



Challenges and ways forward in pesticide emission and toxicity characterization modeling for tropical conditions

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Abstract

Purpose In tropical cropping systems, pesticides are extensively used to fight pests and ensure high crop yields. However, pesticide use also leads to environmental and health impacts. While pesticide emissions and impacts are influenced by farm management practices and environmental conditions, available Life Cycle Inventory (LCI) emission models and Life Cycle Impact Assessment (LCIA) toxicity characterization models are generally designed based on temperate conditions. There is, hence, a need for adapting LCI and LCIA models for evaluating pesticides under tropical conditions. To address this need, we aim to identify the characteristics that determine pesticide emissions and related impacts under tropical conditions, and to assess to what extent LCI and LCIA models need to be adapted to better account for these conditions.

Methods We investigated the state-of-knowledge with respect to characteristics that drive pesticide emission patterns, environmental fate, human and ecological exposures, and toxicological effects under tropical conditions. We then discuss the applicability of existing LCI and LCIA models to tropical regions as input for deriving specific recommendations for future modeling refinements.

Results and discussion Our results indicate that many pesticide-related environmental processes, such as degradation and volatilization, show higher kinetic rates under tropical conditions mainly due to higher temperatures, sunlight radiation, and microbial activity. Heavy and frequent rainfalls enhance leaching and runoff. Specific soil characteristics (e.g., low pH), crops, and cropping systems (e.g., mulching) are important drivers of distinct pesticide emission patterns under tropical conditions. Adapting LCI models to tropical conditions implies incorporating specific features of tropical cropping systems (e.g., intercropping, ground cover management), specific drift curves for tropical pesticide application techniques, and better addressing leaching processes. The validity domain of the discussed LCI and LCIA models could be systematically extended to tropical regions by considering tropical soil types, climate conditions, and crops, and adding active substances applied specifically under tropical conditions, including the consideration of late applications of pesticides before harvest and their effect on crop residues and subsequent human intake.

Conclusions Current LCI and LCIA models are not fully suitable for evaluating pesticide emissions and impacts for crops cultivated in tropical regions. Models should be adapted and parameterized to better account for various characteristics influencing emission and impact patterns under tropical conditions using best available data and knowledge. Further research is urgently required to improve our knowledge and data with respect to understanding and evaluating pesticide emission and impact processes under tropical conditions.

Keywords Life cycle assessment · Pesticides · Emission models · Toxicity characterization models · Tropical regions

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1 Introduction

Tropical conditions are located mainly between the Tropic of Cancer and the Tropic of Capricorn. They are characterized according to the Köppen-Geiger climate classification by warm temperatures with an alternating rainy and dry season, or by an equatorial climate with humid conditions prevailing all year round (Kottek et al. 2006; Beck et al. 2018). These conditions are very suitable for diversified agricultural production. A common characteristic of tropical crop farming is the possibility to grow crops all year

round without interruption by a cold season, as is the case in temperate climates. However, such environmental conditions are also favorable for the occurrence of pests (insects, weeds, fungi, etc.). To fight pests and to preserve high crop yields and quality, most farmers use a wide diversity of pesticides at high frequency (Racke et al. 1997; Lewis et al. 2016) and sometimes all year round (Daam and van den Brink 2010; Mottes et al. 2017). In many tropical contexts, farmers have received no or little training about proper pesticide application and have a limited awareness of pesticide risk (Williamson et al. 2008; Raksanam et al. 2012). Therefore, farmers often do not respect good application practices (Settle et al. 2014; Houbraken et al. 2017; Elibariki and Maguta 2017), practice excessive use, and misuse of pesticides (Montes et al. 2012; Pouokam et al. 2017). Furthermore, structural adjustment policies, e.g., in African countries, led to a decline in compliance control services and an increase in reported misuses, including the use of unauthorized pesticides (de Bon et al. 2014). Under such circumstances, pesticide uses lead to increased environmental and health pressure (Arias-Estévez et al. 2008; Aktar et al. 2009). As in all cultivated areas in the world, pesticides can be detected in all environmental compartments in tropical regions, including groundwater (Sorensen et al. 2015). For example, Bocquené and Franco (2005) found pesticides in water and sediment from rivers in Martinique, Pillai (1986) in soil and air in India, and Dickinson and Lepp (1984) in non-agricultural plants and soils in Kenya. Moreover, Arias-Andrés et al. (2018) observed ecotoxicity effects of pesticides on freshwater organisms in Costa Rica, and Peters et al. (1997) on marine organisms in tropical conditions. Pesticides have also been detected in food crops grown in tropical regions, which might exceed the recommended maximum residue limits (e.g., tomato (*Solanum lycopersicum*) in Tanzania: Kariathi et al. 2016; and vegetables in Bangladesh: Hossain et al. 2015). Finally, food crop consumption was identified as the main pesticide exposure pathway for the general human population (Fantke and Jolliet 2016). This is particularly relevant for fruits and vegetables, mainly consumed in fresh form, which increases the risk of ingestion of pesticide residues (Weinberger and Lumpkin 2007).

To evaluate the potential environmental and health impacts of crop production systems in relation to their function as part of a global environmental assessment, life cycle assessment (LCA) is widely used, and pesticides are generally one of the main contributors to human and ecosystem toxicity impacts in cradle-to-farm-gate LCA studies (Bessou et al. 2013). However, current models for applied to evaluate emissions and toxicity-related impacts of pesticides in LCA were developed and parameterized typically reflecting temperate conditions for climate, soil, application techniques, and crops (Rosenbaum et al. 2008; Fantke et al. 2011b; Dijkman et al.

2012; Fantke et al. 2017a), questioning their relevance for tropical conditions. Under tropical conditions, pesticide emissions and impacts are not as well understood or supported by measurements as in temperate regions (Racke et al. 1997; Sanchez-Bayo and Hyne 2011). For example, ecotoxicological tests on aquatic ecosystems are rare in tropical countries (Castillo et al. 1996).

Fantke et al. (2017a) highlighted the lack of data and model parameters for characterizing emission patterns under tropical conditions, suggesting to develop specific pesticide application scenarios for tropical regions. However, the development of such scenarios requires pesticide emission and impact characterization models that are able to compare agricultural practices and conditions in tropical regions. There is an urgent need for adapting and parameterizing the existing Life Cycle Inventory (LCI) emission and Life Cycle Impact Assessment (LCIA) toxicity characterization models to better account for pesticide impacts under tropical conditions.

This paper, hence, aims at providing an overview of how to adapt currently available LCI and LCIA models to evaluate the use of pesticides in agriculture under tropical conditions, based on addressing three specific objectives. First, we explore factors influencing emission and toxicity impact patterns under tropical conditions. Second, we analyze current LCI and LCIA models with a focus on how they currently reflect tropical conditions. Third, we provide insights of model improvements to better account for tropical conditions and derive specific recommendations for future research to adapt LCI and LCIA models to address emissions and impacts of pesticides applied under tropical conditions.

2 Methods

2.1 Study area—tropical conditions and crops

The tropical conditions defined by the Köppen-Geiger climate classification (Kottek et al. 2006; Beck et al. 2018) are divided into three categories: tropical rainforest climate, tropical monsoon climate, and tropical savannah climate with dry summer or winter. These climates, the regions and countries they cover, and the main related crops are summarized in Table 1. In this paper, we always refer to this Köppen-Geiger climate classification. We note that a large diversity of climates might be present even in a small territory, for example in the Martinique Island, where all three above-described tropical climates are present on an area of only 1128 km². Other climatic conditions between the Tropics of Cancer and Capricorn, as arid desert conditions or temperate conditions in highlands (e.g., mountain area in South America), are not considered as tropical conditions and are hence not addressed in our study. In some regions, tropical conditions are found

Table 1 Presentation of tropical climates, their main characteristics, regions/countries, and main crops grown

Tropical climates	Main characteristics		Regions/countries	Main crops grown in these climates
	Temperature	Humidity		
Equatorial rainforest, fully humid	$T_{\min} \geq +18 \text{ }^\circ\text{C}$	$P_{\min} \geq 60 \text{ mm}$	Generally found within 15° North and South of the equator: in Central Africa (e.g., Uganda), in Southeast Asia (e.g., Malaysia, Indonesia), parts of Central and South America (e.g., Colombia, Costa Rica)	Rice, palm oil, roots, and tubers
Equatorial monsoon		$P_{\text{ann}} \geq 25 \times (100 - P_{\min})$	Caribbean islands (e.g., Dominican Republic), West and Central Africa (e.g., Guinea, Cameroon), South Asia (e.g., Philippines)	Rice, pulses, sorghum, sugarcane
Equatorial savannah with dry summer or dry winter		$P_{\min} < 60 \text{ mm}$ in summer or $P_{\min} < 60 \text{ mm}$ in winter	Central and Northern parts of South America (e.g., Brazil), Central Africa (e.g., Tanzania, Madagascar), Southeast Asia (e.g., Thailand, India), Northern Australia	Rice, maize, sorghum, pulses, groundnuts (<i>Arachis hypogaea</i>), sugarcane

T_{\min} , monthly mean temperature of the coldest month

P_{\min} , mean precipitation of the driest month

P_{ann} , mean cumulative annual precipitation

only part of the year. These climates are called humid subtropical climate, are characterized by hot and humid summer (e.g., east of Australia, east of China), and are not considered in this study.

Even if climate conditions are widely different between tropical and temperate regions, certain crops can be grown in both, e.g., maize (*Zea mays*) and tomato. However, some crops can usually only be grown under tropical conditions, e.g., palm oil (*Elaeis guineensis*), cassava (*Manihot esculenta*), or sugarcane (*Saccharum officinarum*), because the sum of temperatures in temperate climates is too low to finish the crop cycle during the warm season. Some crops are present in the three different equatorial climates (e.g., banana *Musa* spp.). According to FAOSTAT (2019), the main crops in terms of area harvested in the countries with tropical climates are in decreasing order of importance the following: rice (*Oriza* spp.), maize, soybean (*Glycine max*), sorghum (*Sorghum bicolor*), bean (*Phaseolus vulgaris*), cassava, sugarcane, and palm oil. As synthesized in Racke et al. (1997), in tropical conditions depending on rain patterns, two types of crop production exist. In equatorial humid climates, the main staple crops are roots and tubers (e.g., sweet potato *Ipomoea batatas* and cassava), and fruits (e.g., banana), whereas in tropical climates with a dry season, the staple foods are cereals (e.g., rice, maize, and sorghum). Beyond the mentioned crops, the production of fruits and vegetables is generally important in these regions for the nutritional balance of people's diet (Weinberger and Lumpkin 2007; Williamson et al. 2008). Fruits and vegetables thereby constitute preferential targets for pests, and as nutritional high-value crops, they usually receive intensive pesticide applications.

2.2 Methodological approach

As the first step, available literature was reviewed to analyze the state-of-the-art in data describing pesticide emissions and impacts under tropical conditions. According to the tropical climates from the Köppen-Geiger classification, we identified all countries with at least one of the three tropical climates. Using these countries as spatial scope, we did a bibliographic search (on Agricola, Agris, and CAB Abstract) using an "AND" combination of two main search criteria. One criterion was related to pesticides (using search keywords, such as "fungicide" and "insecticide") and one criterion related to Life Cycle Assessment, (eco)-toxicity and environmental dissipation of pesticides (using search keywords, such as "degradation," "leaching," and "fate"). More than 600 articles were identified and 576 were selected and organized in three categories by reading the abstracts: environmental processes ($n = 288$), (eco)-toxicity ($n = 331$), and farmers' behavior with pesticide application ($n = 41$). Some articles could appear in more than one category. These articles were analyzed and classified considering different aspects: country or region, crop, pesticide target class, environmental compartments and processes, etc. This bibliographic work enabled us to realize that there were many articles available on the subject. Some key review papers allowed us to identify the major and specific processes of pesticide dissipation in the environment under tropical conditions (e.g., Racke et al. 1997; Sanchez-Bayo and Hyne 2011). Consequently, another more focused bibliographic search has been conducted, using Web of Science. Subsequently, those publications that were most relevant with respect to the focus on tropical conditions were analyzed in more detail, with 17 articles studying water flow processes (e.g., leaching, runoff), 17 articles focusing on pesticide drift when applying pesticides, and 20 articles analyzing the effects

of farm management practices on pesticide dissipation. Overall, there is a rich body of risk assessment literature, which could additionally be used to improve and refine existing models applied in LCI and LCIA for pesticides (e.g., Brock et al. 2009; Thorbek et al. 2009).

As a final step, the validity and completeness of state-of-the-art models for characterizing pesticide emissions and toxicity-related impacts in LCA, namely PestLCI, USEtox, and dynamiCROP, were assessed based on the references presented in Table 2. Furthermore, the equations, assumptions, and database of the PestLCI model were analyzed in detail. Finally, improvement recommendations were derived according to the relevant processes and characteristics identified for tropical conditions and with specific relation to the studied models.

2.3 Pesticide modeling in LCA

In order to estimate pesticide impacts in LCA, models are required as well as an exhaustive and reliable inventory of pesticide emissions under various relevant production systems and conditions. We selected the three most up-to-date pesticide emission and toxicity-related characterization models, namely the adapted PestLCI model as pesticide emission inventory model, USEtox 2.1 as general (eco-)toxicity characterization model, and dynamiCROP 3.1 as model characterizing human exposure to pesticide residues in food crops. The models are presented in detail further below, and related references are summarized in Table 2. The inter-connections between the considered models along with their inputs and outputs are presented in Fig. 1. As part of a global pesticide consensus-building effort for LCA (Rosenbaum et al. 2015; Fantke et al. 2017a), some modifications to the PestLCI 2.0 model were proposed, mainly focusing on including

additional drift functions and adapting certain model parameters. We refer to this version in the following text as “adapted PestLCI model.”

2.3.1 PestLCI to quantify pesticide emissions

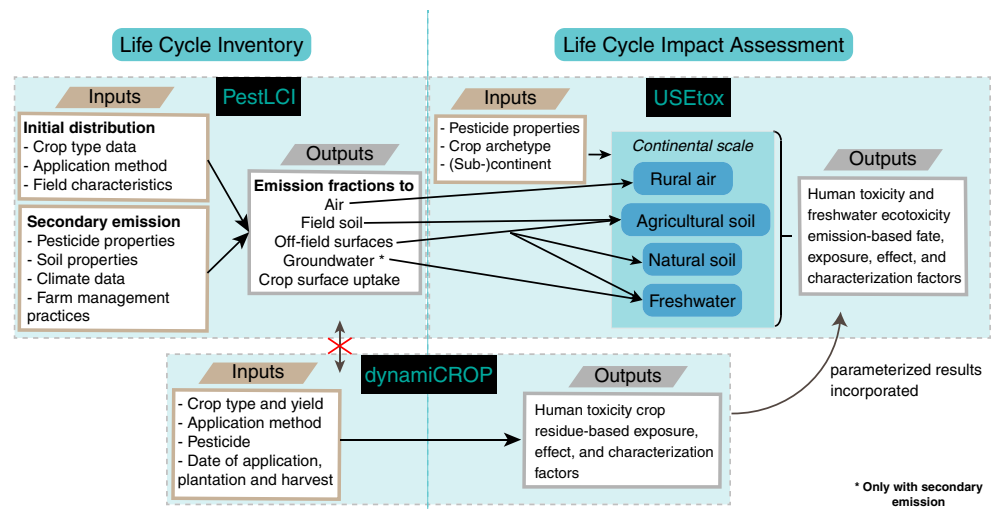
The adapted PestLCI model is a model to estimate pesticide emissions for LCA of agricultural products (Dijkman et al. 2012; Fantke et al. 2017a). Based on the framework proposed by Hauschild (2000), this model estimates emissions to air, surface water, groundwater, and soil from pesticide application in open fields, through two sets of distributions. Primary distribution covers initial processes within a few minutes after pesticide application. When the pesticides have been deposited on crop, soil, and off-field surfaces, and emitted to air via wind drift, secondary distribution estimates emissions covering more continuous processes on crop leaves (degradation, volatilization, plant uptake) and soil (volatilization, degradation, leaching, runoff). As a result of the secondary distribution, pesticides are emitted to surface water, to groundwater, to soil, to air, and to plant compartments (Dijkman et al. 2012). These processes are captured until the first rainfall event occurs (according to the frequency of rainfall events by month). The model was not developed for pesticide emission quantification for greenhouse production. However, from the same framework by Hauschild (2000), Antón et al. (2004) developed a proposition to evaluate pesticide emissions in greenhouses for LCA studies. Depending on the goal and scope of an LCA study, the agricultural soil and the buffer zone may be considered part of the ecosphere (i.e., environment) or the technosphere (i.e., agricultural production system). This will influence the results, as in LCA, an emission is a chemical flow crossing the boundary between technosphere and ecosphere. The interest of using PestLCI has been demonstrated

Table 2 References used for the analysis of the models PestLCI, USEtox, and dynamiCROP

Models	Original publications/documentation	Consensus publications/model update/model analyses	Publications on model case studies
PestLCI	Birkved and Hauschild 2006	Dijkman et al. 2012; Dijkman 2013; Fantke et al. 2017a; Fantin et al. 2019; Rosenbaum et al. 2015	<i>PestLCI 1.0</i> : Vázquez-Rowe et al. 2012; Salomone and Ioppolo 2012; Bojacá et al. 2012; Ingwersen 2012* <i>PestLCI 2.0</i> : Dijkman 2013; Nordborg et al. 2014, 2017; Xue et al. 2015; Renaud-Gentié et al. 2015; Vázquez-Rowe et al. 2017
USEtox	Rosenbaum et al. 2008; Fantke et al. 2017b	Henderson et al. 2011; Rosenbaum et al. 2011; Westh et al. 2015	Juraske et al. 2009; Berthoud et al. 2011; Vázquez-Rowe et al. 2012; Dijkman et al. 2017; Hunt et al. 2017 Used in combination with PestLCI or dynamiCROP: Fantke et al. 2011b; Vázquez-Rowe et al. 2012, 2017; Ingwersen 2012; Dijkman 2013; Antón et al. 2014; Xue et al. 2015; Renaud-Gentié et al. 2015; Fantke and Jolliet 2016
dynamyCROP	Fantke et al. 2011a,b	Fantke et al. 2012b, 2013; Fantke and Jolliet 2016	Juraske et al. 2011; Fantke et al. 2011a; Juraske et al. 2012; Itoiz et al. 2012; Fantke et al. 2012a; Jacobsen et al. 2015; Fantke and Jolliet 2016; Feng et al. 2018

*Only one study for tropical conditions

Fig. 1 Life Cycle Inventory and Impact Assessment models for evaluating pesticides, their inputs, outputs, and inter-connections



by Vázquez-Rowe et al. (2012, 2017), Renaud-Gentié et al. (2015), Fantke et al. (2017a), and Fantke (2019), in comparison with other methods as, e.g., ecoinvent where 100% of the applied dose of pesticides is assumed to be emitted directly to the agricultural soil (Nemecek and Schnetzer 2011). In contrast, PestLCI allows to integrate much more specificity than such generic assumptions, and estimates are derived as function of crop, location, growing season, pesticide, farming practice, and application method (Vázquez-Rowe et al. 2017). The adapted PestLCI model reflects the state-of-the-art in estimating pesticide emissions in LCA. This model is hence used to analyze its suitability for quantifying pesticide emissions under tropical conditions. The LCA study from Ingwersen (2012) of fresh pineapple (*Ananas comosus*) in Costa Rica constitutes a first application of the PestLCI model to estimate emissions under tropical conditions, which we therefore include in the discussion of model suitability.

2.3.2 USEtox to characterize human toxicity and ecotoxicity impacts

For characterizing human toxicity and ecotoxicity impacts in LCA, the most consensual model is USEtox (Hauschild et al. 2013). USEtox was developed as an outcome of a global scientific consensus-building process aiming to harmonize existing LCIA models for assessing environmental and health exposure to toxic substances (Rosenbaum et al. 2008; Westh et al. 2015). USEtox is a continental-scale model with six environmental compartments at continental level: urban air, rural air, agricultural soil, natural soil, freshwater, and coastal marine waters. This steady-state model allows calculating two impact categories with three indicators, two for human toxicity, namely human cancer toxicity and human non-cancer toxicity, and one for freshwater aquatic ecotoxicity of chemical emissions (including pesticides). Depending on the goal and scope of each LCA, USEtox allows calculating potential

impact results at the midpoint level or damage results at the endpoint level. Ecotoxicity impact results are expressed as potentially affected fraction of species (midpoint) and potentially disappeared fraction of species (damage), integrated over exposure time and volume per unit mass of a substance emitted. Human toxicity impact results are expressed as number of disease cases (midpoint) and disability-adjusted life years (damage) per unit mass of a substance emitted. Human exposure factors account for air inhalation and ingestion of drinking water, exposed produce (= leaf, fruit, and cereals), unexposed produce (= root crops), meat, dairy products, and fish. The consideration of pesticide residues in food crops was recently included based on the parameterization of the dynamiCROP model for six major food crops (Fantke et al. 2017b).

2.3.3 dynamiCROP to characterize exposure to crop residues

The dynamic plant uptake model dynamiCROP was developed, to include in LCA human exposure to pesticide residues in food crops as a predominant exposure pathway for the general human population (Jurasko et al. 2009; Fantke et al. 2012b). This model estimates pesticide plant uptake and residue exposure in open-field contexts, but also allows for pesticide greenhouse applications. To calculate the human impacts of pesticides residues through food crop consumption, dynamiCROP follows the general LCIA cause-effect chain combining factors representing environmental fate, human exposure, and health effects (Fantke et al. 2011b). The dynamiCROP model relates the mass that is ultimately taken in by humans via crop residues to the mass of applied pesticide (Fantke and Jolliet 2016). Food processes, such as peeling of fruits, are taken into account using generic food processing factors. Pesticide fate in plants is mainly influenced by degradation in and on crops, time between pesticide application and crop harvest, overall residence times in soil, and substance

molecular weight, based on a detailed analysis of influencing factors (Fantke et al. 2013; Fantke et al. 2014). These five key parameters are responsible for between 80 and 93% of the variation in pesticides residues and allowed to create parameterized exposure models for six important food crops (Fantke et al. 2012b). When combining human exposure estimates with human toxicity effect information, human toxicity results in dynamiCROP are compatible with results from USEtox and are expressed in disease cases (midpoint) or DALY (endpoint) per kilogram pesticide applied (or per kg emitted based on linking mass applied to mass emitted). Since 2016, parameterized dynamiCROP results are incorporated in USEtox (direct input in intake fraction matrix), but to use the model in its full version, LCA practitioners will need to couple dynamiCROP results with the applied pesticide mass on crops, which is currently not included in LCI databases (Rosenbaum et al. 2015).

3 Results and discussion

3.1 Characteristics of pesticide emission and impact patterns under tropical conditions

Tropical crop production systems and their use of pesticides are very different compared with cropping systems under temperate conditions. To highlight the main differences, we first present the specificities of tropical abiotic and biotic features. Second, agricultural practices and farmers' behaviors are detailed. Figure 2 summarizes the identified key processes and characteristics influencing pesticide emission distribution under tropical conditions.

3.1.1 Environmental characteristics of tropical conditions

Abiotic conditions Temperature-dependent processes, such as degradation, have higher kinetic rates under tropical conditions due to higher average temperatures (Daam and van den Brink 2010), which facilitates higher biological activity (Racke et al. 1997). Increasing temperature also enhances volatilization (Sanchez-Bayo and Hyne 2011) because of higher vapor pressure (Fig. 2). Even if vapor pressure is an intrinsic pesticides' characteristic, higher temperatures enhance the ability of a pesticide to turn into vapor and volatilize into the air. Just after pesticide application, a higher sunlight radiation allows for increased photodegradation on plant leaf surfaces compared with that under more average latitudes. Likewise, the photolysis of pesticides on soil surfaces is more important in tropical regions especially for pesticides applied on soil, without shadow from the crop, notably at the beginning of crop growth (Daam and van den Brink 2010).

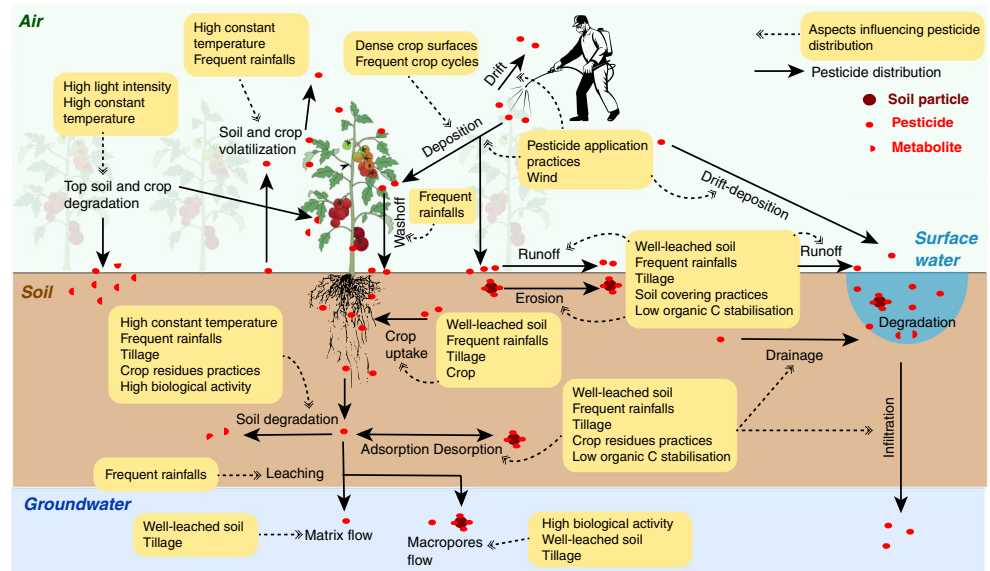
Pesticide emission patterns are also influenced by rainfall distribution patterns and intensity, especially in tropical

conditions, where extreme rainfall events and/or very dry seasons occur frequently (Fig. 2). Extreme rainfall causes high runoff and leaching, resulting in more pesticide residues found in surface waters and higher mobility toward groundwater (Sanchez-Bayo and Hyne 2011). In Martinique (French West Indies), where the climate is humid tropical, Mottes et al. (2017) showed high rates of river contamination by pesticides, especially herbicides. In these circumstances, rainfall events directly after pesticide application generated the pollution peaks. Likewise, in Guadeloupe, Charlier et al. (2009) highlighted for cadusaphos that the main contributor to stream contamination is shallow groundwater, due to the permeability of the soil and abundant rainfall.

In such tropical climatic conditions, a huge diversity of soils is present with various characteristics. One particularity of tropical soils is their substantial anion exchange capacity (Racke et al. 1997; Sansoulet et al. 2007). Soil characteristics (organic carbon content and pH) are also important influencing factors of pesticide distribution under tropical conditions, as demonstrated by, e.g., Sanchez-Bayo and Hyne (2011) (Fig. 2). In tropical contexts, the decomposition of organic matter is five times higher as compared with temperate environments (Racke et al. 1997). The organic carbon content might be low due to high rainfall and high microbial activity, which results in less adsorption and consequently more availability to be transferred to water and air (Sanchez-Bayo and Hyne 2011). Nevertheless, organic carbon content deficit can be compensated by organic matter inputs from crop residues, leading to soil stabilization, especially where microbial degradation and biomass production occur all year round. Furthermore, when soil pH is low, which is the case for most soils in Brazil and Southeast Asia, the desorption of acidic herbicides leaves more residues available for leaching (Sanchez-Bayo and Hyne 2011).

Biotic conditions In tropical regions, biodiversity in terrestrial and freshwater aquatic ecosystems is generally higher than in temperate regions, mainly due to less limiting aspects related to rain and temperature (Brown 2014). Few studies exist, however, on the specificity of the environmental impact of pesticide use under these conditions. In their study, Kwok et al. (2007) compared the sensitivity of tropical and temperate freshwater organisms for 18 chemical substances, and demonstrated that tropical aquatic organisms seem to be more sensitive to some organic chemicals and less sensitive to metals. Furthermore, the potential effect of pesticides on aquatic organisms might be reinforced by potentially high pesticide concentrations in water due to pesticide distribution processes in tropical environments (e.g., runoff) (Sanchez-Bayo and Hyne 2011). For pesticide impacts on terrestrial ecosystems, it has been reported that different pesticides show negative effects on non-target tropical species (e.g., Alves et al. 2013). Arias-Andrés et al. (2018) presented specific acute toxicity data with

Fig. 2 Key processes and characteristics that influence pesticide emission distribution in the tropics. Normal arrows represent the pesticide distribution and dotted arrows represent aspects influencing pesticide distribution under tropical conditions



tropical native species (earthworm). A recent study also synthesized available toxicological data of freshwater shrimps for insecticides and fungicides under tropical conditions (Daam and Rico 2018). These data were compared with data for temperate species (*Daphnia magna* and aquatic invertebrates), showing that the shrimps were less sensitive to sodium channel modulator insecticide, e.g., lindane and cypermethrin, and to acetylcholinesterase inhibiting fungicides and insecticides, e.g., diazinon. In their review, Aktar et al. (2009) also warned against the risks for soil microorganisms, insects, plants, aquatic organisms, and birds, associated to the use of organochlorine pesticides in India, which are usually phased out and not used anymore in temperate regions dominated by developed countries.

3.1.2 Agricultural practices and farmers' behavior

Thanks to the particular environmental conditions of tropical cropping systems, and according to the crop production target for export (e.g., palm oil, cocoa (*Theobroma cacao*), rice, banana), local market (e.g., fruits, vegetables, and rice), or self-sufficiency (e.g., roots and tubers, fruits, and vegetables), farming systems and associated crops cultivated are highly diversified (Biénabe et al. 2016). While in certain cropping systems one single crop is grown intensively and years after years over a vast and flat area (e.g., sugarcane), in small-scale farming systems, agro-forestry systems cash crops (e.g., coffee (*Coffea* spp.), cocoa can be combined with fruit trees (e.g., avocados (*Persea americana*), guava tree (*Psidium guajava*), and/or vegetable crops) in intercropping in mountain areas. Thus, application methods and farm management practices can vary a lot depending on cropping systems and environmental characteristics. Due to these different types of cropping systems and practices, pesticide emissions to the environment

also greatly differ from temperate conditions. Tropical crops also have specific characteristics that can influence pesticide distribution. Their canopy might have a greater volume compared with temperate crops, and due to faster crop growth in the tropics, several production cycles can be run one after the other and generally all year round.

Pesticide use and application methods In tropical agriculture, one of the main application methods used is the hand-operated sprayer, such as the backpack sprayer or knapsack sprayer as for horticulture production (Charlier et al. 2009) and for cash crops such as coffee and cocoa as shown by Matthews et al. (2003) in Cameroon. Hand-operated sprayers constitute for instance over 90% of the spraying equipment in Kenya (Mitoko 1997). More conventional boom sprayers and airblast sprayers are also used, respectively, in monocultures such as soybean (Bueno et al. 2017) and in fruit production (Alves and da Cunha 2014). Aerial application is banned in certain countries but is still in use in others, in particular in huge tropical banana or sugarcane cropping systems. Therefore, since pesticide applications are mainly done directly by hand or with manual applicators, occupational exposure might be higher in the tropics especially in developing countries where farmers often have a reduced education on pesticides' risks for their health. In addition to that, the warm and humid conditions make the wearing of personal protective equipment (PPE) difficult (Raksanam et al. 2012). Furthermore, due to the generally high diversity of crop productions and pests under tropical conditions, there are certain pests for which no authorized pesticides are currently available (Laplace 2018). These orphan uses represent a major risk for human health and the environment, since farmers might be tempted to use unauthorized plant protection products for their crops.

Due to a low level of knowledge about pesticide use (no or little training in pesticide application) and weak awareness of pesticide risk (Settle et al. 2014; Houbraken et al. 2017; Elibariki and Maguta 2017), non-compliance with the approved dose and/or with the frequency of application is also common in tropical regions. The non-compliance with the minimum required pre-harvest period after the last application and the use of prohibited pesticides (Weinberger and Lumpkin 2007; Montes et al. 2012; Poukam et al. 2017) further increase human and ecological risks under tropical conditions.

Agricultural practices Specific agricultural practices in the tropics affect pesticide emissions at the field and catchment scales (Mottes et al. 2014), in particular, practices influencing the hydraulic processes in and on the soil, and concern mostly tillage and ground cover management (Fig. 2). For example, the implementation of cover plants or crops between crop rows allows to reduce runoff, as shown for banana plantations in intercropping with pineapple (Abbasi and Jamal 1999). Likewise, the use of crop residues as straw in sugarcane production (Pereira-Junior et al. 2015) or biochars (Kookana 2010; Mendes et al. 2018) increases herbicide sorption and reduces leaching. In conclusion, these specificities of tropical conditions and farm management practices are expected to strongly influence emission patterns and should therefore be accounted for in modeling pesticide emissions.

3.2 Improvements to better model pesticides under tropical conditions in LCA

The results of our critical analysis of the models' validity for tropical conditions are summarized in Table 3, providing specific recommendations for model improvement, which are either specific to tropical conditions or considered generally applicable for all contexts. Subsequently, margins of improvements and proposals for further research for the adapted PestLCI model, the impact model USEtox and the dynamiCROP model, are presented.

3.2.1 General limitations of the use of models

There are some general limitations of the discussed models, which reduce the possible extension of their validity to assess pesticides under tropical conditions. The uncertainty of toxicity impact results increases dramatically when generic or average values across pesticides belonging to a certain chemical family are used or when applying an averaged characterization factor across pesticides as a proxy for certain substances (Basset-Mens et al. 2019). In emission and impact modeling, biological/natural substances, metal-based pesticides, or inorganic substances are currently not included (Meier et al. 2015), such as copper pesticide (Peña et al. 2018). Likewise, active substances' metabolites, which may have even higher

toxic effects than their parent compounds (e.g., diuron) are not accounted for in practice (Oturán et al. 2008).

Beyond the improvements relevant for each model, the interface between emission and impact characterization models is not perfect, as presented in Fig. 1. More research is needed on the best way to deal with the soil, which could in fact belong to both the ecosphere and the technosphere, which affects both the modeling of emissions and related impacts on humans and ecosystems (van Zelm et al. 2014). Despite remaining research needs, preliminary recommendations have been proposed to achieve a coherent use of LCI and LCIA models for pesticides (Rosenbaum et al. 2015; Fantke et al. 2016, 2017a, 2018). The recommendations mainly refer to the delineation between technosphere and ecosphere and what to include in LCI or LCIA in order to model pesticides in a consistent way. However, the adapted PestLCI model and the impact model USEtox have different spatiotemporal boundary systems (Dijkman et al. 2018). To avoid omissions or double counting of mass transport processes, only the primary pesticide distribution from the adapted PestLCI model was recommended to be used as direct input for the LCIA model USEtox, and the recommended timeframe of the adapted PestLCI model to consider environmental processes was 1 day. This, however, means that processes beyond the considered timeframe are currently not considered in LCI emission models for pesticides. This affects, for example, leaching and runoff, two processes that are particularly relevant in tropical contexts (Racke et al. 1997). Instead, these rather long-term processes are currently considered in USEtox and dynamiCROP, which do not have the spatial level of disaggregation of the emission model to account for variations in soil and climate characteristics. Consequently, soil and climate characteristics influencing these processes are not taken into account properly, while the calculation of emission fractions is exclusively depending on drift curves and crop stage. One possible solution is to extend the temporal coverage of environmental processes in the emission modeling. Another possible solution is to spatialize the impact assessment modeling as recently proposed by Wannaz et al. (2018). Moreover, the use of the primary distribution only in the adapted PestLCI model to estimate pesticide emission fractions in a tropical context is even less relevant, since the drift curves are defined for temperate crops, climates, and application methods. In conclusion, some of these recommendations do not allow a good consideration of pesticides in LCA, by excluding key factors influencing pesticide emissions.

3.2.2 Emission modeling for tropical conditions

The proposed improvements that were summarized in Table 3 are detailed in Table 4 according to the relevance of the processes for modeling pesticide emissions under tropical conditions. Adaptations and recommendations from previous case

Table 3 Recommendations for improving the adapted PestLCI model, USEtox, and dynamiCROP to be suitable for assessing pesticides under tropical conditions and more generally for agricultural LCA

	Adapted PestLCI model	USEtox	dynamiCROP
General context	<ul style="list-style-type: none"> - Adding ground cover management and other agricultural practices or techniques (such as greenhouse production) ○ - Adding active substances, notably biological/natural substances, metals, and inorganics; and methods for characterizing additional substances (e.g., inorganic salts and plant-based pesticides) ○ - Offering the possibility to parameterize the model with users' set of data (crop, soil, and climate) ● - Including metabolites emission and impact modeling, notably with guidance ○ - Incorporating seedlings and seeds, and post-harvest pesticide applications○ 	<ul style="list-style-type: none"> - Adding missing characterization factors for active substances (for organic, metal, inorganic, and biological/natural pesticides) ○ - Including marine, terrestrial, pollinators, and birds' toxicity ○ - Adding exposure pathways for human toxicity (bystanders, workers) ○ - Adding groundwater, sediment, and plant compartments ○ 	<ul style="list-style-type: none"> - Adding missing exposure factors for active substances (for organic, metal, inorganic, and biological/natural pesticides) ● - Improving the estimation of human intake due to late application of pesticides before harvest ○
Tropical context	<ul style="list-style-type: none"> - Adding tropical crop data (plant development and growth, archetypes) ● - Adding drift curves for tropical pesticide application techniques ● - Correction of empirical equations defined based on temperate conditions ○ - Allowing modeling of small plots (less than 50 m) ○ - Integrating processes occurring after the first rainfall event (such as leaching) ○ - Including drainage ditches ○ - Adding specific pesticide characteristics depending on tropical conditions and crops ● - Adding tropical climate and soil types ● - Complementing substance data (e.g., half-lives) under tropical conditions ○ 	<ul style="list-style-type: none"> - Adding ecotoxicological data specific to tropical biota ○ 	<ul style="list-style-type: none"> - Adding crop data (plant development and growth, archetypes) for tropical crops ○

●For aspects that require limited effort

○For aspects that require substantial model adaptations and additional research

studies using PestLCI 1.0 and PestLCI 2.0 are also presented in Table 4. In open fields, PestLCI 2.0 has been tested only under temperate conditions by Dijkman (2013) on barley (*Hordeum vulgare*) and kiwi (*Actinidia deliciosa*), by Xue et al. (2015) on maize, by Renaud-Gentié et al. (2015), and by Vzquez-Rowe et al. (2017) on vineyard. In tropical conditions, only PestLCI 1.0 has been tested by Ingwersen (2012) on pineapple. More generally, we recommend that PestLCI is made more user-friendly by, e.g., running multiple scenarios in a single run and by offering an import/export function to common LCA software formats.

Extension of the validity domain of the model First, the validity domain of the model needs to be extended to account for tropical crop type and cropping systems (e.g., multi-annual banana and sugarcane production and their associated farm management practices, crop morphology), and climate and soil characteristics. When tested in case studies, the model was generally adapted to local conditions (Table 4). A first analysis of the equations and parameters used in the emission

model highlights that some parameters rely on fixed default or average values. As highlighted by Renaud-Gentié et al. (2015) based on a sensitivity analysis, some of these parameters have a strong effect on final results. In certain contexts, results might be sensitive to the fraction of continuous macropores in the soil (e.g., in vineyard soils Renaud-Gentié et al. 2015), to the volume fraction of water in the soil, and to the fraction intercepted by leaves. Consequently, the leaf area index and associated fraction intercepted by leaves should be adapted for all crops and growth stages, with a correspondence table as done by Linders et al. (2000) but including the main tropical crops. Furthermore, Renaud-Gentié et al. (2015) argue for the possibility to add the user's own dataset on climate and soil, because soil and climate characteristics have strong influences on results. Furthermore, some equations for important processes of pesticide distribution in tropical conditions are based on Danish circumstances as the calculation of the length of a rainfall event in case of macropores flow, which is used to estimate the leached fraction. A deeper understanding is necessary of how and to what degree certain aspects like

Table 4 Factors influencing pesticide emissions under tropical conditions, and how they are currently considered in the adapted PestLCI model (as part of primary pesticide distribution or as part of secondary emissions) based on conclusions and improvements proposed by previous studies applying this model

Type	Aspect	Relevance for modeling pesticides in tropical regions (processes)	References for the relevance of process	Integration in the adapted PestLCI model	Distribution in the adapted PestLCI model	References with case studies
Agricultural practices	Application technique and target	Airborne emissions, volatilization, and plant uptake	(García-Santos et al. 2016; Lewis et al. 2016)	Missing plant growth/stage No drift curve from tropical conditions	Primary (drift); secondary	Adapted in (Renaud-Gentié et al. 2015)
	Ground cover (mulching, crops residues, cover crops, etc.)	Sorption, dissipation at the field scale, and wash off from ground cover	(Mottes et al. 2014; Lewis et al. 2016)	Practices not integrated	Secondary	Developed and added in (Renaud-Gentié et al. 2015)
	Other farm management practices (e.g., tillage, buffer zone, biochar, drainage ditches)	Pesticide transport to water compartments	(Pereira-Junior et al. 2015; Mutua et al. 2016; Mendes et al. 2018)	Practices integrated: tillage, buffer zone, and pipe drainage Practices not integrated: biochar, drainage ditches	Secondary	
Environmental characteristics	Climate	Chemical and physical processes that change with temperature to different degrees (e.g., volatilization, degradation on the leaf)	(Daam and van den Brink 2010)	Most of the processes are temperature-dependent (average temperature in the month of application)	Secondary	Adapted in (Ingwersen 2012; Xue et al. 2015; Renaud-Gentié et al. 2015; Vázquez-Rowe et al. 2017)
	Rainfall	Pesticide transport outside the field by runoff, leaching, drainage, and wash off	(Daam and van den Brink 2010)	No modeling of processes occurring after the first rainfall	Secondary	
	Sunlight	Photodecomposition and volatilization	(Daam and van den Brink 2010)	Definition of rainfall event questionable Parameter not integrated into the processes	Secondary	
Active substances	Soil properties (e.g., OC content, pH)	Soil adsorption and desorption, plant uptake, macropores flow	(Charlier et al. 2009; Lewis et al. 2016)	Parameters integrated into the model	Secondary	
	Chemical properties (e.g., DT50 soil, DT50 plant, solubility, Koc)	Plant uptake and transfer to water bodies	(Racke et al. 1997; Arias-Estévez et al. 2008; Sanchez-Bayo and Hynes 2011; Fantke and Juraska 2013; Fantke et al. 2016)	Variability of some chemical properties due to plant and environmental conditions not integrated (e.g., biological degradation level, temperature dependency, pesticide-plant species combinations)	Secondary	Completed for missing substances in (Xue et al. 2015; Renaud-Gentié et al. 2015; Vázquez-Rowe et al. 2017)
	Inorganic substances/metals	Integrate toxicity impact of these substances, need to evaluate distribution into the environment	(Peña et al. 2018)	No modeling on inorganic active substance	Primary; secondary	Issue highlighted in (Renaud-Gentié et al. 2015)

temperature influence emission results, in order to extend the applicability of the model to tropical conditions. Further research is also required for modeling the emissions of metals and other inorganic substances. These substances can largely increase impact on freshwater ecosystems (Vzquez-Rowe et al. 2012), but another approach is required to integrate their specific behavior in the environment into the adapted PestLCI model (Renaud-Gentié et al. 2015; Peña et al. 2018). Adapting the PestLCI model for special cropping systems is finally relevant, for example for flooded crops such as rice, with specific pesticide field emissions, getting inspiration from models specifically parameterized for such cropping systems (Capri and Miao 2002; Inao et al. 2018).

Primary drift distribution In the primary distribution, the spray drift allows to estimate the fraction of pesticides dropped out of the field within a few minutes after field application. This corresponds to the transfer by air of spray droplets out of the treated field, which could be on water surfaces, vegetation, soil, or urbanized area. Current drift curves available in the adapted PestLCI model mainly consider German (Ganzelmeier et al. 1995) and Dutch (Holterman and van de Zande 2003) conditions. These drift curves were calibrated for crops present in these two countries and for the application methods prevalent in these countries, and more generally in Europe. While drift curves are mainly categorized according to application methods, several factors that vary widely between tropical and temperate conditions influence wind drift, such as crop density, soil conditions, and rain patterns. Hence, currently implemented drift curves focus on a temperate climate, defined as oceanic climate (Kottek et al. 2006). As one of the main application methods under tropical conditions, the knapsack sprayer has a drift curve available. It was calculated on potato (*Solanum tuberosum*) production with the IMAG calculator (from the Dutch model) in Boyacá, a highland region in Colombia (Garca-Santos et al. 2016), which corresponds to a temperate oceanic climate. Given that the main factors of the variation of spray drift are the application method and the nozzle's type, the climatic conditions (temperature, hygrometry, wind), the formulation of pesticide (e.g., powder, liquid) and his adjuvant, the composition and state of vegetation, and the farmers' use of equipment (Franke et al. 2010), the use of this drift curve in tropical conditions is questionable and should be done with caution. A literature review on drift in tropical conditions highlighted the low number of studies on pesticide drift under these conditions. Gouda et al. (2018) presented a drift experiment and calculated a drift curve for a knapsack sprayer on cotton (*Gossypium* spp.) production in Benin. Awadhwal et al. (1991) and Snelder et al. (2008) studied pesticide drift for a knapsack sprayer on rice production in the Philippines, and da Cunha et al. (2003) studied drift curves for an airblast sprayer on bean production in Brazil. Due to differences in the methodology of drift measurements, a more

in-depth analysis of these studies is required to validate their potential integration into the adapted PestLCI model as additional drift curves for tropical conditions. Drift models should also be explored, since several could be relevant for tropical conditions. In conclusion, research is still needed on the mechanisms of pesticide drift during field application under tropical conditions. New drift curve estimates are required to best estimate pesticide field emission in these contexts.

Secondary emission distribution In the adapted PestLCI model, water flows are not adequately modeled in secondary distribution estimates. After the first rainfall event, no more biophysical processes occur whereas, in the reality, runoff and leaching continue to occur several days or months after the pesticide has been applied depending on its persistence in the environment. This is particularly relevant under tropical conditions and must be considered, especially where farm management practices have an effect on pesticide transfers to water. Ground cover management is particularly critical in tropical conditions. Weeds are present almost all year, soil moisture should be maintained in the dry season, and soil erosion due to heavy rainfall events should be reduced as much as possible. As presented in Table 4, some farm management practices are already modeled in the adapted PestLCI model, such as tillage, buffer zone, and pipe drainage. However, other farm management practices, which also influence the mobility of pesticides to the environment, are not yet considered (see Table 4). PestLCI 2.0 was customized for viticulture to take into account the effect of cover plants (grass) between the rows of vines (*Vitis vinifera*) on pesticide distribution (Renaud-Gentié et al. 2015). This adaptation is not yet included in the available adapted PestLCI model. This specific module could be extended to tropical productions, such as banana (Abbasi and Jamal 1999), with the possibility to choose the type of ground cover between rows by either a cover crop, a cover plant, or a mulch. Other farm management practices have a strong influence on pesticide drift, such as the control of the tractor speed or the compliance of recommended climatic conditions to apply pesticides (Arvidsson et al. 2011). However, in general, this level of detail of information cannot be accounted for in LCA, and some uncertainty from the farmers' practice remains. Furthermore, some practices already integrated into the model could be improved by adding more possibilities, such as drainage ditches. Finally, the diversity of cropping systems should be integrated into the model, such as intercropping.

3.2.3 (Eco-)toxicity characterization for tropical conditions

Built as a mechanistic model, USEtox is based on averaging conditions across all continents, yielding recommended factors for a generic average continent. However, while continental and sub-continental parameterizations are available, they

are only recommended for sensitivity analysis and do not reflect the specific conditions of tropical regions, where, e.g., the ecotoxicity effects on tropical species or temperature-dependent processes are considered. More specifically, information on effects on tropical ecosystem species is required to assess pesticides in tropical conditions. When such information is missing, pesticides cannot be characterized, leading to a possible underestimation in results whenever such pesticides are used, but not considered in related impact scores (Vzquez-Rowe et al. 2017)

In Pennington et al. (2005), the authors highlighted that the uncertainty of toxicity characterization factors evaluated with a non-spatial model (IMPACT 2002) is at least of 2 to 3 orders of magnitude for some chemicals. As a consequence, Ingwersen (2012) proposed to customize USEtox to the Costa Rican environment in his LCA study of fresh pineapple. USEtox could use spatial differentiation considering tropical conditions and ecosystems (e.g., mangrove) on the one hand and temperate conditions on the other, as already proposed in other spatial differentiation models (e.g., Wannaz et al. 2018). However, the benefit of applying spatial differentiation impact assessment models relies on the availability of spatial data for underlying input parameters, such as species distribution, life cycle emissions, and background exposure levels, which is often not available in LCA studies with a tropical context. Given that in many LCA studies, spatially explicit data are often not available, current models are not primarily designed for regionalized toxicity characterization. In cases, where spatial data are becoming available, the models should be adapted to account for spatial aspects, which is discussed, e.g., in Peña et al. (2018, 2019). More generally, for all pedoclimatic contexts, some impacts are not adequately taken into account or not included at all in some models, such as terrestrial and marine ecotoxicity (Notarnicola et al. 2017). As recommended by Fantke et al. (2018), efforts are required on on-field impacts and missing impact categories including terrestrial/pollinator ecotoxicity, especially so in tropical conditions (Brown 2014). USEtox could have a groundwater compartment to better distribute emission fractions from the adapted PestLCI model to surface water and groundwater, currently fully allocated to the freshwater compartment by default (Fantke et al. 2018) (see Fig. 1), but also to take into account ecotoxicity in groundwater where biodiversity is specific (Danielopol et al. 2000). Whereas groundwater is relevant in most climate conditions, it plays a particular role in tropical contexts with plenty of rain and high water flow rates. Although a different sensitivity of tropical species has been demonstrated for some active substances compared with that of temperate species studies (Kwok et al. 2007; Daam and van den Brink 2010), ecotoxicological data for tropical species is scarce and current knowledge in ecotoxicology mainly comes from Europe and North America with temperate conditions (Kwok et al. 2007). The few data available on tropical species

sensitivity to pesticides (Alves et al. 2013; Arias-Andrés et al. 2018; Daam and Rico 2018) should be integrated into the model. However, Kwok et al. (2007), Daam and van den Brink (2010), and Leboulanger et al. (2011) highlighted the need for further development of toxicity tests with indigenous species in tropical conditions. In priority, for a better estimation of pesticide environmental impacts in tropical conditions, further research on indigenous species in tropical conditions and organisms' sensitivity to pesticides from tropical origins is required. Some pesticides exposure pathways in agriculture are missing as occupational exposure (when preparing and applying pesticides) (Ingwersen 2012), residential bystanders, and family of exposed workers (Ryberg et al. 2018). This is of particular concern in tropical conditions, where human exposure to pesticides might be higher because of the proximity of dwellings to treated plots, the mainly manual use of pesticides without, most of the time, personal protective equipment and skills to apply them, and the frequent storage of pesticides in households (Williamson et al. 2008). A framework for assessing residential bystander exposure to field pesticide applications (potatoes) in LCIA has been recently presented by Ryberg et al. (2018). However, this work must be further adapted and extended to additional tropical crops and application methods, in particular to hand-operated spraying, which is important under tropical conditions. Other sources of pesticide exposure and contamination could be added as post-harvested treatment and seed treatment that can have environmental impact (e.g., seed treatment on the terrestrial ecosystem—worms; Alves et al. 2013) and impacts on human health (e.g., pesticide residues from post-harvest treatments; Bajwa and Sandhu 2014).

3.2.4 Crop residue modeling for tropical conditions

In dynamiCROP, the development of a user interface to change easily default values on climate data (e.g., average relative humidity, mean temperature in air, precipitation rate during wet period), soil data (e.g., pH, soil organic carbon content), and plant characteristics (e.g., leaf area index, density of fruit) would be useful to optimize the use of dynamiCROP for tropical (and other) contexts. Furthermore, important crop archetypes relevant for tropical contexts are missing as for example banana or soybean production. As part of a study on passion fruits cultivated in Colombia (Jurassek et al. 2012), the passion fruit crop model has been parameterized into dynamiCROP and constitutes the unique tropical crop. Archetypes already modeled should be used carefully for assessments focusing on tropical conditions, because crop growth and varieties are different and could imply differences in pesticide distribution in the modeled plant-environment system. Hence, plant characteristics should always be checked prior to their use in related models. For example, to model the uptake of pesticides by taro (*Colocasia esculenta*) crops (a

tuber), currently, the user must choose the potato archetype, whereas the crops' family and farm management practices are widely different from taro. Currently, data for pesticide dissipation half-lives in plants can be estimated based on Fantke et al. (2014), where dissipation from the plant is influenced by active substance properties, plant characteristics, and environmental conditions (mainly temperature). However, differences in rain, sunlight, and other conditions relevant for tropical regions are currently not considered in such estimates, and hence, further research is required to measure half-lives on plants for tropical crops and conditions. Furthermore, the estimation of human intake due to the late application of pesticides before harvest should be improved. This is particularly important in many tropical agricultural productions, where harvesting takes place throughout the year with plants and fruits/legumes at different stages of maturity in the same plot (e.g., vegetable production). Finally, dynamiCROP has never been used in combination with the adapted PestLCI model. The calculation chain between both models could be achieved by using the fraction of drift and volatilization in the adapted PestLCI model to refine the respective fixed fractions lost to air per crop in dynamiCROP. With this step, we could have a consistently estimated fraction of pesticide reaching the plant. The model is currently tested in combination with the adapted PestLCI model and USEtox on open-field tomato production in tropical soils and climates, in the Martinique island. When related results become available, recommendations are expected how to best align the combined use of the three discussed models.

4 Conclusions

The present study showed that processes driving pesticide emission and impact patterns under tropical conditions are specific in relation to soil, climate, cropping practices, and crops. The three most up-to-date and consensual LCI and LCIA models commonly reflect temperate conditions for climate, soil, application techniques, and crops and are not yet suited for the evaluation of the impacts of pesticides in LCA of crops cultivated in tropical regions. Under tropical conditions, higher temperatures, sunlight radiation, and microbial activity enhance degradation and volatilization of pesticides. Heavy and frequent rainfall events lead to higher leaching and runoff. Tropical crops, cropping systems, and practices also widely differ as compared with temperate regions in relation to natural and human drivers, and we demonstrated how these aspects can alter the transfers and impacts of pesticides. In developing countries with a tropical climate, pesticides are most often applied manually or with a hand-operated sprayer. Farmers generally have less awareness of pesticides' danger and less training on good practices of application leading to higher risks of transfers and impacts on the environment and

human health. Under tropical conditions, certain practices, such as ground cover management, can play a major role in the transfer of pesticides to the water compartment by affecting the soil hydraulic processes. Furthermore, biodiversity is naturally higher in tropical regions and preliminary research revealed a different sensitivity of tropical species to pesticides compared with species in temperate regions, while in most ecotoxicity experiments, they are currently not represented.

We provided a set of recommendations to better account for the specificities of pesticide emissions and impacts in tropical conditions in the three discussed models. Databases need to be extended to integrate tropical crops characteristics, soil and climate specificities for tropical conditions, and active substances' chemical characteristics. In the primary distribution of the adapted PestLCI model, the addition of specific drift curves for tropical conditions has the potential to make a difference in the results and to reduce uncertainty. In the secondary emission distribution, specific features of tropical cropping systems and farm management practices should be included, especially ground cover management (e.g., mulching) in combination with a better accounting of the leaching process over time. In dynamiCROP, the development of a user interface to change easily default values on climate, soil, and plant characteristics would be useful and important crop archetypes for tropical conditions should be added. The estimation of human intake due to the late application of pesticides before harvest should also be improved to account for characteristics of cropping systems in the tropics.

Additional perspectives for the future include the need to test in combination PestLCI, USEtox, and dynamiCROP in real LCA case studies under tropical conditions, in order to contribute to their better understanding and parametrization.

In summary, emission and impact evaluation processes are not as well understood for tropical conditions as they are for temperate conditions, with fewer measurements available for the former. Further experimental research in these contexts is therefore urgently needed. In the adapted PestLCI model, mechanisms of pesticide drift during field application, according to tropical conditions and applications methods and mechanisms to account for metals and other inorganic substances, should be explored and included. Research on organisms' sensitivity to pesticides from tropical origins is also essential. In current impact models, different exposure populations (consumers, workers, and bystanders) and effects on relevant organisms (freshwater, marine, terrestrial, pollinators, and birds) should progressively be modeled. Reflection and consensus on the conceptual framework of the LCI-LCIA calculation chain and the soil's belonging to ecosphere or technosphere are needed for a better consistency of the modeling of pesticide emissions and impacts in LCA studies focusing on tropical conditions. Current model limitations highlighted in our study are a useful starting point for focusing future research and model refinement efforts, with the aim to

help reducing uncertainty in LCA results representing tropical conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

- Abbasi MA, Jamal T (1999) Soil loss and runoff measurement from banana-pineapple intercropping system. *Pak J Bio Sci* 2:689–692
- Aktar MW, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. *Interdiscip Toxicol* 2:1–12
- Alves GS, da Cunha JPAR (2014) Field data and prediction models of pesticide spray drift on coffee crop. *Pesq Agrop Brasileira* 49:622–629
- Alves PRL, Cardoso EJBN, Martines AM, Sousa JP, Pasini A (2013) Earthworm ecotoxicological assessments of pesticides used to treat seeds under tropical conditions. *Chemosphere* 90:2674–2682
- Antón A, Castells F, Montero JI, Huijbregts M (2004) Comparison of toxicological impacts of integrated and chemical pest management in Mediterranean greenhouses. *Chemosphere* 54:1225–1235
- Antón A, Torrellas M, Núñez M, Seigné E, Amores MJ, Muñoz P, Montero JI (2014) Improvement of agricultural life cycle assessment studies through spatial differentiation and new impact categories: case study on greenhouse tomato production. *Environ Sci Technol* 48:9454–9462
- Arias-Andrés M, Rämö R, Torres FM et al (2018) Lower tier toxicity risk assessment of agriculture pesticides detected on the Río Madre de Dios watershed, Costa Rica. *Environ Sci Pollut Res* 25:13312–13321
- Arias-Estévez M, López-Periágo E, Martínez-Carballo E, Simal-Gándara J, Mejuto JC, García-Río L (2008) The mobility and degradation of pesticides in soils and the pollution of groundwater resources. *Agri Ecosyst Environ* 123:247–260
- Arvidsson T, Bergström L, Kreuger J (2011) Spray drift as influenced by meteorological and technical factors. *Pest Manag Sci* 67:586–598
- Awadhwal NK, Cabrido EF, Quick GR (1991) Minimizing drift and exposure from knapsack sprayers. *J Environ Sci Health B* 26:589–600
- Bajwa U, Sandhu KS (2014) Effect of handling and processing on pesticide residues in food- a review. *J Food Sci Technol* 51:201–220
- Basset-Mens C, Edewa A, Gentil C (2019) An LCA of French beans from Kenya for decision-makers. *Indones J Life Cycle Assess Sust* 3:11
- Beck HE, Zimmermann NE, McVicar TR et al (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data* 5:180214
- Berthoud A, Maupu P, Huet C, Poupart A (2011) Assessing freshwater ecotoxicity of agricultural products in life cycle assessment (LCA): a case study of wheat using French agricultural practices databases and USEtox model. *Int J Life Cycle Assess* 16:841–847
- Bessou C, Basset-Mens C, Tran T, Benoist A (2013) LCA applied to perennial cropping systems: a review focused on the farm stage. *Int J Life Cycle Assess* 18:340–361
- Biénabe E, Rival A, Loeillet D (2016) Développement durable et filières tropicales, Quae. Versailles, France
- Birkved M, Hauschild MZ (2006) PestLCI—A model for estimating field emissions of pesticides in agricultural LCA. *Ecol Model* 198:433–451
- Bocquené G, Franco A (2005) Pesticide contamination of the coastline of Martinique. *Mar Pollut Bull* 51:612–619
- Bojacá CR, Gil R, Casilimas H et al (2012) Modelling the environmental impact of pesticides sprayed on greenhouse tomatoes: a regional case study in Colombia. *Acta Hort* 61–68. <https://doi.org/10.17660/ActaHortic.2012.957.6>
- Brock TC, Alix A, Brown C et al (2009) Linking aquatic exposure and effects: risk assessment of pesticides. CRC Press
- Brown JH (2014) Why are there so many species in the tropics? *J Biogeogr* 41:8–22
- Bueno MR, da Cunha JPAR, de Santana DG (2017) Assessment of spray drift from pesticide applications in soybean crops. *Biosyst Eng* 154:35–45
- Capri E, Miao Z (2002) Modelling pesticide fate in rice paddy. *Agronomie* 22:363–371
- Castillo LE, de la Cruz E, Ruppert C (1996) Ecotoxicology and pesticides in tropical aquatic ecosystems of Central America. *Environ Toxicol Chem* 16:41–51
- Charlier JB, Cattani P, Voltz M, Moussa R (2009) Transport of a nematode in surface and groundwaters in a tropical volcanic catchment. *J Environ Qual* 38:1031–1041
- da Cunha JPAR, Teixeira MM, Coury JR, Ferreira LR (2003) Evaluation of strategies to reduce pesticide spray drift. *Planta Daninha* 21:325–332
- Daam MA, Rico A (2018) Freshwater shrimps as sensitive test species for the risk assessment of pesticides in the tropics. *Environ Sci Pollut Res* 25:13235–13243
- Daam MA, van den Brink PJ (2010) Implications of differences between temperate and tropical freshwater ecosystems for the ecological risk assessment of pesticides. *Ecotoxicology* 19:24–37
- Danielopol DL, Pospisil P, Rouch R (2000) Biodiversity in groundwater: a large-scale view. *Trends Ecol Evol* 15:223–224
- de Bon H, Huat J, Parrot L, Sinzogan A, Martin T, Malézieux E, Vayssières JF (2014) Pesticide risks from fruit and vegetable pest management by small farmers in sub-Saharan Africa. A review. *Agron Sustain Dev* 34:723–736
- Dickinson NM, Lepp NW (1984) Pollution of tropical plantation crops by copper fungicides: a copper budget for Kenyan coffee plantation. *Stud Environ Sci*:341–346
- Dijkman TJ (2013) Modelling of pesticide emissions for Life Cycle Inventory analysis: model development, applications and implications. Department of Management Engineering, Technical University of Denmark, Dissertation
- Dijkman TJ, Basset-Mens C, Antón A, Núñez M (2018) LCA of food and agriculture. In: Hauschild MZ (ed) *Life Cycle Assessment - theory and practice*. Springer, Cham, Switzerland, pp 723–754

- Dijkman TJ, Birkved M, Hauschild MZ (2012) PestLCI 2.0: a second generation model for estimating emissions of pesticides from arable land in LCA. *Int J Life Cycle Assess* 17:973–986
- Dijkman TJ, Birkved M, Saxe H, Wenzel H, Hauschild MZ (2017) Environmental impacts of barley cultivation under current and future climatic conditions. *J Clean Prod* 140:644–653
- Elibariki R, Maguta MM (2017) Status of pesticides pollution in Tanzania – a review. *Chemos* 178:154–164
- Fantin V, Buscaroli A, Dijkman T, Zamagni A, Garavini G, Bonoli A, Righi S (2019) PestLCI 2.0 sensitivity to soil variations for the evaluation of pesticide distribution in life cycle assessment studies. *Sci Total Environ* 656:1021–1031
- Fantke P (2019) Modeling the environmental impacts of pesticides in agriculture. In: Weidema, B.P. (Ed) *Assessing the environmental impact of agriculture*, Burleigh Dodds Science Publishing, Cambridge, United Kingdom, pp 177–228. <https://doi.org/10.19103/AS.2018.0044.08>
- Fantke P, Antón A, Grant T, Hayashi K (2017a) Pesticide emission quantification for life cycle assessment: a global consensus building process. *J Life Cycle Assess* 13:245–251
- Fantke P, Arnot JA, Doucette WJ (2016) Improving plant bioaccumulation science through consistent reporting of experimental data. *J Environ Manag* 181:374–384
- Fantke P, Aurisano N, Bare J, Backhaus T, Bulle C, Chapman PM, de Zwart D, Dwyer R, Ernstoff A, Golsteijn L, Holmquist H, Jolliet O, McKone TE, Owsianiak M, Peijnenburg W, Posthuma L, Roos S, Saouter E, Schowanek D, van Straalen NM, Vijver MG, Hauschild M (2018) Toward harmonizing ecotoxicity characterization in life cycle impact assessment. *Environ Toxicol Chem* 37:2955–2971
- Fantke P, Bijster M, Guignard C et al (2017b) USEtox® 2.0 documentation (Version1)
- Fantke P, Charles R, de Alencastro LF et al (2011a) Plant uptake of pesticides and human health: dynamic modeling of residues in wheat and ingestion intake. *Chemosphere* 85:1639–1647
- Fantke P, Friedrich R, Jolliet O (2012a) Health impact and damage cost assessment of pesticides in Europe. *Environ Int* 49:9–17
- Fantke P, Gillespie BW, Juraske R, Jolliet O (2014) Estimating half-lives for pesticide dissipation from plants. *Environ Sci Technol* 48:8588–8602
- Fantke P, Jolliet O (2016) Life cycle human health impacts of 875 pesticides. *Int J Life Cycle Assess* 21:722–733
- Fantke P, Juraske R (2013) Variability of pesticide dissipation half-lives in plants. *Environ Sci Technol* 47:3548–3562
- Fantke P, Juraske R, Antón A, Friedrich R, Jolliet O (2011b) Dynamic multicrop model to characterize impacts of pesticides in food. *Environ Sci Technol* 45:8842–8849
- Fantke P, Wieland P, Juraske R, Shaddick G, Itoiz ES, Friedrich R, Jolliet O (2012b) Parameterization models for pesticide exposure via crop consumption. *Environ Sci Technol* 46:12864–12872
- Fantke P, Wieland P, Wannaz C, Friedrich R, Jolliet O (2013) Dynamics of pesticide uptake into plants: from system functioning to parsimonious modeling. *Environ Model Softw* 40:316–324
- FAOSTAT (2019) FAOSTAT. In: FAOSTAT. <http://www.fao.org/faostat/en/#home>. Accessed 15 Jan 2019
- Feng X, Wang K, Pan L, Xu T, Zhang H, Fantke P (2018) Measured and modeled residue dynamics of famoxadone and oxathiapiprolin in tomato fields. *J Agric Food Chem* 66:8489–8495
- Franke AC, Kempenaar C, Holterman HJ, van de Zande JC (2010) Spray drift from knapsack sprayers, a study conducted within the framework of the Sino-Dutch pesticide environmental risk assessment project PERAP. Wageningen, Plant Research International B.V
- Ganzelmeier H, Rautmann D, Spangenberg R et al (1995) Studies on the spray drift of plant protection products. Federal Biological Research Centre for Agriculture and Forestry, Berlin
- García-Santos G, Feola G, Nuyttens D, Diaz J (2016) Drift from the use of hand-held knapsack pesticide sprayers in Boyacá (Colombian Andes). *J Agric Food Chem* 64:3990–3998
- Gouda AI, Mehoba MHL, Toko II et al (2018) Comparison of drift of two types of sprayers used in cotton production in Benin. *Biotechnol Agron Soc* 22:94–105
- Hauschild MZ (2000) Estimating pesticide emissions for LCA of agricultural products. In: Weidema BP (ed) *Agricultural data for life cycle assessments*. Agricultural Economics Research Institute (LEI), The Hague, pp 64–79
- Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O, Margni M, de Schryver A, Humbert S, Laurent A, Sala S, Pant R (2013) Identifying best existing practice for characterization modeling in life cycle impact assessment. *Int J Life Cycle Assess* 18:683–697
- Henderson AD, Hauschild MZ, van de Meent D, Huijbregts MAJ, Larsen HF, Margni M, McKone TE, Payet J, Rosenbaum RK, Jolliet O (2011) USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *Int J Life Cycle Assess* 16:701–709
- Holterman HJ, van de Zande JC (2003) IMAG Drift Calculator v1.1: user manual. http://www.pesticidemodels.eu/sites/default/files/documents/IDCmanual_0.pdf. Accessed 28 Dec 2018
- Hossain MS, Fakhruddin ANM, Chowdhury MAZ et al (2015) Health risk assessment of selected pesticide residues in locally produced vegetables of Bangladesh. *Int Food Res J* 22:110–115
- Houbraken M, Habimana V, Senaev D, López-Dávila E, Spanoghe P (2017) Multi-residue determination and ecological risk assessment of pesticides in the lakes of Rwanda. *Sci Total Environ* 576:888–894
- Hunt ND, Hill JD, Liebman M (2017) Reducing freshwater toxicity while maintaining weed control, profits, and productivity: effects of increased crop rotation diversity and reduced herbicide usage. *Environ Sci Technol* 51:1707–1717
- Inao K, Iwafune T, Horio T (2018) An improved PADDY model including uptake by rice roots to predict pesticide behavior in paddy fields under nursery-box and submerged applications. *J Pestic Sci* 43:142–152
- Ingwersen WW (2012) Life cycle assessment of fresh pineapple from Costa Rica. *J Clean Prod* 35:152–163
- Itoiz ES, Fantke P, Juraske R, Kounina A, Vallejo AA (2012) Deposition and residues of azoxystrobin and imidacloprid on greenhouse lettuce with implications for human consumption. *Chemosphere* 89:1034–1041
- Jacobsen RE, Fantke P, Trapp S (2015) Analysing half-lives for pesticide dissipation in plants. *SAR QSAR Environ Res* 26:325–342
- Juraske R, Fantke P, Ramírez ACR, González A (2012) Pesticide residue dynamics in passion fruits: comparing field trial and modelling results. *Chemosphere* 89:850–855
- Juraske R, Mutel CL, Stoessel F, Hellweg S (2009) Life cycle human toxicity assessment of pesticides: comparing fruit and vegetable diets in Switzerland and the United States. *Chemosphere* 77:939–945
- Juraske R, Vivas CSM, Velásquez AE et al (2011) Pesticide uptake in potatoes: model and field experiments. *Environ Sci Technol* 45: 651–657
- Kariathi V, Kassim N, Kimanya M (2016) Pesticide exposure from fresh tomatoes and its relationship with pesticide application practices in Meru district. *Cogent Food & Agriculture* 2:1196808. <https://doi.org/10.1080/23311932.2016.1196808>
- Kookana RS (2010) The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review. *Soil Res* 48:627–637
- Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. *Meteorol Z* 15:259–263

- Kwok KW, Leung KM, Lui GS et al (2007) Comparison of tropical and temperate freshwater animal species' acute sensitivities to chemicals: implications for deriving safe extrapolation factors. *Integr Environ Asses* 3:49–67
- Laplace D (2018) L'usage des phytosanitaires dans le bassin amazonien : entre problèmes spécifiques à l'agriculture en zone tropicale et fragilité de l'écosystème. *Innovations Agronomiques*:1–10 <https://doi.org/dx.doi.org/10.15454/1.5407989444908796E12>
- Leboulanger C, Schwartz C, Somville P, Diallo AO, Pagano M (2011) Sensitivity of two mesocyclops (Crustacea, Copepoda, Cyclopidae), from tropical and temperate origins, to the herbicides, Diuron and Paraquat, and the insecticides, Temephos and Fenitrothion. *B Environ Contam Tox* 87:487–493
- Lewis SE, Silburn DM, Kookana RS, Shaw M (2016) Pesticide behavior, fate, and effects in the tropics: an overview of the current state of knowledge. *J Agric Food Chem* 64:3917–3924
- Linders J, Mensink H, Stephenson G et al (2000) Foliar interception and retention values after pesticide application: a proposal for standardised values for environmental risk assessment. *Pest Manag Sci* 58:315–315
- Matthews G, Wiles T, Baleguel P (2003) A survey of pesticide application in Cameroon. *Crop Prot* 22:707–714
- Meier MS, Stoessel F, Jungbluth N, Juraske R, Schader C, Stolze M (2015) Environmental impacts of organic and conventional agricultural products – are the differences captured by life cycle assessment? *J Environ Manag* 149:193–208
- Mendes KF, Hall KE, Takeshita V, Rossi ML, Tornisiello VL (2018) Animal bonechar increases sorption and decreases leaching potential of aminocyclopyrachlor and mesotrione in a tropical soil. *Geoderma* 316:11–18
- Mitoko GJAO (1997) Occupational pesticide exposure among Kenyan agricultural workers : an epidemiological and public health perspective. *Ohayo-Mitoko*
- Montes AM, González-Farias FA, Botello AV (2012) Pollution by organochlorine pesticides in Navachiste-Macapule, Sinaloa, Mexico. *Environ Monit Assess* 184:1359–1369
- Mottes C, Lesueur-Jannoyer M, Le Bail M, Guéné M, Carles C, Malézieux E (2017) Relationships between past and present pesticide applications and pollution at a watershed outlet: the case of a horticultural catchment in Martinique, French West Indies. *Chemosphere* 184:762–773
- Mottes C, Lesueur-Jannoyer M, Le Bail M, Malézieux E (2014) Pesticide transfer models in crop and watershed systems: a review. *Agron Sustain Dev* 34:229–250
- Mutua GK, Ngigi AN, Getenga ZM (2016) Degradation characteristics of metribuzin in soils within the Nzoia River Drainage Basin, Kenya. *Toxicol Environ Chem* 98:800–813
- Nemecek T, Schnetzer J (2011) Methods of assessment of direct field emissions for LCIs of agricultural production systems. Data v3.0. Swiss Center for Life Cycle Inventories, Duebendorf, Switzerland
- Nordborg M, Cederberg C, Berndes G (2014) Modeling potential freshwater ecotoxicity impacts due to pesticide use in biofuel feedstock production: the cases of maize, rapeseed, Salix, soybean, sugar cane, and wheat. *Environ Sci Technol* 48:11379–11388
- Nordborg M, Davis J, Cederberg C, Woodhouse A (2017) Freshwater ecotoxicity impacts from pesticide use in animal and vegetable foods produced in Sweden. *Sci Total Environ* 581–582:448–459
- Notarnicola B, Sala S, Antón A et al (2017) The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. *J Clean Prod* 140:399–409
- Oturan N, Trajkovska S, Oturan MA, Couderchet M, Aaron JJ (2008) Study of the toxicity of diuron and its metabolites formed in aqueous medium during application of the electrochemical advanced oxidation process “electro-Fenton.” *Chemosphere* 73: 1550–1556
- Peña N, Antón A, Kamilaris A, Fantke P (2018) Modeling ecotoxicity impacts in vineyard production: addressing spatial differentiation for copper fungicides. *Sci Total Environ* 616–617:796–804
- Peña N, Knudsen MT, Fantke P, Antón A, Hermansen JE (2019) Freshwater ecotoxicity assessment of pesticide use in crop production: testing the influence of modeling choices. *J Clean Prod* 209: 1332–1341
- Pennington DW, Margni M, Ammann C, Jolliet O (2005) Multimedia fate and human intake modeling: spatial versus nonspatial insights for chemical emissions in Western Europe. *Environ Sci Technol* 39: 1119–1128
- Pereira-Junior EV, Giori FG, Nascimento AL, Tornisiello VL, Regitano JB (2015) Effects of soil attributes and straw accumulation on the sorption of hexazinone and tebutiuron in tropical soils cultivated with sugarcane. *J Environ Sci Health B* 50:238–246
- Peters EC, Gassman NJ, Firman JC, Richmond RH, Power EA (1997) Ecotoxicology of tropical marine ecosystems. *Environ Toxicol Chem* 16:12–40
- Pillai MKK (1986) Pesticide pollution of soil, water and air in Delhi area, India. *Sci Total Environ* 55:321–327. [https://doi.org/10.1016/0048-9697\(86\)90189-0](https://doi.org/10.1016/0048-9697(86)90189-0)
- Pouokam GB, Lemnyuy Album W, Ndikontar AS, Sidatt MEH (2017) A pilot study in Cameroon to understand safe uses of pesticides in agriculture, risk factors for farmers' exposure and management of accidental cases. *Toxics* 5(4):E30. <https://doi.org/10.3390/toxics5040030>
- Racke KD, Skidmore MW, Hamilton DJ, Unsworth JB, Miyamoto J, Cohen SZ (1997) Pesticides report .38. Pesticide fate in tropical soils - (Technical report). *Pure Appl Chem* 69:1349–1371
- Raksanam B, Taneepanichskul S, Siriwong W, Robson MG (2012) Factors associated with pesticide risk behaviors among rice farmers in rural community, Thailand. *J Environ Earth Sci* 2:32–39
- Renaud-Gentié C, Dijkman TJ, Bjørn A, Birkved M (2015) Pesticide emission modelling and freshwater ecotoxicity assessment for grapevine LCA: adaptation of PestLCI 2.0 to viticulture. *Int J Life Cycle Assess* 20:1528–1543
- Rosenbaum RK, Antón A, Bengoa X et al (2015) The Glasgow consensus on the delineation between pesticide emission inventory and impact assessment for LCA. *Int J Life Cycle Assess* 20:765–776
- Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod M, Margni M, McKone TE, Payet J, Schuhmacher M, van de Meent D, Hauschild MZ (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *Int J Life Cycle Assess* 13:532–546
- Rosenbaum RK, Huijbregts MAJ, Henderson AD, Margni M, McKone TE, van de Meent D, Hauschild MZ, Shaked S, Li DS, Gold LS, Jolliet O (2011) USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. *Int J Life Cycle Assess* 16: 710–727
- Ryberg MW, Rosenbaum RK, Mosquero L, Fantke P (2018) Addressing bystander exposure to agricultural pesticides in life cycle impact assessment. *Chemosphere* 197:541–549
- Salomone R, Ioppolo G (2012) Environmental impacts of olive oil production: a Life Cycle Assessment case study in the province of Messina (Sicily). *J Clean Prod* 28:88–100
- Sanchez-Bayo F, Hyne RV (2011) Comparison of environmental risks of pesticides between tropical and nontropical regions. *Integr Environ Assess Manag* 7:577–586
- Sansoulet J, Cabidoche YM, Cattani P (2007) Adsorption and transport of nitrate and potassium in an Andosol under banana (Guadeloupe, French West Indies). *Eur J Soil Biol* 58:478–489
- Settle W, Soumare M, Sarr M et al (2014) Reducing pesticide risks to farming communities: cotton farmer field schools in Mali. *Philos*

- Trans R Soc B Biol Sci 369:20120277. <https://doi.org/10.1098/rstb.2012.0277>
- Snelder DJ, Masipiqueña MD, de Snoo GR (2008) Risk assessment of pesticide usage by smallholder farmers in the Cagayan Valley (Philippines). *Crop Prot* 27:747–762
- Sorensen JPR, Lapworth DJ, Nkhuwa DCW, Stuart ME, Goody DC, Bell RA, Chirwa M, Kabika J, Liemisa M, Chibesa M, Pedley S (2015) Emerging contaminants in urban groundwater sources in Africa. *Water Res* 72:51–63
- Thorbeck P, Forbes EV, Heimbach F et al (2009) Ecological models for regulatory risk assessments of pesticides: developing a strategy for the future. CRC Press
- van Zelm R, Larrey-Lassalle P, Roux P (2014) Bridging the gap between life cycle inventory and impact assessment for toxicological assessments of pesticides used in crop production. *Chemosphere* 100:175–181
- Vázquez-Rowe I, Torres-García JR, Cáceres AL et al (2017) Assessing the magnitude of potential environmental impacts related to water and toxicity in the Peruvian hyper-arid coast: a case study for the cultivation of grapes for pisco production. *Sci Total Environ* 601–602:532–542
- Vázquez-Rowe I, Villanueva-Rey P, Moreira MT, Feijoo G (2012) Environmental analysis of Ribeiro wine from a timeline perspective: harvest year matters when reporting environmental impacts. *J Environ Manag* 98:73–83
- Wannaz C, Fantke P, Lane J, Jolliet O (2018) Source-to-exposure assessment with the Pangea multi-scale framework – case study in Australia. *Environ Sci: Processes Impacts* 20:133–144
- Weinberger K, Lumpkin TA (2007) Diversification into horticulture and poverty reduction: a research agenda. *World Dev* 35:1464–1480
- Westh TB, Hauschild MZ, Birkved M, Jørgensen MS, Rosenbaum RK, Fantke P (2015) The USEtox story: a survey of model developer visions and user requirements. *Int J Life Cycle Assess* 20:299–310
- Williamson S, Ball A, Pretty J (2008) Trends in pesticide use and drivers for safer pest management in four African countries. *Crop Prot* 27:1327–1334
- Xue X, Hawkins TR, Ingwersen WW, Smith RL (2015) Demonstrating an approach for including pesticide use in life-cycle assessment: estimating human and ecosystem toxicity of pesticide use in Midwest corn farming. *Int J Life Cycle Assess* 20:1117–1126

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