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Modeling ecotoxicity impacts in vineyard production: Addressing spatial differentiation for copper fungicides

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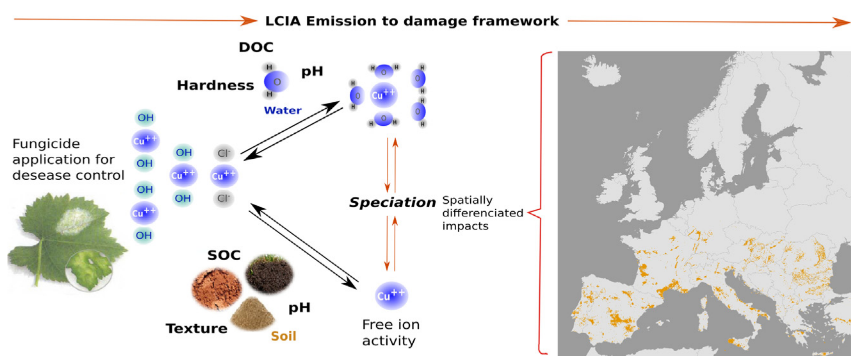
HIGHLIGHTS

- USEtox 2.02 was used to compare the freshwater ecotoxicity impacts of 12 fungicides AI.
- Impacts for Cu(II) vary ~3 orders of magnitude among the 7 European water types analyzed.
- Site-dependent characterization factors for Cu(II) in 15,034 European vineyards soils were derived.
- Soil impacts for Cu(II) vary 2 orders according to different agricultural scenarios.
- Including spatial differentiation in copper hazard for LCA provide more accurate results in toxicity impact evaluation.

GRAPHICAL ABSTRACT



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ABSTRACT

Application of plant protection products (PPP) is a fundamental practice for viticulture. Life Cycle Assessment (LCA) has proved to be a useful tool to assess the environmental performance of agricultural production, where including toxicity-related impacts for PPP use is still associated with methodological limitations, especially for inorganic (i.e. metal-based) pesticides. Downy mildew is one of the most severe diseases for vineyard production. For disease control, copper-based fungicides are the most effective and used PPP in both conventional and organic viticulture. This study aims to improve the toxicity-related characterization of copper-based fungicides (Cu) for LCA studies. Potential freshwater ecotoxicity impacts of 12 active ingredients used to control downy mildew in European vineyards were quantified and compared. Soil ecotoxicity impacts were calculated for specific soil chemistries and textures. To introduce spatial differentiation for Cu in freshwater and soil ecotoxicity characterization, we used 7 European water archetypes and a set of 15,034 non-calcareous vineyard soils for 4 agricultural scenarios. Cu ranked as the most impacting substance for potential freshwater ecotoxicity among the 12 studied active ingredients. With the inclusion of spatial differentiation, Cu toxicity potentials vary 3 orders of magnitude, making variation according to water archetypes potentially relevant. In the case of non-calcareous soils ecotoxicity characterization, the variability of Cu impacts in different receiving environments is about 2 orders of magnitude. Our results show that Cu potential toxicity depends mainly on its capacity to interact with the emission site, and the dynamics of this interaction (speciation). These results represent a better approximation to

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understand Cu potential toxicity impact profiles, assisting decision makers to better understand copper behavior concerning the receiving environment and therefore how restrictions on the use of copper-based fungicides should be considered in relation to the emission site.

1. Introduction

Life Cycle Assessment (LCA) is a comprehensive methodology that aims at quantifying the potential environmental impacts of any product system over its entire lifecycle (ISO-14040, 2006). Within the agricultural sector, LCA has proven to be useful for assessing the environmental performance of many cropping systems (Boone et al., 2016; Parajuli et al., 2017; Torrellas et al., 2012). However, often a limited number of impact categories is evaluated in comparative LCAs of agricultural systems (Meier et al., 2015). Although plant protection products (PPP) are routinely applied in agriculture, one of the critical points within the life cycle impact assessment (LCIA) phase in LCAs of agricultural systems is the lack of characterizing potential toxicity-related impacts for PPP use in crop production. This lack is even more apparent when it comes to the evaluation of inorganic pesticides (i.e. metal-based pesticides), approved for organic farming, as these are not as well understood and characterized as synthetic[1] pesticides. Furthermore, freshwater ecotoxicity is among those LCIA impact categories that, only in recent years, has started to be considered mature enough for inclusion in LCA studies.

Nowadays, the European Commission authorizes >500 active ingredients[2] (AI). Around 340,000 tons of PPP are used each year in Europe (EU28), from which fungicides represent the most used AI in conventional and organic agriculture, with a total annual use in the EU28 of 169,000 t for 2014. Furthermore, Inorganic fungicides account for 39–55% of the total applied fungicides in the EU (European Comission, 2009; Eurostat, 2016). PPP have become vital elements in modern agriculture as they provide many benefits, but their extensive and continuous applications also have several negative implications for the environment. Some of these implications include human exposure to crop residues (Fantke et al., 2012), potential impacts on non-target organisms (Felsot et al., 2010), a shift in dominating pest species and increasing pest resistance (Pimentel, 2005). The two latter problems, in turn, push crop growers towards an even more intensified use of PPP, and consequently, crop production costs rise, and potential risks of toxic impacts on humans and the environment may further increase (Nesheim et al., 2015).

European vineyards represent >50% of the total world area of vines (OIV, 2016), and the long-term use of PPP in vineyards has contributed to increased concentrations of these substances in different environmental compartments (Hildebrandt et al., 2008; Ribolzi et al., 2002; Wightwick et al., 2008). Concerning PPP use, one of the main differences between conventional and organic viticulture production is that in general synthetic pesticides are not allowed for use in organic pest management, whereas inorganic pesticides are indispensable for organic vine cultivation.

Furthermore, copper-based fungicides are the most efficient and widely used PPP in Europe in both conventional and organic viticulture to control vine fungal diseases, such as downy mildew caused by *Plasmopara viticola*, one of the most severe and devastating diseases for grapevine (Agrios, 2005). Therefore, the extensive use of fungicides to control this and other fungal pests has posed significant environmental problems, such as unwanted residues in plants and water, reduction of the quality and degradation of soils, as well as some ecotoxicological threats in non-target organisms (Fantke et al., 2011a; Komarek et al., 2010).

Different studies have evaluated the environmental profile of viticulture and wine production from a life cycle perspective (Bartocci et al., 2017; Benedetto, 2013; Point et al., 2012). In line with LCA studies of other agricultural systems, one of the repeatedly assessed impact category for viticulture is the evaluation of global warming potential (Bosco et al., 2011; Steenwerth et al., 2015) with particular focus on water or carbon footprint indicators (Bonamente et al., 2016; Bosco et al., 2013; Lamastra et al., 2014). In contrast, impact categories related to toxicity are often disregarded, partly due to missing data for all involved chemicals including PPP and partly due to high perceived and real uncertainties (Fantke et al., 2016; Rosenbaum et al., 2015). Consequently, PPP and their effects on freshwater and terrestrial ecosystems are frequently omitted, even though they are one of the significant environmental concerns linked with agriculture (Meier et al., 2015). Furthermore, including ecotoxicity in LCA does not necessarily mean that the toxic effects of PPP use are being considered. For instance, Benedetto (2013) reports PPP emissions without including the related impact factors despite available characterization models. Other studies evaluated ecotoxicity impacts related to PPP production but do not quantify the impacts in the use phase (Jimenez et al., 2014; Point et al., 2012). Although numerous studies acknowledge the use of copper in vineyard production, and the impacts of the production of copper-based fungicides are included in a few of them (Point et al., 2012; Villanueva-Rey et al., 2014), the impact resulting from the use of these fungicides is not considered.

Freshwater ecotoxicity can be characterized with different available methods, such as the UNEP-SETAC scientific consensus model for toxicity characterization of chemical emissions in LCIA (Rosenbaum et al., 2008) that is endorsed by the UNEP-SETAC Life Cycle Initiative (Westh et al., 2015). In the case of soil ecotoxicity characterization, several emerging approaches exist (Haye et al., 2007; Lofts et al., 2013; Owsianiak et al., 2013), but no method has yet been widely adopted. Finally, there is a lack of agreement on how to assess ecotoxicity-related impacts of metal-based PPP that are currently not adequately characterized by any existing model (Hauschild and Huijbregts, 2015; Meier et al., 2015).

Characterization of the toxic effects of metal-based emissions in LCIA assumes that the toxicity is a function of the activity of the free metal ion (Campbell, 1995; Owsianiak et al., 2015), which is related to the relevant chemical species, Cu(II). Factors such as water pH, dissolved organic carbon (DOC) and water hardness (Allen and Janssen, 2006; Gandhi et al., 2010), and soil organic carbon (SOC), soil pH and texture (Komarek et al., 2010) control metal speciation and thus its potential toxic effects. Consequently, incorporating and defining these geographically distinct characteristics in which the inventory flows (i.e. pesticide emissions) occur will have a significant influence on the ecotoxicological impact assessment of copper-based fungicide AIs in LCA (Gandhi et al., 2011b; Potting and Hauschild, 2006).

The main objective of the present work is to improve the consideration of copper-based fungicides in LCA with focus on three specific aims: First, to characterize fungicide emissions and freshwater ecotoxicity impacts to compare results of copper-based fungicides with commonly used AIs to control downy mildew in European

[1] The terms synthetic pesticides and synthetic fungicides in this study refer to pesticides that contain xenobiotic organic compounds as active ingredients that are prohibited in organic crop and livestock production (European Comission, 2008).

[2] Active ingredient is any chemical, plant extract, pheromone or micro-organism (including viruses), that are the biologically active part in any plant protection product (European Commission, 2017).

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