KEYNOTE LECTURE

Life cycle assessment (LCA) to move towards more environmentally friendly winegrowing

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Keywords: environmental sustainability, viticultural practices, ecodesign, serious game, environmental impacts, climate change

INTRODUCTION

As six on the nine planetary boundaries have already been crossed, putting our safe life on Earth at risk (Rockström et al., 2024) and agriculture is significantly responsible for it (Campbell et al., 2017), viticulture, faces the challenge of reducing its environmental impacts through fundamental changes to its practices. However, the diversity of the environmental impacts of winegrowing activities on the environment is not commonly identified by the production stakeholders or advisors. This makes it difficult for winegrowers to identify the most environmentally friendly practices. When information is available to winegrowers, usually focuses on one single impact: carbon footprint.

Nevertheless, a detailed impact assessment that is as exhaustive as possible is the best way to inform improvement decisions. The Life Cycle Assessment (LCA) method, which is based on life cycle thinking, like are carbon or water footprints, considers the impacts of the entire life cycle of a product. By assessing all phases of the production process, it ensures that local environmental improvements do not result in the shifting of pollutant loads (Jolliet et al., 2010). LCA offers a comprehensive list of environmental impacts. It is standardised (ISO, 2006) and considered by the International Organization for Standardization (ISO) to be the method that should be used for ecodesign (ISO, 2011). It is also the method chosen by the European Union (Pedersen and Remmen, 2022) and France for environmental footprinting of consumer goods.

The LCA methodology has been implemented in the wine industry for two decades, for various purposes such as quantifying the environmental impact of a bottle of wine and identifying the main life cycle phases that contribute the most (Ferrara and De Feo, 2018). For instance, the global warming potential impact of a bottle of wine ranges from 0.6 to 3.5 kg CO_2 (Pinto da Silva and Esteves da Silva, 2022), which is equivalent to the greenhouse gas emissions of 5 to 26 km by car. Viticulture contributes 15–60% to the carbon footprint of a bottle of wine, depending on vineyard, cellar and packaging practices. The glass bottle alone accounts for around half of the carbon footprint of a full bottle of wine (Navarro et al., 2017). LCA is also used to compare the environmental impact of different types of wine (European-Commission, 2021). In the last decade, the research unit GRAPPE has been developing the use of LCA to inform the choice of winegrowing techniques (Renaud-Gentié et al., 2020, Gentil et al., 2020) and to conduct ecodesign (Perrin et al., 2022, Renaud-Gentié and Julien, 2024).

RESEARCH OBJECTIVES

Thus, the focus of this paper is to propose an overview of the methods, tools and applications of life cycle assessment to guide the evolution of viticultural practices towards greater environmental sustainability.

First, we will present the principles of Life Cycle assessment application to viticulture. Then, we will develop the assessment of viticultural practices and its facilitation and their ecodesign as developed in the GRAPPE research unit. We will finally outline the current limitations and perspectives for using and developing LCA for viticulture.

MATERIAL AND METHODS

Once the system boundaries and purpose of the LCA have been clearly defined, the inventory of inputs and outputs of the system is compiled through on-field data collection (e.g. equipment and input use) and the calculation of pollutant emissions. These are converted into fluxes of substances, which are then multiplied by characterisation factors that are specific to each impact category and substance. These factors express the intensity of the substances' effect on the environment. The results are expressed in a functional unit, which represents the product's primary function. In viticulture, these are typically a bottle of wine, a kilogram of grapes, or a hectare of vineyard cultivated for one year. This is because viticulture fulfils various functions, such as wine or grape production, and landscape maintenance.

Applying LCA to viticulture requires specific adjustments to the generic LCA methodology. As with any other form of agricultural production, the outdoor application of inputs such as pesticides and fertilisers results in the direct emission of pollutants into the environment. Quantifying these emissions requires models that consider vineyard-specific factors such as its perennial nature, canopy shape, and potential grass cover (Renaud-Gentié et al., 2015). The perennial nature of the vineyard also implies that non-productive phases must be accounted for, and their impact included in the assessment. Specific frameworks for viticulture have been proposed by Bellon-Maurel *et al*. (2015), in Agribalyse guidelines (Koch and Salou, 2022) and by Renaud-Gentié (2015) and Rouault *et al*. (2016).

RESULTS

Hotspots identification and practice comparison

To assess the precise impact of viticultural practices and inform changes towards more environmentally friendly viticulture, it is necessary to explore how each operation contributes to each impact in order to identify hotspots. The main hotspots identified in studies conducted in the Loire Valley (Beauchet et al., 2019, Renaud-Gentié et al., 2020, Rouault et al., 2016), Alsace and Rhône Valley vineyards (Renaud-Gentié et al., 2020) were diesel combustion emissions and production, emissions and production of fertilisers, and pesticide, in line with the literature, but also trellis production and transport, which was scarcely included in other published studies. Significant contributions have also been reported for irrigation in irrigated vineyards (Fusi et al., 2014). A comparison of the existing options for vineyard management between cases representing the five viticultural types in the Anjou region (defined on the basis of a comprehensive survey by Renaud-Gentié *et al.* (2014), showed that the intensity of the practices was a better explanation for the differences in impact than whether the management was organic or conventional. This analysis also identified areas for improvement in the most impactful management practices.(Renaud-Gentié, 2015).

More recently, we observed significant differences between the available anti-frost protection methods in viticulture in terms of their impact. Candles had the highest impact on most impact categories, while wind machines had the lowest. The ranking of the solutions changed slightly in relation to the annual number of frost hours (Baillet et al., 2024, Baillet et al., 2025). Replacing such solutions across the entire technical operations pathway of a vineyard demonstrated their significant contribution and impact. (Baillet et al., submitted).

Streamlining LCA calculation for viticulture professionals

Winegrowers cannot easily use LCA results as LCAs are complex calculations that require specific databases and software, expertise, time and data. This is why customised calculation tools can facilitate LCAs for agents of change (Renouf et al., 2018b) who can then share the results with farmers. The Vit'LCA© calculator, first developed as an Excel tool, has recently been made available online to facilitate its use by professionals. It is tailored to the needs of winegrowers and enables them to calculate the LCAs of viticulture and compare different vineyard management options. It incorporates the various stages of vineyard life. (Renouf et al., 2018a).

Ecodesign of vineyard management

LCA results provide an ideal foundation for ecodesign, which ISO defines as "integrating environmental aspects into the design and development of a product with the aim of reducing its negative environmental impact throughout its life cycle". In viticulture, ecodesign levers can be defined from hotspot identification, and applied theoretically or in collaboration with winegrowers. Such an ecodesign project was conducted at farm level in the Anjou region. A typology of the existing diversity of vineyard management on the farm was identified in collaboration with the farmer. This was then supplemented by the diversity of geomorphological situations influencing input emissions and, consequently, LCA results. Ecodesign levers and scenarios were then proposed and discussed with the winegrower (Figure 1)(Renaud-Gentié and Julien, 2024).

Significant decreases in impacts require deep changes in practices. Nevertheless, providing LCA results and ecodesign proposals to producers is often insufficient to initiate such changes. Exchanges between farmers within collectives play a key role in facilitating transitions (Slimi et al., 2021). Therefore, Rouault *et al*. (2020) developed a framework and tools for the participatory eco-design of vineyard management. These were converted into Vitigame© (figure 2), a serious game based on LCA results that can be used by winegrower collectives or for teaching viticulture students. The principle of the game is the collective redesign of the vineyard management of a real case starting from its LCA results. The players face the same weather and disease pressures as the winegrower. They must select an ecodesign strategy and, operation by operation, develop the technical operations pathway (PTO). Their scenario is then evaluated using the Vit'LCA© tool and compared to the original scenario. Finally, the game master and the players debrief on the decisions made and their consequences. The IPE2vit tool (Ben Jaballah et al., 2019) which is used for the economic assessment of practice changes, has recently been adapted to allow joint assessment with LCA. This can now be used to inform debriefing. Currently used with students and winegrowers, Vitigame has also been successfully implemented with PDO representatives to encourage forward thinking about the evolution of soil management practices in their territory, achieving average improvement rates of between 22% and 51%, according to the tables. It has also raised awareness among participants of the levers of ecodesign and generated topics for future research. (Renaud-Gentié et al., 2024).

Limitations and research perspectives

Although LCA is a powerful method due to its comprehensiveness, stakeholders often find it difficult to use the results for decision-making purposes due to the large amount of information provided and the multi-criteria nature of the results. We are currently working on ways to make these results more accessible. While LCA provides insights into many environmental impacts, indicators of the effect of changes in viticultural practices on biodiversity, such as those developed for vegetable production(Pépin et al., 2023), are lacking in viticulture. Finally, as part of the Vitarbae project, we are developing the inclusion of these ecodesign workshops within broader support pathways for groups of winegrowers, to ensure that the results are monitored and changes are implemented more efficiently. The next step is to develop these methods, frameworks and tools for winemaking and make them available in other countries by translating them and including local case studies.

CONCLUSION

LCA takes environmental impacts into account comprehensively and enables informed changes to be made to viticultural practices to reduce their environmental impact. Streamlined tools such as Vit'LCA© can help extension staff provide advice to farmers. Eco-design based on LCA results can work at different scales: individually; in a participatory process; and with diverse participant profiles, thanks to Vitigame©.

The next steps are to facilitate the transfer of LCA results to agents of change and to develop the assessment and eco-design of winemaking phases. The tools should be made available in other languages and include real cases from vineyards around the world.

ACKNOWLEDGEMENTS

The author thanks the whole LCA of viticulture team of the GRAPPE research unit which is behind all the presented results, as well as the wine sector stakeholders who took part to the research. We also acknowledge different funding bodies, which supported the research through projects: CASDAR, OFB, Region Pays de la Loire, ADEME, and FEDER

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FIGURES

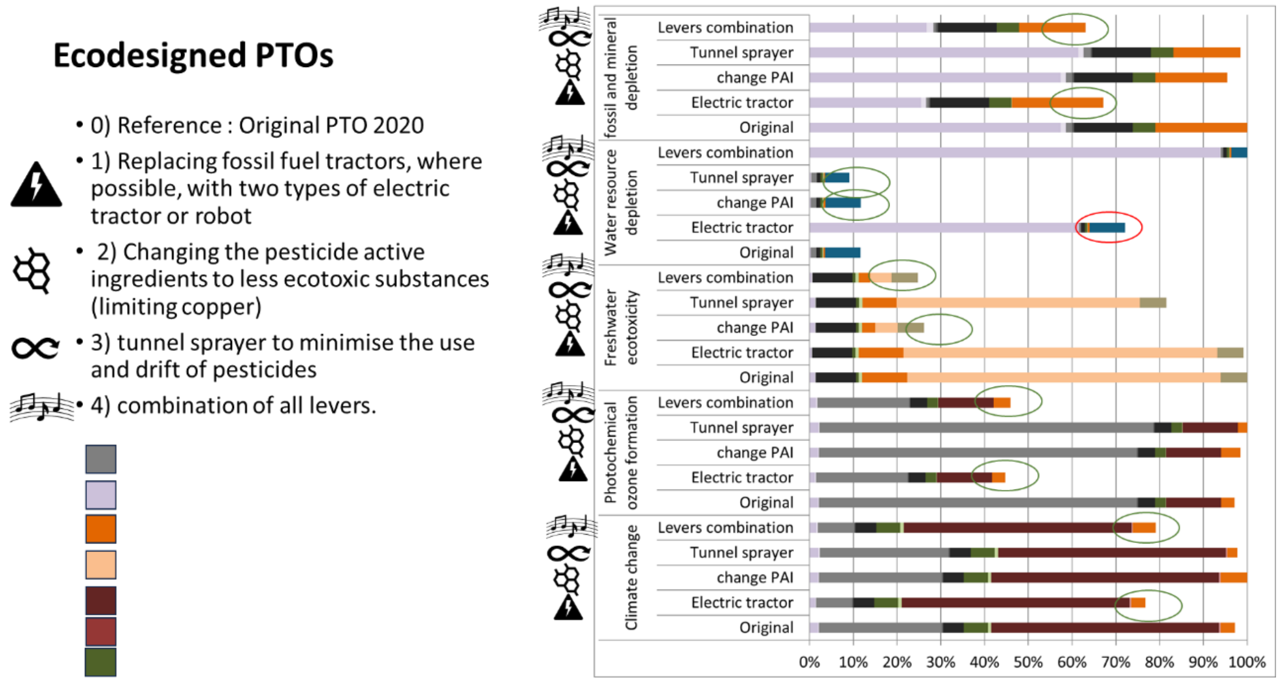

Figure 1. Example of proposal of four ecodesign scenarios of pathways of technical operations (PTO) to a wine grower of Anjou and their compared environmental impacts on five impact categories, calculated by LCA, ILCD 2011 method, with the VitLCA excel tool V2.0.

Figure 2. The serious game Vitigame© facilitates participatory ecodesign with winegrowers, students or wine sector stakeholders, based on LCA results of real vineyard management cases.