel)	mg	834.0	511.1	1478.3	853.9	3.69	2.77
CO (diesel)	mg	265.3	162.6	470.2	271.6	1.17	0.88
NH_3 (diesel)	mg	0.12	0.07	0.21	0.12	0.51	0.39
CH_4 (diesel)	mg	2.82	1.73	5.00	2.89	12.47	9.35
N_2O (diesel)	mg	21.39	13.11	37.91	21.90	94.60	70.95
N_2O (fertilizers)	mg	–	–	–	–	53.99	42.63
Emissions to water							
NO^{3-}	g	–	–	–	–	14.06	10.28
PO_4^{3-}	mg	–	–	–	–	56.19	44.36

spreading of fertilisers, since the performed soil analysis disregarded the need to do so.

2.4.3. Conventional viticulture

This winery presents conventional patterns of grape production, with the use of fertilising agents and synthetic pesticides. These fertilisers, despite being organic, do not originate within the farm (see Table 3). In fact, the inventory shows the amounts of synthetic pesticides that are used in field operations, as well as the use of herbicides, such as glyphosate and terbuthylazine.

When Table 3 is examined based on a cross-site approach, the use of diesel appears to be up to 4 times lower in the BD and BD-CV when compared to the CV exploitation. This is due to the high degree of mechanisation of CV wine-growing as compared to BD or BD-CV, where artisanal methods are implemented. In terms of the materials used for vine support, the CV site only uses stainless steel and iron, while BD and BD-CV use a mix of abiotic and biotic materials.

A final issue that shows strong variability between the three agricultural techniques is the use of plant protection agents. On the one hand, copper-based pesticides were used in much higher quantities in the CV site with respect to the other two techniques. In fact, copper application in the BD-CV and BD sites was below the maximum standards recommended for organic wine by the EU (European Commission, 2008). On the other hand, for sulphur-based products the highest use was found in the BD-CV site. In fact, the BD winery did not use any sulphur-based pesticides, using only powdered quartz in homoeopathic doses for the same purposes – increase the resistance of the plant to pathogens (Fauteux et al., 2005) – (biodynamic preparation 501 – Table 1), while the BD-CV winery made a mixed application of powdered quartz and sulphur, in order to reduce the amounts of sulphur needed.

2.5. Allocation and other assumptions

Allocation is a critical issue in LCA studies. However, in this case it was not necessary to apply allocation to the outputs, since there is one sole product exiting the system: grapes for vinification. The existence of co-products in the vinification phase (e.g. marc), does not fall within the system boundaries of the production system analysed. Allocation of the environmental impact of fertilisers has shown to be a controversial issue in agricultural systems (Luo et al., 2009; Vázquez-Rowe et al., 2012a). In this specific study it was decided to include only those impacts linked to fertilisers that are directly connected to viticulture practices (i.e. transport of the compost and associated emissions in the vineyards), as described in Section 2.2. Consequently, this cut-off approach allowed disregarding previous upstream impacts of the sheep manure in the CV site, assuming that this item is a residue of a separate production system.

2.6. Impact category selection

The life cycle impact assessment (LCIA) stage was performed using the CML baseline 2000 methodology (Guinée et al., 2001). The selected impact categories from the CML methodology were abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), ozone layer depletion (ODP) and photochemical oxidant formation (POFP). This selection was based on commonly used impact categories in prior wine LCA studies (Petti et al., 2010), as well as on a flexible interpretation of the recommendations from the ILCD handbook for impact assessment in Europe (ILCD, 2011). Furthermore, toxicity (Etox) was analysed following the USEtox method proposed by Rosenbaum et al. (2008). The selection of this assessment method for toxicity categories is also linked to the ILCD recommendations due to a higher coverage of chemical substances (Rosenbaum et al., 2008), the evaluation of model uncertainty and the extensive review process by model developers (ILCD, 2011). Finally, regarding land use, the land competition (LC) impact category from the CML 2001 method was selected to obtain a quantitative assessment, while the Soil Organic Matter (SOM) model developed by Milà i Canals et al. (2007), considered as a soil quality indicator, was used for a qualitative assessment following the ILCD recommendations (ILCD, 2011). Finally, regarding labour computation in wine-LCA, human labour (HL) input–output datasets were used (Rugani et al., 2012). The latter methodological issues, while not being a core objective of the study, are presented in Section 4.2 using the ReCiPe assessment method (Goedkoop et al., 2009). The software used to compute the results was SimaPro 7.3 (PRè-Product Ecology, 2011).

3. Results

3.1. Biodynamic farm (BD)

The environmental impacts obtained per FU for the BD farm are lower for the 2011 harvest year as compared to 2010, with environmental gains ranging from 3% for Etox to 32% for AP (Table 4). The production and consumption of diesel for field operations constitutes the main carrier of environmental impacts, with relative contributions ranging from 49% (EP) to 78% (AP) for the CML categories.

The trellis of the vineyard was identified as the second most important source of environmental impacts in most categories. The contribution of the trellis ranged from 13% (AP) to 35% for POFP. Pesticide production represented 19% of the environmental impact for EP and 4% for AP. Finally, the sum of the remaining inputs, including machinery or water use, represented from 5% (AP) to 15% (ADP).

Regarding the ecotoxicity impact category, vine support materials were the main source of environmental impact (77%), followed by other inputs – machinery, electricity… – (12%) and pesticide production (9%).

3.2. Biodynamic-conventional farm (BD-CV)

The environmental profile obtained for grape production in the BD-CV farm shows, similarly to the BD farm, higher impacts for the 2010 harvest year (Table 4). In fact, the decrease in environmental burdens in 2011 is substantial, ranging from 40% for ADP to 51% for AP. Diesel production and combustion represented on average 71% of the total environmental impact, ranging from 55% (POFP) to 84% (ODP).

Production of plant protection products (i.e. pesticides) was the second source of environmental burdens in three impact

Table 4
Characterisation results for the assessed viticulture sites for years 2010 and 2011 (Data per FU: 1.1 kg of grapes).

Impact category	Units	BD		BD-CV		CV	
		2010	2011	2010	2011	2010	2011
ADP	g Sb eq	0.62	0.47	0.92	0.55	2.17	1.64
AP	g SO_2 eq	0.88	0.60	2.00	0.98	5.04	3.82
EP	g PO_4^{3-} eq	0.23	0.17	0.35	0.19	2.29	1.68
GWP	g CO_2 eq	97.17	71.11	147.60	87.32	375.31	283.42
ODP	g CFC-11 eq	9.89E-06	6.94E-06	1.60E-05	9.33E-06	5.82E-05	4.45E-05
POFP	g C_2H_4 eq	3.72E-02	2.89E-02	7.30E-02	3.66E-02	0.18	0.13
Etox	CTUe	3.51E-01	3.40E-01	3.29E-01	2.17E-01	3.62E+01	1.73E+01
LC	m^2a	2.45	2.45	2.04	1.56	1.18	0.93

BD = biodynamic viticulture; BD-CV = biodynamic-conventional viticulture; CV = conventional viticulture; ADP = abiotic depletion potential; AP = acidification potential; EP = eutrophication potential; GWP = global warming potential; ODP = ozone layer depletion potential; POFP = photochemical oxidant formation potential; Etox = ecotoxicity; LC = land competition.

categories: EP (20%), AP (24%) and POFP (26%). Vine support materials (wood and iron) represented 13% of the impacts for ADP and POFP, and 10% for GWP. Finally, other inputs, such as machinery, water use or electricity, summed, at the most, 8% of the total environmental profile (ADP).

Concerning eco-toxicity, the Etox environmental burdens were dominated by the vine support materials (64%), followed by the production of pesticides (20%) and other inputs (12%). Diesel production only accounted for 4% of the environmental impact.

3.3. Conventional farm CV

The overall environmental impact of grape production in the conventional winery was lower in the year 2011, in a similar way as to the decrease observed for BD and BD-CV (Table 4). More specifically, decreases in the environmental profile ranged from 24% (ODP) to 52% (Etox). The main hot spot in conventional grape production was the production and consumption of diesel, ranging from 24% (EP) to 80% (ADP). On average, the relative contribution of diesel was 59%. The trellis of the vineyards (mainly stainless steel) represented relevant contributions to most impact categories, such as POFP (38%), AP (30%), ADP (11%) and GWP (10%). Fertilisation and associated on field emissions constituted the main environmental burden in terms of EP (64%). The production of pesticides represented the main impact in terms of ODP (40%), and was also significant for EP (11%) and POFP (9%). Other inputs, such as electricity use, machinery or water consumption presented minor contributions to the global environmental profile of conventional grape production.

Finally, for the Etox impact category, the use of synthetic pesticides, such as folpet or terbuthylazine represented over 99% of the total environmental burdens (Fig. 3). The remaining active substances used as plant protection agents presented a very low environmental impact despite the fact that mancozeb, fosetyl-Al or glyphosate are emitted in similar quantities to folpet or terbuthylazine. This is due to the lower characterisation factors of the latter in terms of eco-toxicity. Finally, the environmental change from one harvest year to another was associated with a decrease in emissions to water in 2011 and to the higher characterisation factors for water emissions in this particular impact category.

4. Discussion

4.1. Identification of the main hot spots

Diesel production and consumption used in field operations demonstrated to be the main source of environmental impacts in the three different agricultural management techniques for all impact categories, except for EP and Etox. In the latter categories, the importance of this activity depended on the management technique. For instance, at the CV site the main source of environmental impact in terms of EP was the on field emissions due to fertilisation. In the case of Etox, vine support was the main carrier for BD and BD-CV, while the CV site profile was dominated by pesticide emissions.

When the current study is compared to other published studies, similar hot spots are observed: diesel and fertilisers (Aranda et al., 2005; Gazulla et al., 2010; Point et al., 2012; Vázquez-Rowe et al., 2012a). Nonetheless, the absolute environmental burdens per FU show that there is a substantial decrease in the environmental profile of wine produced with biodynamic techniques, in accordance with other studies analysing other crop production systems (Alaphilippe et al., 2012; Stavi and Lal, 2012; Venkat, 2012). For instance, most conventional wines analysed in the literature in recent years showed environmental impacts at least 100% higher for most impact categories when compared to the biodynamic wine evaluated in this case study (Benedetto, 2013; Bosco et al., 2011; Point et al., 2012; Vázquez-Rowe et al., 2012a, 2013). For example, in terms of global warming, as shown in Table 5, the greenhouse gas (GHG) emissions linked to the agricultural stage of wine production ranged from 220 g CO_2 eq./bottle to 803 g CO_2 eq., at least 126% higher than the GHG emissions for the BD site in 2010 and 209% higher than in 2011. However, these same literature values appear to be in a similar range to the conventional site, including those reported for another Galician appellation – *Rías Baixas* (Benedetto, 2013; Bosco et al., 2011; Vázquez-Rowe et al., 2012b). Finally, overall environmental impacts for the BD-CV site were considerably higher than for BD wine in both years of assessment, but in a similar range to organic wineries evaluated in the literature (Carta, 2009; Rugani et al., 2009, 2013; Vázquez-Rowe et al., 2013).

Finally, it is important to remark the relevant variations in environmental burdens identified when different harvest years are compared, in accordance with analysis performed in previous studies concerning wine-LCA (Vázquez-Rowe et al., 2012a) and other food and beverage products (Ramos et al., 2011), as can be seen in Table 4. A common reason for this decrease throughout the three viticulture sites is related to the lower consumption of diesel in 2011, which is linked to favourable climatic conditions that

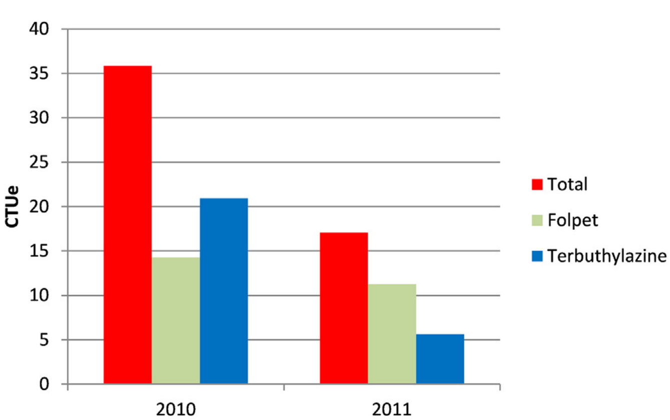

Fig. 3. Characterisation results for the main sources of environmental impact in terms of eco-toxicity (Etox) in the conventional viticulture site (Data per FU: 1.1 kg of grapes).

Table 5
Global warming potential (GWP) for the analysed viticulture sites as compared to previous publications (results reported in g CO_2 eq./bottle). NOTE: Not all wines have the same conversion rate of kg of grapes into mL of wine; therefore, the selected comparison basis was the amount of grapes needed to produce a bottle of wine.

	Publication	GWP (g CO_2 eq.)	Ratio wine/ BD-2010	Ratio wine/ BD-2011
BD-2010	Current study	97.2	1.00	1.37
BD-2011	Current study	71.1	0.73	1.00
BD-CV-2010	Current study	148	1.52	2.08
BD-CV-2011	Current study	87.3	0.90	1.23
CV-2010	Current study	375	3.86	5.27
CV-2011	Current study	283	2.91	3.98
Vermentino (2009)	Vázquez-Rowe et al., 2013	241	2.48	3.39
Nova Scotia (2006)	Point et al., 2012	803	8.26	11.3
Rías Baixas (2010)	Vázquez-Rowe et al., 2012b	377	3.88	5.30
Monteregio di Massa Maritima (2009)	Bosco et al., 2011	330	3.40	4.64
Morellino di Scansano (2009)	Bosco et al., 2011	220	2.26	3.09

BD = biodynamic viticulture; BD-CV = biodynamic-conventional viticulture; CV = conventional; GWP = global warming potential.

minimised the development of powdery and downy mildew and, therefore, produced a decline in the number of machinery interventions in the vineyards. Nevertheless, these decreases were more noticeable in the CV site due to the higher dependence on phytosanitary treatments. For instance, this very dry season favoured lower inputs of folpet, as well as lower emissions associated with the application of terbuthylazine (73% lower impacts than in 2010 for this pesticide). Moreover, the lessening of diesel impacts is also influenced by a decrease in certain agricultural activities, such as clearing cuttings and in the case of the CV and BD-CV sites, to a higher harvest yield in 2011 (see Table 2).

4.2. Comparing LCA results between viticulture techniques

Whenever the environmental profiles of grape production are compared for the three different production sites (Table 4), results suggest that biodynamic production implies the lowest environmental burdens, followed by the BD-CV site. The highest environmental impacts, therefore, were linked to conventional agricultural practices. The main reasons for this strong decrease in environmental impacts when BD and CV are compared is related to an 80% decrease in diesel inputs, which, at the same time, have to be matched with a lower application of plant protection products and fertilisers, and the introduction of manual work rather than mechanised activities on the vineyards.

Therefore, the environmental benefits of producing grape for vinification under biodynamic agricultural practices entail reductions ranging from 71% (ADP) to 99% (Etox) for harvest year 2010. Nevertheless, despite the considerable differences in global impacts between the production years, the relative environmental gains are similar for the two years of operation. In contrast, if the BD-CV site is compared to the CV winery, the decrease in environmental impacts is slightly lower, ranging from 58% for ADP and POFP to 99% for Etox in 2010. For the 2011 harvest year the reduction in environmental impacts is considerably higher, ranging from 67% (ADP) to 99% (Etox).

Whenever the LC impact category is compared between the different viticulture sites, the results show a completely different pattern. Due to the higher harvest yields for the CV site, this wine farm needs the lowest amount of available agricultural surface per FU. BD, on the contrary, shows the worst environmental profile in terms of land use. These results must be interpreted with caution, since vineyards that have suffered conversions from conventional practices to biodynamic or organic activities, experiment very low harvest yields during the conversion period (Hokazono and Hayashi, 2012). Nevertheless, in the case studies that have been provided in this study, the BD site did not have a conversion period, since the vines were directly planted for biodynamic purposes. In the BD-CV case study, despite the existence of a conversion period, it did not affect the harvest years analysed in this study. In fact, if the results in this study are matched to prior publications in which a certain crop or livestock activity is compared depending on the agricultural practices, it can be observed that in all cases the shift to biodynamic or organic production involves an important reduction in environmental burdens due to a reduction in operational inputs, but at the same time there is an increase in the occupation of land (Cederberg and Mattson, 2000; Pelletier et al., 2008; Meisterling et al., 2009; Boggia et al., 2010), as well as in human labour in some cases (Niccolucci et al., 2008).

Land occupation in LCA studies has traditionally been evaluated in a quantitative manner (Milà i Canals et al., 2007), without taking into consideration the degradation of the quality of the land that may occur during the occupation for human activities (Garrigues et al., 2012). Therefore, the SOM impact category, which is an easily defined impact category to compute land use occupation and transformation burdens which influence life support functions (Milà i Canals et al., 2007), has been modelled for the CV and BD viticulture sites assessed in this study (see Section S2 in the SM).

One single soil sample available for viticulture land was used for modelling the three different sites. On the one hand, the BD site was modelled based on the fact that it underwent a short transition period from pasture land in 2008. On the other hand, the CV site was initially a woody area when it was created in 1988. Changes in organic content of the vineyards were modelled based on the data available in Poeplau et al. (2011) concerning temporal dynamics in soils due to land use changes (see Section S2 in the Supporting Material – SM – for more details).

The results prove, in a similar way to the results shown in the LC impact category presented in the Results section, that the transition to biodynamic and other organic types of viticulture may imply an increased necessity for land, due to the lower harvest yields of these cultivation sites (Table 6). However, despite the strong difference shown in Table 6 regarding the SOM results, further field sampling should be done on site, in order to detect how the specific cultivation practices of conventional vs. biodynamic viticulture affect the carbon retention of the land.

Finally, it should be noted that the regular use of SOM in wine LCA studies would allow identifying not only the qualitative aspects of land occupation of the viticulture stage, but would also facilitate the inclusion of C dynamics when reporting the CF of viticulture products (Bosco et al., 2013). Moreover, the local characteristics of SOM (ILCD, 2011) allow unveiling the site-specific effects on land use of changing cultivation patterns. In fact, given the limited land availability in most European countries, including NW Spain, it is expected that land quality issues will become an important issue when applying consequential LCA approaches to viticulture (Rugani et al., 2013).

Human labour (HL) has been repeatedly disregarded from the system boundaries in previous wine LCA studies. The rationale behind this decision is that HL is not directly affected by changes in the FU. However, a recent study by Rugani et al. (2012) suggests its inclusion through a hybrid input–output LCI mechanism in order to provide a less anthropogenic perspective on how to deal with ecosystem services. The methodology in Rugani et al. (2012) is based on household expenditures and different levels of work skills, which eventually lead to variable human consumption behaviours. The method was adapted to HL in Spain, and thereafter computed for the specific characteristics of the CV and BD wineries. Finally, it is important to note that the assessment method used for this calculation was ReCiPe – midpoint H (Goedkoop et al., 2009), in order to maintain the same methodological criteria as Rugani et al. (2012).

The results, which can be observed in Fig. 4 and in Section S3 in the SM, show that HL represents a higher proportion of the environmental impact for the BD winery, representing up to 54% of the environmental impact in the case of terrestrial eco-toxicity – TET (only 15% in the case of the CV winery) and 44% for marine eutrophication (ME). Regarding a commonly used impact category,

Table 6
Indicator results for the soil organic matter (SOM) impact category model in the conventional (CV) and biodynamic (BD) viticulture sites evaluated.

Cultivation site	SOM per ha	SOM per FU
	kg CO_2	g CO_2
Conventional (CV)	38.67	4.95
Biodynamic (BD)	53.12	15.56
FU = 1.1 kg of grapes		

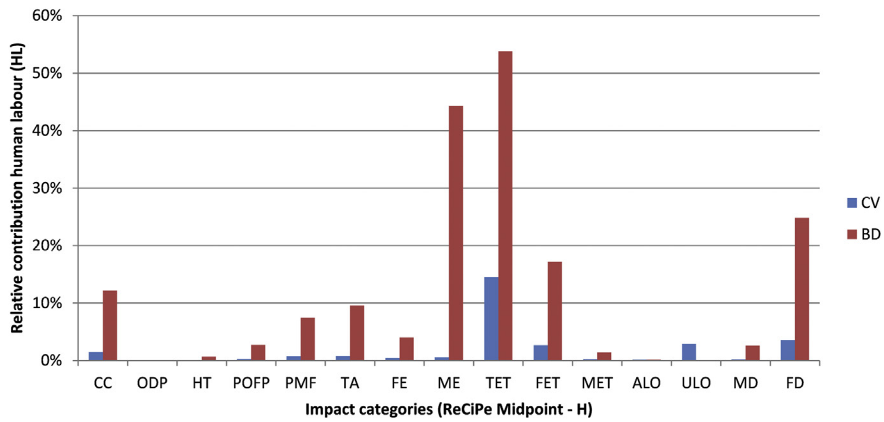

Fig. 4. Relative contribution of human labour to the total environmental impact of conventional (CV) and biodynamic (BD) wine, using ReCiPe Midpoint (H). NOTE: CC = Climate Change; ODP = Ozone Depletion; HT = Human Toxicity; POFP = Photochemical Oxidant Formation; PMF = Particulate Matter Formation; TA = Terrestrial Acidification; FE = Freshwater Eutrophication; ME = Marine Eutrophication; TET = Terrestrial Eco-toxicity; FET = Freshwater Ecotoxicity; MET = Marine Eco-toxicity; ALO = Agricultural Land Occupation; ULO = Urban Land Occupation; MD = Mineral Depletion; FD = Fossil Depletion.

such as climate change (CC), the relative environmental impacts of HL for the BD site represented 12% of the total impact, whereas in the case of the CV winery is was only 1.5%. The discrepancies between the two viticulture sites are mainly linked to the higher labour input per unit of produced output, and to the lower overall environmental impact of biodynamic grape production.

Consequently, HL environmental impacts, despite their minor importance in most impact categories, show that they can be of crucial relevance in specific environmental dimensions. In fact, they support previous findings that suggested that the labour inputs in organic grape production are substantially higher (Loake, 2001; Guzmán and Alonso, 2008). Moreover, the expected increasing transition from conventional to organic/biodynamic viticulture in years to come will enhance the relative importance of labour activities (Fogarty, 2008).

4.3. Improvement actions

The main improvement actions to reduce the environmental impact should be focused on the CV site, since the impacts associated with this winery are substantially higher than for the other two sites. Moreover, the reduction in the environmental impacts between CV and BD or BD-CV is higher than the reduction attained through improvement actions proposed for conventional viticulture in previous publications (Point et al., 2012; Vázquez-Rowe et al., 2012a). Therefore, an improvement in the environmental profile of conventional viticulture can be accomplished, on the one hand, through the optimisation of the main operational input in terms of environmental impact: diesel. This reduction can be performed through the reduction in the use of fertilisers with a correct management of nutrient balance and soil analysis. In fact, if plant protection products are managed taking into consideration meteorological conditions, anticipating pestilences, diesel inputs can be further reduced (Simon et al., 2011). Decision support systems, such as DOSAVIÑA, can be applied to calculate the optimal volume rate for spray applications in vineyards (Gil et al., 2011). In fact, these reductions in fertiliser and plant protection products would also imply an important reduction in environmental burdens related to the optimisation of these products.

An alternative scenario would be the conversion of CV viticulture into BD-CV or BD. This approach would guarantee a strong decrease in most environmental impacts (except LC and HL). However, it is important to note that during the conversion period (at least 3 harvest years) the harvest yield is very low (e.g. in the analysed appellation the yield during conversion period ranges 1–2 t/ha), which involves very high environmental impacts per FU during this period. Hence, CV viticulture wine-growers who already have environmental monitoring and/or reporting schemes implemented, but want to shift to organic or biodynamic practices, may choose to perform a gradual conversion by plots in order not to damage the yield, and hence, the environmental profile of the entire winery.

It is important to remark that biodynamic farming implies a lower harvest yield (see Table 2; Pfiffer et al., 1992). However, in terms of economic expenditure, the reduction of external operational inputs lowers production costs considerably (Scialabba et al., 2002), but they do not compensate for the increase in HL costs. Hence, current biodynamic wine prices are on average 25–30% higher than their conventional equivalents (Bernabéu, 2008). Nevertheless, it should be highlighted that a wide range of studies have alerted about the energy scarcity that human populations will face in the following decades (Hall et al., 2003; Day et al., 2009). Consequently, it seems feasible that a growing number of wineries will shift to low-input viticulture techniques in an effort to avoid increasing oil prices (Wright, 2009). Moreover, recent publications have demonstrated that consumers are willing to spend more to acquire these types of wine (Bernabéu et al., 2007; ICEX, 2010). However, the increasing number of wineries that are shifting to biodynamic and other organic practices will eventually lead to a steady conversion between conventional and biodynamic wine prices (Greentrade market place, 2006).

5. Conclusions

As far as we were able to ascertain, the current study is the first one to analyse from a life-cycle perspective biodynamic viticulture, as well as its comparison with two other types of viticulture techniques: conventional viticulture and biodynamic-conventional viticulture. The obtained results do not only confirm prior findings that the environmental impact linked to a specific viticulture surface can have relevant variations on an interannual basis, but also demonstrate strong variability between viticulture practices. In fact, biodynamic viticulture, and to a lesser extent, an intermediate biodynamic-conventional winery, showed a substantially lower environmental profile for all the environmental impacts assessed, except for LC.

In decades to come, an increase in the scarcity of fossil fuels will affect many developed nations, including their agricultural practices and the price of food. Therefore, an alternative farming and food production and supply systems will be needed to face these important challenges. Despite the need to verify the results obtained in this case study under other climatic or geographical conditions, the shift to biodynamic viticulture seems an attractive alternative in terms of environmental sustainability and organoleptic characteristics of the wine. However, it remains unknown how a widespread shift in winegrowing activities towards biodynamic practices, which imply substantial yield decreases, would influence, on the one hand, land use changes in areas (i.e. appellations) that are strongly constrained by land availability, and, on the other, wine supply to meet the steadily increasing global demand after the economic downturn. Accordingly, from an LCA perspective, the implementation of consequential approaches in future studies would allow the use of life cycle management beyond the identification of environmental improvements in individual sites, triggering results that may be of use on a policy making level to guide land and environmental management at an appellation scale.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.08.026.

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