LIFE CYCLE ASSESSMENT OF VITICULTURAL TECHNICAL MANAGEMENT ROUTES (TMRs) : COMPARISON BETWEEN AN ORGANIC AND AN INTEGRATED MANAGEMENT ROUTE

Anthony ROUAULT[1], Sandra BEAUCHET[1,2], Christel RENAUD-GENTIE[1*], Frédérique JOURJON[1]

1 : Unité de Recherche GRAPPE, Univ Bretagne Loire, Ecole Supérieure d'Agricultures (ESA)-INRA, 55 rue Rabelais, BP 30748, 49007 Angers cedex, France
2 : ADEME, SAF, 20, Avenue du Grésillé, 49 000 Angers, France

Abstract

Aims : Using Life Cycle Assessment (LCA), this study aims to compare the environmental impacts of two different viticultural technical management routes (TMRs) ; integrated and organic) and to identify the operations that contribute the most to the impacts.

Methods and results : LCA impact scores were expressed in two functional units : 1 ha of cultivated area and 1 kg of collected grape. We studied all operations from field preparation before planting to the end-of-life of the vine. Inputs and outputs were transformed into potential environmental impacts thanks to SALCA™ (V1.02) and USETox™ (V1.03) methods. Plant protection treatments were a major cause of impact for both TMRs for fuel-related impact categories. For both TMRs, the main contributors to natural resource depletion and freshwater ecotoxicity were trellis system installation and background heavy metal emissions, respectively.

Conclusion : This study shows that the studied organic TMR has higher impact scores than the integrated TMR for all the chosen impact categories except eutrophication. However, the chosen TMRs are only typical of integrated and organic viticulture in Loire Valley and some emission models (heavy metal, fuel-related emissions, and nitrogen emissions) have to be improved in order to better assess the environmental impacts of viticulture. Soil quality should also be integrated to LCA results in viticulture because this lack may be a disadvantage for organic viticulture.

Significance and impact of study : This study is among the first to compare LCA results of an integrated and an organic TMR.

Key words : environmental assessment, vineyard management, organic viticulture, integrated viticulture, life cycle thinking

Résumé

Objectifs : En utilisant l'Analyse du Cycle de Vie (ACV), cette étude compare les impacts environnementaux de deux itinéraires techniques viticoles (ITK) différents (raisonné et biologique) et identifie les opérations qui contribuent le plus aux impacts.

Méthodes et résultats : Les scores d'impacts ACV ont été exprimés en deux unités fonctionnelles : 1 ha de surface cultivée et 1 kg de raisin récolté. Toutes les opérations depuis la préparation de la parcelle jusqu'à la fin de vie de la vigne ont été prises en compte. Entrants et sortants ont été transformés en impacts potentiels à l'aide des méthodes SALCA™ (V1.02) et USETox™ (V1.03). Les traitements phytosanitaires sont un impact majeur pour les deux ITK pour les impacts liés à la consommation de carburant. Pour les deux ITK, les principaux contributeurs aux impacts épuisement des ressources naturelles et écotoxicité aquatique (eau douce) sont respectivement l'installation du palissage et les émissions de fond d'éléments traces métalliques (ETM).

Conclusion : Cette étude montre que l'ITK biologique étudié a des scores d'impact plus élevés que l'ITK raisonné pour tous les impacts sélectionnés sauf l'eutrophisation. Cependant, les ITK sélectionnés pour l'étude sont uniquement représentatifs au niveau du Val de Loire d'une viticulture biologique « intensive » et d'une viticulture raisonnée et certains modèles d'émission (ETM, émissions liées aux carburants, émissions azotées) doivent être améliorés pour une meilleure évaluation des impacts environnementaux de la viticulture. La qualité du sol devrait aussi être intégrée aux résultats ACV car ce manque désavantage sans doute la viticulture biologique.

Signification et impact de l'étude : Cette étude est parmi les premières à comparer les résultats ACV d'un ITK raisonné et d'un ITK biologique.

Mots clés : évaluation environnementale, gestion du vignoble, viticulture biologique, viticulture raisonnée, approche cycle de vie

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*Corresponding author : c.renaud@groupe-esa.com

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INTRODUCTION

Over the past few years, the environmental impacts of human activities, and of intensive farming in particular, often have been singled out. Human toxicity, eutrophication, ecotoxicity, global warming, soil degradation and acidification are among the most significant environmental impacts of agricultural practices for the second half of the 20th century (Andersson, 2000 ; Tilman *et al.*, 2002 ; Van der Werf and Petit, 2002 ; Stoate *et al.*, 2009). In this context, environmentally-friendly food products are created and consumer demand for such products is increasing (Ruviaro *et al.*, 2012 ; Jourjon and Symoneaux, 2013 ; Symoneaux and Jourjon, 2013). For example, we recently saw the emergence and progression of « organic » wine (from organic viticulture). Its sales increased by 56 % between 2010 and 2013 in France, which represents the best progression among organic products (AgenceBio, 2014). Moreover, the surface of French organic vineyard almost tripled between 2007 and 2012 and keeps increasing (+22 % between 2012 and 2013) (AgenceBio, 2014). In Europe, this surface has been multiplied by 2.3 between 2007 and 2011 (Willer, 2013).

Since 2008, the French government has been adressing environmental issues through the « Grenelle de l'Environnement ». This governmental project aims to restructure French environmental policy (ADEME, 2014). Within this framework, the « EcoPhyto » plan has been launched in 2008 with the objective of reducing pesticide use by 50 % between 2008 and 2018. The « Grenelle de l'Environnement » also aims to increase organic agricultural surface by 20 % by 2020 and to spread environmentally-friendly practices (République Française, 2014a ; République Française, 2014b).

In order to integrate these new demands and rules, the entire wine sector continues its efforts to reduce pesticide use, resulting in a slight decrease between 2006 and 2010 in France (Agreste, 2012 ; Jourjon *et al.*, 2015). The major impacts of viticulture are indeed linked to pesticide use but also to mechanization (Boulanger-Fassier, 2008).

Life Cycle Assessment (LCA) is a quantitative method enabling the evaluation of the potential environmental impacts of a product, process or service during its whole life cycle. Because it takes into account all the life cycle steps of a product (from "cradle to grave"), LCA enables the identification of the most impacting elements and gives accurate advices to reduce impacts. LCA also aims to avoid pollution transfers : reducing one impact while increasing another or transfering impacts from one life cycle step to another (ISO, 2006a ; ISO 2006b ; Benoist *et al.*, 2008 ; Jolliet *et al.*, 2010).

LCA includes four mandatory steps (ISO, 2006a ; ISO 2006b), as shown in figure 1.

Nonetheless, LCA does not answer all questions. It can quantify pollutant emissions and potential impacts but, for example, it cannot show the effects of a pollutant on the nearby population of an industry nor evaluate systems from an economic or social point of view, even if research work has started to include these issues to LCA studies (Jolliet *et al.*, 2010).

LCA is now well-known as a useful tool to develop more sustainable agricultural systems (Andersson, 2000). Lots of agricultural LCA studies have been published in the last few years (for review, see Roy *et al.*, 2009). Moreover, application of LCA on a plot scale has been identified as relevant to assess environmental impacts of agriculture (Bessou *et al.*, 2013 ; Renaud-Gentié, 2015). LCA studies on wine have been published in recent years ; they enabled adaptation of LCA method to wine industry. In these studies, vine growing phase has an important part in total impacts of wine's life cycle (Gazulla *et al.*, 2010 ; Point *et al.*, 2012 ; Vázquez-Rowe *et al.*, 2012 ; Neto *et al.*, 2013 ; Rugani *et al.*, 2013 ; Fusi *et al.*, 2014). Thus, recent LCA studies only focussed on the vine growing phase (Villanueva-Rey *et al.*, 2014 ; Renaud-Gentié, 2015). Bellon-Maurel *et al.* (2015) proposed a method to use traceability data to generate life cycle inventory for viticulture. Renaud-Gentié (2015) proposed a LCA framework method to assess environmental impacts of viticultural technical

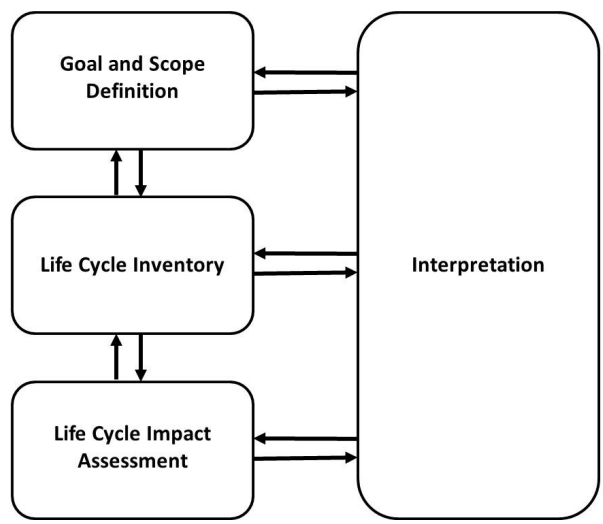


Figure 1 - LCA steps (ISO, 2006a ; ISO 2006b).

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management routes (TMRs) on a plot scale. This method was then applied to several TMRs in the Loire Valley and methodological improvements were identified (Renaud-Gentié, 2015). According to Villanueva-Rey *et al.* (2014), there is a strong variability concerning environmental impacts between different TMRs. For example, in that study, the studied biodynamic system "showed a substantially lower environmental profile" (Villanueva-Rey *et al.*, 2014).

This study aims to evaluate and compare the environmental performance of two different TMRs applied to a same vineyard, one fulfilling organic viticulture requirements, the other defined as integrated viticulture. A TMR is a logical successions of technical options designed by the farmers (Renaud-Gentié *et al.*, 2014a). Major impacts of both systems and the most impacting practices are identified. Measures to reduce major impacts are therefore recommended for each TMR. Finally, the study sheds light on methodological issues about applying LCA on a TMR scale.

MATERIALS AND METHODS

1. Goal and scope definition

1.1 Goals and scope

This study evaluates and compares environmental impacts of an organic and an integrated vineyard parcel with identical environmental conditions.

Integrated and organic viticulture both aim to respect the environment while producing grapes. Concerning dry white wine production from Chenin Blanc grape variety in Loire Valley, five TMR categories were identified in a typology, of which two were organic: one « moderate » organic TMR (few operations) and one « intensive » organic TMR (lots of operations) (Renaud-Gentié *et al.*, 2014a). Both categories include the non-use of synthetic pesticides, the use of copper and sulfur as fungicides and tillage under vines. The major difference between « moderate » and « intensive » organic TMR is the frequence of copper and sulfur application and canopy management operations, which are more numerous in « intensive » TMRs (Renaud-Gentié *et al.*, 2014a). The organic TMR included in this study belongs to the « intensive » organic TMR category. In integrated viticulture, synthetic pesticide use is not forbidden. However, the purpose of integrated viticulture is to limit their use as much as possible. A trade-off between grape quality objectives and environmental concerns must be found. The winegrower must explain each operation with an accurate diagnosis and evaluation of his vineyard (FARRE, 2014). The studied integrated TMR belongs to « moderate pesticide use » TMR in the previously quoted classification (Renaud-Gentié *et al.*, 2014a).

The studied systems are two TMRs applied by the same winegrower during 2013 in a Chenin Blanc vineyard located in Loire Valley for the same dry white wine production objective (AOC Saumur Blanc). Both parcels are covered with the same width of grass (30 % of the surface), planted with the same vine density (4785 vines/ha) and espalier trained.

The function of a TMR could be defined as growing vine on a given area in order to produce as much grapes as possible with a given grape quality target.

1.2 Functional Units

The Functional Unit (FU) is known as the chosen reference unit in LCA. This unit allows comparison of different systems that have the same function. It characterizes and quantifies the system's function (ISO, 2006a; ISO 2006b; Jolliet *et al.*, 2010). As Andersson (2000) said, the choice of the FU is critical when the goal is to compare different products and this choice "can significantly influence the conclusions" of the study.

The first function of a vineyard TMR is the production of grapes. However, considering that all the operations are done on a parcel scale, we can also choose to express LCA results depending on the cultivated surface area as winegrowers often reason their practices on a hectare basis (Renaud *et al.*, 2010).

In our case, we chose to express our results with the two following FUs:

- 1 hectare (ha) of land used for Chenin Blanc grape production for the same dry white wine production (AOC Saumur Blanc).

- 1 kilogram (kg) of Chenin Blanc grapes for the same dry white wine production (AOC Saumur Blanc).

We chose to express impact scores with those two units in order to be consistent with many agricultural LCA studies. Indeed, the most used FUs in agricultural LCA studies are mass of final products (kg), energy or protein content in food products (kJ), area (ha), unit of livestock (Roy *et al.*, 2009). Moreover, when comparing organic and integrated viticulture, considering both units allows seeing the influence of the yield on LCA results.

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1.3 System boundaries

In this study, we assessed the environmental impacts of two wine-grape production systems. We assessed impacts from cradle to farm gate, like lots of agricultural LCA studies do. All the steps following grape production (wine making, transport, consumption, etc.) are not integrated into system boundaries (Roy *et al.*, 2009). We consider the parcel as an agronomic surface into a vineyard.

The vine life cycle can be divided into four main stages : planting phase, non-productive years (3 years), productive phase (several decades), and end-of-life phase. On a parcel scale, a soil preparation phase can be added before planting (Reynier, 2011).

In order to consider the whole vine life cycle while assessing the impacts of one productive year (2013), we divided the impacts of non-productive phases (soil preparation, planting, non-productive years, end-of-life) by 30, as we considered this as the mean lifetime for a vineyard parcel. Occasional operations (not executed each year but contributing to several vintages, e.g. fertilisation, interplanting, etc.) are divided by their frequency of occurrence.

Transport of supplies and products (pesticides, fertilisers, etc.) used during productive and non-productive phases and during occasional operations has also been taken into account.

Like many agricultural LCA studies, biogenic carbon is not accounted for in this study. Indeed, emitted by the vine, biogenic carbon (contained in the vine plant) is reabsorbed during photosynthesis as CO_2. It is thus a closed loop where human actions have no effect.

Machine and worker movements from the farm (or from the main office of the service supplier) to the parcel, and time for coupling and uncoupling the machine and washing the sprayers and tractors are also included into system boundaries on a standardized basis. The spray of the washing water to the parcel is also taken into account. Workers' private travel from home to the farm is not included.

1.4 Sensitivity analysis

Based on our results, a sensitivity analysis was done. This analysis enables comparing both systems. We considered a lower yield for the organic parcel and analysed the differences between the two studied systems using several yield assumptions. We could not have an accurate yield for the organic parcel from the winegrower. We only had an overall yield of 5.7 t/ha for the two parcels. For this sensitivity analysis, we thus chose to test a 20 % lower yield for the organic parcel, which is consistent with other studies (Nicoletti *et al.*, 2001 ; Niccolucci *et al.*, 2008 ; Pizzigallo *et al.*, 2008 ; Point *et al.*, 2012).

2. Life cycle inventory for both TMRs

2.1 Data collection method

Data concerning operations realised in the vineyard during 2013 and non-productive phases were collected thanks to winegrower's traceability documents (operation report and treatment calendar), a data inventory file filled by the winegrower, discussions by e-mails and interviews with the winegrower. The following informations were collected :

- Dates of the operations,

- Duration of each operation,

- Machine and equipment types used for each operation,

- Names of the products used for supplies (posts, stakes, wires, etc.), plant protection treatments, weeding and fertilisation,

- Characteristics of machines and equipments used for each operation.

Interviews with the winegrower enabled collecting references for machines and supplies and thus their characteristics (weight, power, etc.) from manufacturers.

2.2 Data sources

Machine weights are given in manufacturers' documentation. If the information was not available, an estimate by the winegrower was taken into account.

Lifetime and annual use durations for machines were extracted from a document edited by ART (Gazzarin, 2011) and storage surface areas are from a document provided by C. Gazzarin (author of the latter ART document). When data were not available, lifetime was estimated by experts and storage surface areas from machine dimensions or, as a last resort, from winegrower's estimate.

Concerning fuel consumption of some operations, results from viticultural equipment tests were used (Gaviglio, 2009). For operations that were not available in the previously quoted document, data from EcoInvent report (Nemecek *et al.*, 2007) and

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expert estimates (winegrowers, viticultural machine specialists, etc.) were used.

Pesticide compositions are from the pesticide database of the French Agriculture Ministry (E-phy, 2014).

2.3 Direct field emission models

In order to quantify direct emissions linked to the use of all inputs and their distribution in environmental compartments (air, soil, surface and ground water), the use of emission models is essential. This study necessitated emission models for calculating direct field emissions for ammonia (NH_3), nitrate (NO_3^-), nitrogen dioxide (N_2O), nitrogen oxides (NO_x), phosphorus, heavy metals, pesticides and fuel consumption. We used emission models recommended by Agribalyse (Koch and Salou, 2014) except for ammonia and pesticide emissions. The emission models used in the study are listed in table 1.

3. Life cycle impact assessment

SimaPro® software (V8.0.3.14) was used to calculate life cycle impacts.

To calculate life cycle impacts from inventory data, LCA is done through characterization methods. These methods enable classifying inventory data into different impact categories. It also gives each piece of data a characterization factor which tranforms the unit and enables having the same reference unit for all data of the same impact category. We used SALCA™ V1.02 and USETox™ V1.03 characterization methods in this study. SALCA™ impact categories come from different existing characterization methods and inventory categories (Agroscope, 2014).

Within SALCA™, the following impact categories were chosen for this study:

- Demand on fossil resources (MJ-eq) (SALCA™ V1.02). This impact category quantifies the consumption of fossil fuels regarding global demand for each fossil fuel. Impact score is related to quantity and scarcity of each fossil fuel.

- Global Warming Potential (kg CO2-eq) (SALCA™ V1.02). This category models effects of greenhouse gases on global warming.

- Photochemical ozone formation potential (pers.ppm.h) (SALCA™ V1.02). Photochemical ozone is a pollutant created by photochemical reactions between PAHs, NO_2 (and other primary pollutants from vehicles and industries) and O_2. Photochemical ozone is the main cause of photochemical smogs that can be observed around big cities.

- Eutrophication potential (kg N-eq) (SALCA™ V1.02). Eutrophication is caused by nitrogen and phosphorus emissions to water. This surplus of nutrient in water induces a multiplication of micro-organisms that consume more oxygen and can lead to asphyxia of the aquatic environment.

- Acidification potential (m^2 or kg SO_2 eq) (SALCA™ V1.02). Acidification is caused by sulfur and nitrogen emissions to air that can be harmful to ecosystems after deposition on soils and oceans.

- Freshwater ecotoxicity potential (CTUe) (USETox™ V1.03). Toxicity of substances emitted to the aquatic environment on wildlife is assessed in this impact category.

- Resource depletion (kg) (SALCA™ V1.02). Scarcity of mineral and fossil resources is assessed in this impact category.

All these impact categories were chosen because we identified them as key environmental issues for

Table 1 - Emission models used in the study

Modelled phenomenon [Unit]	Bibliographic Reference
Erosion [kg of eroded soil/year]	RUSLE (Foster, 2005)
Phosphorus emissions [kg P/ha]	SALCA-P (Nemecek *et al*., 2007)
Nitrate emissions [kg N/ha]	SQCB (Faist-Emmenegger *et al*., 2009)
Ammonia emissions to air [kg NH_3/ha]	Tier2 approach (Hutchings *et al*., 2013)
Nitrogen oxides and nitrogen dioxide emissions [kg NO_x (ou N_2O)/ha]	EcoInvent (Nemecek and Schnetzer, 2011)
Heavy metal emissions [g HM/ha]	SALCA-ETM (Freiermuth, 2006)
Volatile Organic Compounds, Nitrogen oxides and carbon monoxide emissions from fuel combustion [g/h]	EcoInvent (Nemecek *et al*., 2007)
Active substance emissions from pesticides [kg/ha]	PestLCI 2.0 (Renaud-Gentié *et al.*, 2014b)

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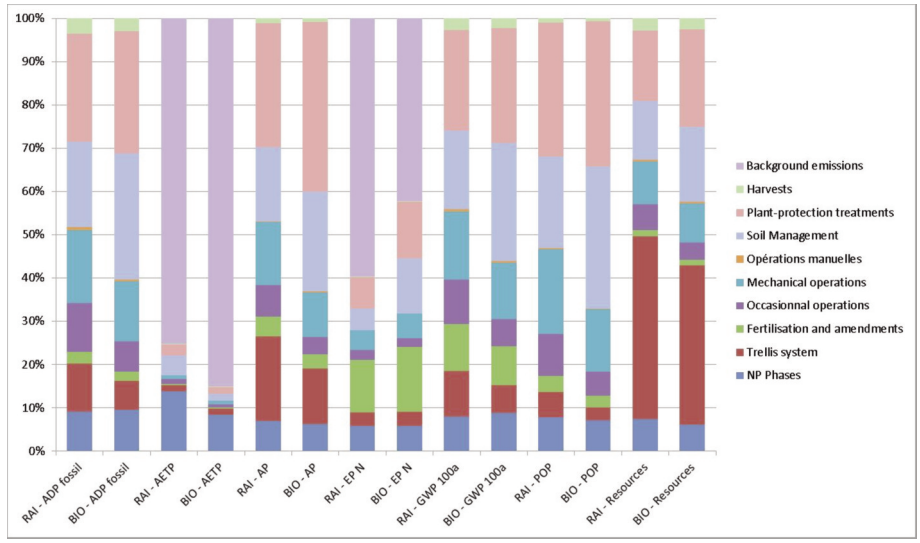


Figure 2 - Operations' contributions to the chosen impact categories
(RAI: Integrated TMR; BIO: Organic TMR; ADP fossil: Abiotic Depletion Potential for fossil resources; GWP: Global Warming Potential; POP: Photochemical ozone formation potential; AP: Acidification potential; EP N: Eutrophication potential (linked to nitrogen); AETP: Freshwater ecotoxicity potential).

viticulture. To be consistent, we chose to select impact categories only within the SALCA™ V1.02 version. We added one impact category from USETox™ V1.03 because it is a consensus model supposed to represent the best application practice for characterization of toxic impacts of chemicals in LCA (Renaud-Gentié *et al.*, 2015) and because of its consistency with the pesticide emission model we used (Pest-LCI).

RESULTS

Results are reported in figure 2. To make results easier to understand, all processes were gathered in different operation categories (or life cycle steps):

- The TMR needed for **trellis system installation** is shown separately from other **non-productive** operations because we noticed high impacts of this process in our first results.

- « **Fertilisation and amendments** » are occasionnal operations we chose to show separately because of their high potential impacts.

- « **Occasional operations** » category gathers operations that are not done every year and have consequences on several vintages: interplanting, trellis system maintenance, grass sowing and subsoiling.

- « **Mechanical operations** » are operations realised thanks to viticultural equipment coupled with a tractor. This category excludes phytosanitary treatments, fertilising operations and soil management operations but includes pre-pruning, shredding of vine shoots, trimming and leaf thinning.

- « **Soil management** » category accounts for all operations linked to weed and grass management, e.g. weeding (chemical or mechanical) and mowing.

- « **Plant protection treatments** » category regroups all phytosanitary treatments realised in the parcel during 2013 (« machines » processes included).

- « **Harvest** » is in a separate category in order to be able to compare manual and mechanic harvests.

- Nitrate, phosphorus and heavy metal emissions which could not be assigned to any specific operation are gathered in a category named « **background emissions** ». These emissions are either natural and, thus, independent from human actions in the vineyard or from a combination of operations and, thus, could not be attributed to only one specific operation. Emissions for non-productive phases are not included in this category but are included in the « non-productive phases » category.

1. Life cycle impact assessment of an integrated TMR

Plant protection treatments are a major source of impact for this TMR as they represent an average of 28 % for ADP fossil, global warming potential, photochemical ozone formation and acidification

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categories. This is mainly due to fuel consumption and fuel-related emissions to air.

Soil management and mechanical operations are also main contributors to TMR's impacts (average of 18 % each for GWP 100a, POP, AP and ADP fossil) mostly because of fuel consumption.

Background emissions have a high contribution to eutrophication (around 60 %) because of nitrate emissions. They also have a high contribution to freshwater ecotoxicity (75 %) because of heavy metal emissions.

Non-productive phases, including trellis system installation and despite they are amortized on vineyard lifetime, have high contributions. Indeed, they represent an average of 20 % of total impacts for GWP 100a, AP, AETP and ADP fossil. Trellis system installation impacts 43 % of resource depletion, mainly because of the amount of zinc used during galvanization of steel wires.

2. Life cycle impact assessment of an organic TMR

Plant protection treatments and soil management together account for more than 50 % of impacts for the following impact categories : fossil resource demand, global warming, photochemical ozone formation and acidification. This is mainly due to fuel consumption and its gas emissions.

Background nitrate emissions related to the global management of the vineyard represent 42 % for eutrophication impacts. For this category, plant protection treatments account for 15 % because of NOx emissions from fuel combustion.

Trellis system installation represents 37 % of natural resource depletion impacts. In this impact category, plant protection treatments account for 22 % and soil management for 17 %.

Concerning freshwater ecotoxicity, heavy metal emissions related to the global management of the vineyard are responsible for 85 % of total impact.

Non-productive phases account for an average of 10 % for each impact category (except resources).

3. Comparison of impacts between the two studied TMRs

For the majority of studied impacts, organic TMR has more impacts than the integrated one. Except for freshwater ecotoxicity (AETP) and eutrophication (EP N), the integrated TMR has, on average, 20 % less impact than organic TMR. Concerning freshwater ecotoxicity, the integrated TMR has 5 % less impact than the organic TMR. Finally, organic TMR has 10 % less impact than integrated TMR for eutrophication (EP N).

Table 2 shows, for each life cycle step and each impact, the differences between the two studied TMRs. Impact scores that are almost equal between the two TMRs (fertilisation and amendments, mechanical operations, harvests) are not shown in this table. Positive values mean a higher score for the organic TMR and negative values a higher score for the integrated TMR.

Impact differences between both TMRs are mostly due to soil management because its impact score has a 45 % variation for all categories except freshwater ecotoxicity. A high difference (34 % on average) can also be observed between plant protection treatment

Table 2 - Impact score variations between the two studied TMRs for some life cycle steps.
Variations are calculated following this equation : *(IS_Org – IS_Int)/Max(IS_Org ;IS_Int)* with IS_Org : Impact Score of the organic TMR and IS_Int : Impact Score of the integrated TMR. For example, impact score of non-productive phases for ADP fossil is 21 % higher in organic TMR than in integrated TMR.

	Non productive phases	Trellis system installation	Occasionnal operations	Manual operations	Soil management	Plant protection treatments	Background emissions
ADP fossil	21%	-27%	-25%	-13%	44%	28%	0%
GWP 100a	26%	-27%	-25%	-4%	45%	28%	0%
POP	20%	-32%	-21%	5%	53%	32%	0%
AP	20%	-7%	-21%	21%	47%	48%	0%
EP N	-17%	-13%	-21%	10%	53%	32%	-42%
Resources	-8%	-3,30%	-23%	2%	30%	35%	0%
AETP	-35%	0%	-33%	-8%	-64%	-34%	16%

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impact scores of both TMRs for the same impact categories.

Concerning freshwater ecotoxicity, the integrated TMR has a higher impact score concerning plant protection treatments (+34 % in comparison with organic TMR), non-productive phases (+35 %) and soil management (+64 %). Organic TMR has a higher total impact score because of a higher impact score related to background emissions (16 %).

Concerning impacts related to fuel consumption (ADP fossil, GWP 100a, POP and AP), total impact differences are mostly due to soil management, plant protection treatments and non-productive phases. However, for these impact categories and concerning trellis system installation, higher impacts of integrated TMR can be observed (from 7 % for AP and around 30 % for ADP fossil, GWP 100a and POP). This is only due to higher fuel consumption (and emissions to air) in integrated TMR which is due to a higher number of wooden posts that had to be planted.

Regarding eutrophication, difference between integrated and organic TMR should be attributed to background emissions as its impact score variation between both TMRs is high (42 % more for integrated) and because background emissions are the main contributor to total impact score for both TMRs. These background emissions are mainly nitrate emissions to water and ammonia emissions to air.

4. Influence of yield on impacts (with kg functional unit)

As explained in section 1.4, a sensitivity analysis has been performed considering this assumption: organic TMR could result in a 20 % lower yield than integrated TMR (Table 3).

DISCUSSION

1. Major impact sources

1.1 Fuel consumption

For both TMRs, plant protection treatments and soil management are the operations that have the highest impacts on global warming, photochemical ozone formation, acidification and fossil resource demand. The main cause of these impacts is the fuel combustion while tractors are working in the vineyard.

Impacts on fossil resource demand are directly related to fuel consumption since only petroleum extraction is taken into account for this impact category.

Global warming scores are related to greenhouse gas emissions from fuel combustion, which are proportional to fuel consumption.

Impact scores concerning photochemical ozone formation potential are mainly due to non-methane volatile organic compound (NMVOC), nitrogen oxide (NO_x) and carbon monoxide (CO) emissions from fuel combustion in tractors.

Similarly, acidification impact scores are related to NO_x emissions from fuel combustion. Consequently, reducing impact scores for these four impact categories requires reducing fuel consumption.

Calculations of NMVOC, NO_x and CO emissions are based on values from Nemecek *et al.* (2007). These emission values are given for several agricultural operations and the hourly fuel consumption considered for each operation is provided. As the hourly fuel consumptions for similar viticultural operations (collected from the winegrowers) were often different from those considered in this document, we considered (in the absence of any

Table 3 - Comparison of potential impacts (expressed in kg of grapes) of both TMRs with the assumption of a lower yield for organic TMR

	Integrated	Organic	Organic (-20 %)
GWP 100a (kg CO_2 eq)	0,2965	0,3613	0,4516
POP (m^2.ppm.h)	4,5585	6,2819	7,8524
AP (m^2)	0,0369	0,0519	0,0649
EP N (kg N)	0,0007	0,0008	0,001
AETP (CTUe)	0,6595	0,6946	0,8683
ADP Fossil (MJ eq)	4,0458	4,9729	6,2161
Resources (kg)	0,0001	0,0001	0,0001

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more reliable information) that gas emissions for each operation type were proportional to the hourly fuel consumption of machines. For example, if values from Nemecek *et al.* (2007) are 9 L/h for fuel consumption with a corresponding NMVOC emission value of 12 g/h and fuel consumption for the same type of operation from our winegrower is 10 L/h, (10*12)/9=13,33 g/h will be considered as the corresponding NMVOC emission value. According to Nemecek *et al.* (2007), emissions of these three pollutants (NMVOC, NO_x, CO) depend on speed and engine power. As we could not take into account these parameters (lack of data), there are uncertainties concerning NMVOC, NO_x and CO emissions. However, in any case, reducing machine use will reduce TMR's contribution to this impact category. Global Warming Potential (GWP) is the most used impact category in viticultural LCA studies. Table 4 compares different GWP results from recently published studies with our results.

Differences between studies can be explained by differences in system boundaries and types of data. However, our results are consistent with other studies, particularly with Villanueva-Rey *et al.* (2014). Indeed, GWP score calculated for BD-2010 is much lower than our values for organic and integrated TMRs. Moreover, GWP score for CV-2010 is higher than our integrated TMR's score and lower than our organic TMR. This is due to a higher machine use in our organic TMR than in the two remaining TMRs and it seems consistent with the machine use in TMR categories defined by Renaud-Gentié *et al.* (2014a).

1.2 Background nitrate emissions

Eutrophication potential of both studied TMRs is mostly due to nitrate emissions leached without nitrogenous fertiliser input applied during the studied year. These emissions are related to leaching of nitrogen already present in the soil by rainfalls during the studied period. There is a pending question concerning influence of nitrogen inputs from previous years because the model we chose makes assumptions about the existing Nitrogen stock without taking into account the real quantity brought in the previous years. Furthermore, nitrogen uptake by grass should be taken into account in future studies. This is not the case in this study and accounting for it may reduce emissions.

Organic fertilisation made during 2013 is the second contributor to eutrophication, because of nitrate emissions from fertilisers. Reducing the use of fertilisers should enable reducing nitrate emissions and thus (nitrogen-related) eutrophication for each TMR. However, these emissions are very low compared to emissions of the whole TMR and the parcel is lacking organic matter so it needs a regular organic input to meet vine's needs.

1.3 Heavy metal emissions

For integrated TMR, background emissions and non-productive phases are the main sources of impact for freshwater ecotoxicity. Score impacts related to the « non-productive phases » category are mainly due to active ingredient emissions whereas score impacts related to the« background emissions » category are mainly due to heavy metal emissions.

In organic TMR results, heavy metal background emissions are also the main source of impact for freshwater ecotoxicity. More specifically, these heavy metal emissions are strongly related to erosion and leaching. Reducing these heavy metal emissions seems difficult as they are not related to inputs. In this study, we did not account for long-term impacts but only short-term impacts. If long-term impacts were accounted for, plant protection treatments could have more impacts because of copper use in organic viticulture.

Background emissions are the main impact source concerning freshwater ecotoxicity. Similarly to impacts of nitrate emissions, impacts from

Table 4 - GWP results from different viticultural LCA studies (calculated with similar methods) (a : BD-2010 corresponds to a biodynamic TMR, b : CV-2010 corresponds to a conventional TMR)

	Publication	GWP (g CO_2-eq/kg of grapes)
Integrated TMR	This paper	289
Organic TMR	This paper	361
BD-2010[a]	(Villanueva-Rey *et al.*, 2014)	88
CV-2010[b]	(Villanueva-Rey *et al*., 2014)	341
Ribeiro (2010)	(Vázquez-Rowe *et al*., 2012)	1 547
Nova Scotia (2006)	(Point *et al*., 2012)	720
Vermentino (2012)	(Fusi *et al.*, 2014)	158

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background heavy metal emissions could be included to plant protection treatment impacts if we consider background emissions are mainly coming from previous vintages.

2. Comparison between integrated and organic TMRs

Organic TMR has more impact (20 % more on average) than integrated TMR concerning the following impact categories: fossil resource demand, global warming potential, photochemical ozone formation potential, acidification potential, eutrophication (nitrogen related) potential and resource depletion. This impact surplus is significantly caused by higher fuel consumption in organic TMR (around 100 kg more than integrated per hectare). Reducing fuel consumption of both TMRs implies reducing machinery use (with biological pest control and improving vine resistance to diseases, for example) or adopting eco-driving or electric tractors. Moreover, organic TMR has more impact than integrated TMR (+5 %) for the freshwater ecotoxicity category, because of lower background heavy metal emissions in the integrated TMR. Indeed, background emissions are the main contributor to AETP impacts for both TMRs and the only operation category where AETP impact score is higher for organic TMR.

As said previously, organic TMR is the most impacting on most of the studied impact categories. Concerning freshwater ecotoxicity category, which is the only category accounting for active ingredient and heavy metal emissions, the comparison between organic and integrated TMRs could be improved. Indeed, background heavy metal emissions are the main impact source for each TMR (around 80 % of the total of this impact category). In the model used for calculation, these background emissions are due to the existing stock in the soil and the atmospheric deposition. In the model, the assumption is made that the stock is higher in organic vineyard soils because of the higher use of copper. Information about these background emissions is interesting but it is not the primary information needed to help winegrowers make choices about practices because the practices have no direct effect on them. Due to missing characterization factors for human toxicity and uncertainty related to this impact category, we chose not to study it although there are lots of concerns about pesticide impacts on human health in viticulture.

Globally, impact score differences between organic and integrated TMR are mainly due to differences in soil management and plant protection treatments. Concerning soil management, organic TMR consisted of one hilling, one ploughing back and two hoeings while, in integrated TMR, it consisted of only two chemical weedings. Moreover, there were 12 plant protection treatments in organic TMR while there are only 8 in integrated TMR. This difference is due to the type of products used: contact products that can easily be removed by the rain versus systemic products for integrated TMR that cannot. Higher impacts in organic TMR can thus be explained by a higher number of mechanic interventions. Indeed, fuel consumption is assumed to be proportional to working time and VOC, NO_x and CO emissions from fuel combustion are assumed to be proportional to fuel consumption.

Concerning plant protection treatments, as the spraying technique is always the same, impact scores of each treatment are the same for all impact categories, except freshwater ecotoxicity whose impact scores are more related to active ingredient emissions. Impact score differences for these six categories can thus be explained by a higher number of treatments for organic TMR. Impact differences for freshwater ecotoxicity can be explained by differences in the amount of active ingredient used and its nature, especially during non-productive phases.

If a lower yield is considered for the organic vineyard compared to the integrated one, impact scores per kg of grapes are heightened for organic TMR. Consequently, the gap between integrated and organic TMRs is widening except for freshwater ecotoxicity.

A TMR aims to produce grapes, a specific quality of grape. This quality is very important in labelled productions like AOC wines where the quality is specified by requirement specifications. In future studies, we will study the eco-efficiency of TMRs relative to the grape quality requirements, which has not been realised at the moment in published viticultural LCA studies.

CONCLUSION

Viticulture is starting to improve its environmental performances in order to fulfill consumers' expectations and environmental regulations. In this context, LCA can help viticulture finding solutions to reduce its environmental impacts and show its improvements. There are few studies about environmental impacts of viticultural techniques in the bibliography.

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This study indicates that the environmental impacts of the two studied TMRs are primarily due to fuel consumption. Indeed, viticulture is a large fuel consumer and emissions from its consumption have several impacts on the environment (global warming, acidification, photochemical ozone formation). The second main contributor to viticulture's impacts is nitrate emissions to water which contribute to eutrophication. However, the nitrate emission model SQCB needs improvements to be better adapted to viticulture (e.g. taking into account : nitrogen stock from nitrogen inputs of previous years, nitrogen uptake by grass, seasonality of nitrate leaching).

Concerning methodological issues, LCA applied to viticulture needs accurate models to quantify emissions to the environment. Improving the quality of models concerning nitrate and heavy metal emission should be a future improvement in viticultural LCA studies, especially concerning background emissions (e.g. taking into account the real quantity of nitrogen and heavy metals from previous years). Furthermore, this study enables showing there is a lack of data concerning fuel consumptions and gas emissions from viticultural machines.

In this paper, we also show that the studied organic TMR has higher impact scores than the studied integrated TMR for fossil resource demand, global warming potential, photochemical ozone formation potential, acidification eutrophication and resource depletion. Integrated TMR impact score for freshwater ecotoxicity is also lower than the organic one but this difference cannot be considered significant regarding uncertainties on background emissions. Additionally, this score does not account for impacts of pesticide degradation metabolites that are until now largely unknown and that can be also toxic and in important quantities. Moreover, impacts on human toxicity have not been taken into account due to missing characterization factors for several active ingredients used in viticulture. Characterization factors are key data in LCA as they enable transforming a quantity of input into its quantity of impact (e.g. 1 kg of CH_4 emitted to air equals 25 kg of CO_2 eq emitted, 1 kg of the active ingredient "folpet" emitted to water equals 8.63 units of impact on human toxicity, etc.).

In coming studies, accounting for grape quality while evaluating environmental performances of quality wine production will be important in order to help decision-making about techniques and TMR choices.

In order to be able to make conclusions on impact sources of these two TMRs and on benefits and drawbacks of both integrated and organic productions, our results should be supported with results on different vintages. Different climate and geographic conditions should be also studied.

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