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SPRINT
SUSTAINABLE PLANT PROTECTION TRANSITION

Report on environmental and economic sustainability of pesticide use regimes

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1 Introduction

The SPRINT-project aims to develop a Global Health Risk Assessment Toolbox to assess impacts of Plant Protection Products (PPPs) on environment and human health and to propose several transition pathways, largely based on information collected from a set of selected case study sites. This includes questionnaires for the farmers of these case study sites, where information on, for example, pesticide application is collected, but also general information on crops grown and farming system. This furthermore includes samples taken at the case study sites to measure pesticide concentrations in the environment and specific human and ecological receptors, such as residents and pollinating insects at and around the case study sites.

Many of the data, methods and tools that are developed in the SPRINT project for the specific case study sites directly feed into current assessments of risks associated with different types of chemical pest control agents, such as measured concentrations in indoor environments of residential bystanders to agricultural fields in Europe. With that, the SPRINT project will make an international contribution to assess integrated risks and impacts of pesticides on human and environmental health, both at regional and European level, as well as inform and accelerate the adoption of innovative transition pathways towards more sustainable plant protection in the context of a global health approach.

However, to enable a global transition away from chemical pesticides that pose a direct risk on local environments and citizens, including workers and residential bystanders, it is important to consider the wider life cycle sustainability impacts of pest control in a holistic and systems approach. This means that there are environmental and human health impacts associated with pest control that go beyond the direct impacts and risks of field-applied pesticide active ingredients (hereafter referred to as "pesticides" for simplicity). These impacts should be comprehensively considered and assessed in order to identify relevant main contributors to overall pest control impacts, and possible trade-offs between different pest control options (e.g. reduced ecotoxicity from avoiding chemical pesticides versus higher greenhouse gas emissions from increased mechanical pest control).

Life cycle sustainability impacts include impacts associated with a wide range of stressors emitted into the environment as well as resources used along the life cycle of a specific pest control option, from resource extraction, manufacturing, use (i.e. application on a given field) and end-of-life (e.g. waste management). A simplified, illustrative example life cycle of a chemical pesticide is provided in Figure 1, showing that environmental impacts associated with pesticides are not restricted to direct impacts on humans and ecosystems related to the field application but also include upstream and downstream processes of the pesticide in its given agricultural application context.

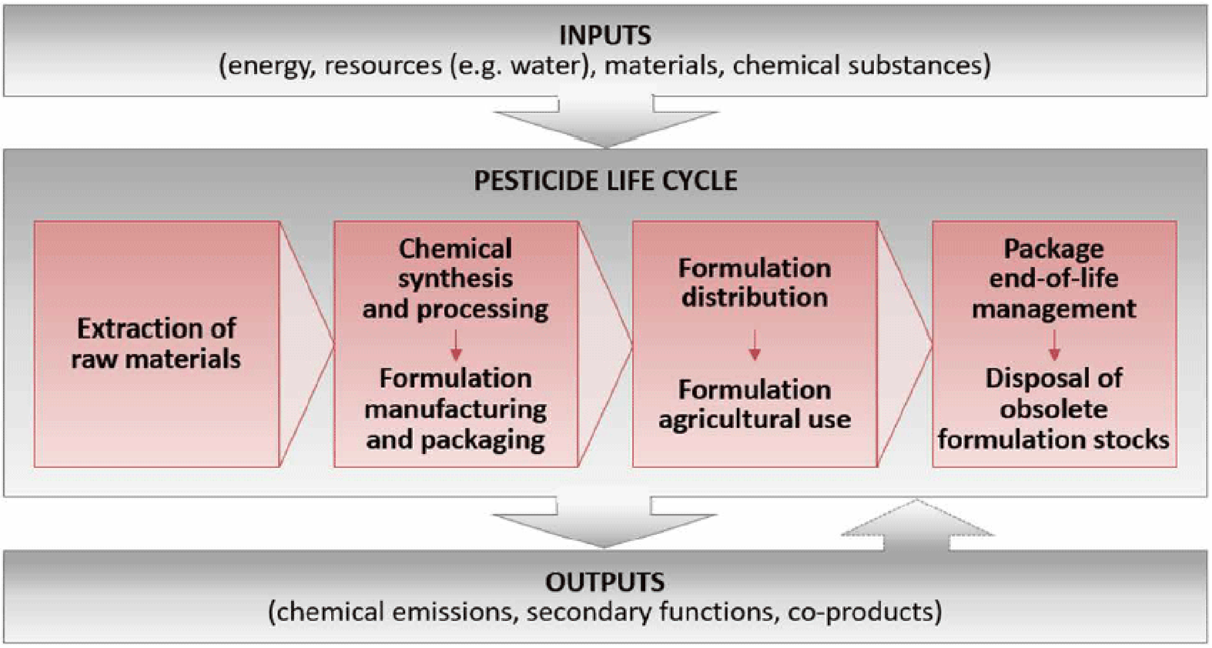


Figure 1. Generic life cycle stages of a pesticide used as an active ingredient in a plant protection formulation that is applied to agricultural crops with inputs from the environment and outputs back into the environment. "Inputs" in this figure are all environmental resources required to produce, use, and end-of-life treat the pesticide (i.e. inputs into the technological pesticide system), and "Outputs" in this figure are flows from the technological system back to the environment (i.e. chemical and other emissions). Together, inputs and outputs constitute inventory flows connecting the technological system to the environment. These inventory flows of a technological system are considered to lead to impacts on the different environmental areas of protection, including human health, ecosystem quality, and natural resources. Secondary functions (e.g. combined heat and electricity generation) and co-products (e.g. sugar and molasses from sugar cane production) are not relevant for the present report. Source: Fantke (2019).

Impacts associated with emissions and resource uses along the life cycle of a pest control system concern a wide range of impact categories. This includes, for example, greenhouse gases and air pollutant emissions from energy consumption during manufacturing processes of chemical pesticides that lead to climate change impacts. This includes, as another example, material resources extracted for building agricultural machinery required in the application process of pesticides on agricultural fields that lead to impacts on mineral resource dissipation. This furthermore includes, as an additional example, toxic chemicals emitted from chemical synthesis processes of pesticides into different environmental media that contribute to human toxicity and ecotoxicity impacts. Environmental sustainability impacts concern a multitude of other impact categories, including ozone depletion, acidification, ionizing radiation, eutrophication, land and water use impacts, and others (see e.g. Hauschild & Huijbregts 2015).

When assessing such life cycle impacts associated with pest control, certain boundary conditions have to be fulfilled (Fantke et al. 2018a). This includes allowing the comparison of different life cycles, such as the application of chemical pesticides in conventional farming versus the use of alternative pest control options in organic farming. Such comparison requires taking a producer or emitter perspective as compared to taking a receptor perspective in risk assessment, where for example a specific human (e.g. worker) or ecological receptor (e.g. a pollinating beehive) is considered. This further includes the consideration of all relevant impact categories concerning the protection of human health, ecosystem quality and natural resources, to allow for a comprehensive picture of environmental life cycle impacts of distinct pest control systems. Furthermore, this includes to assess impacts of different system on a consistent functional basis, such as the production of a certain mass of harvested crop of certain (nutritional or otherwise defined) quality. Finally, this includes to quantitatively linking an emission or resource use flow (i.e. inventory flow) to a certain impact category belonging to a certain area of protection (e.g. climate change impacts contributing to damages on human health and ecosystem quality).

Such quantitative links between emission and resource use flows and related impacts ultimately need to be modelled in a way that allows for aggregating impacts from different impact categories (e.g. climate change impacts, human toxicity impacts) of a given area of protection (e.g. human health) on a consistent unit basis (e.g. disability-adjusted life years, DALY, expressing population-level human lifetime loss). This is essential to understand overall magnitudes of environmental impacts of one pest control system versus another one, in terms of the three different areas of protection that are currently considered in environmental sustainability assessments, namely human health, ecosystem quality, and natural resources.

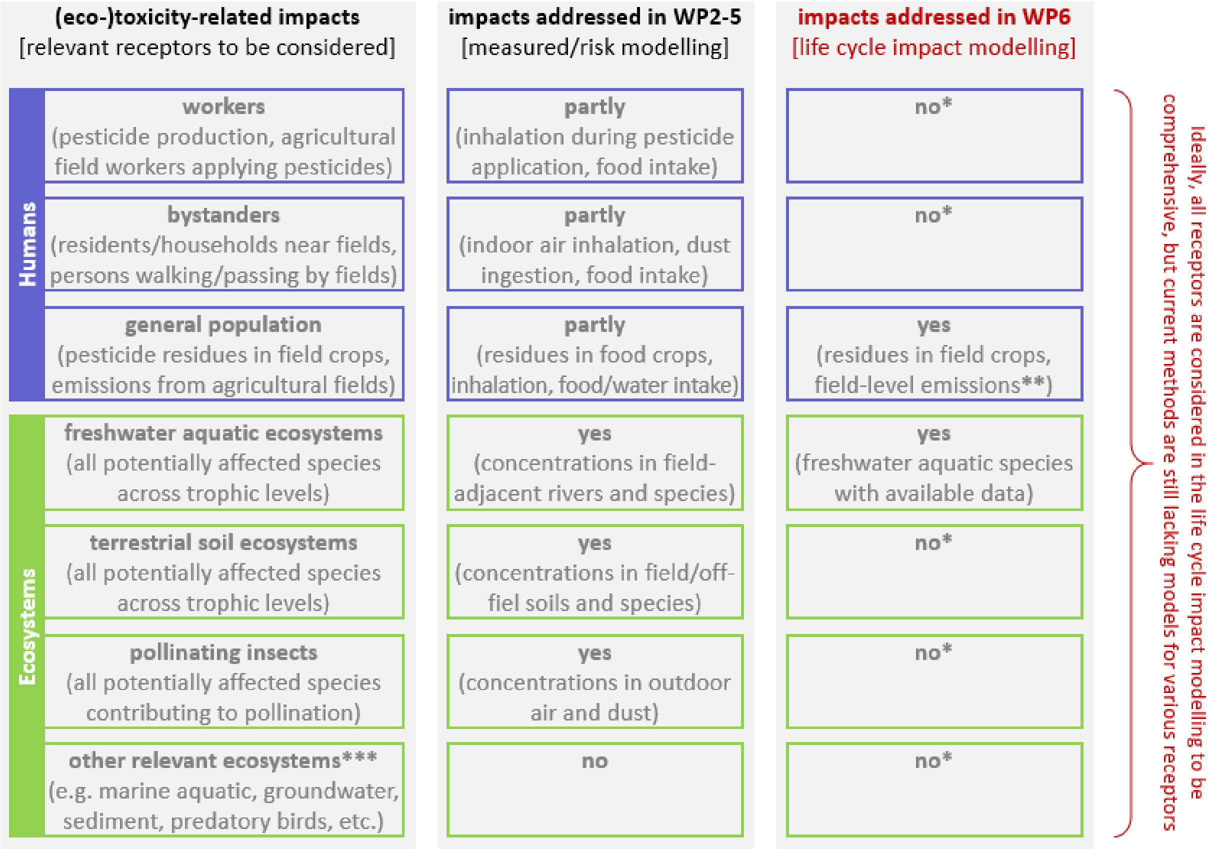
Assessing the wider life cycle impacts of pest control options for the different considered case study sites in the SPRINT project is the focus of the project's work package 6 (WP6), as compared to focusing on individual impact components from a risk and receptor perspective, which is the focus in SPRINT work packages (WP2-5). The present deliverable D6.1 "Report on environmental and economic sustainability of pesticide use regimes" constitutes the first output of WP6 and focuses primarily on the quantification of environmental sustainability impacts of different pest control options across considered SPRINT case study sites in a full life cycle perspective. Considering the above-mentioned boundary conditions that enable a comparison of different pest control options along their entire life cycle from a producer/emitter perspective, environmental life cycle assessment (LCA) is the overall methodological framework applied in WP6 for assessing environmental impacts (e.g. Hauschild 2005).

LCA is an ISO-standardized method to quantify and compare environmental impacts of different products and systems in a full life cycle perspective (ISO International Organization for Standardization 2006b, a). LCA has been applied to a wide range of product, product system, technology and service life cycles (Hellweg & Milà i Canals 2014), and is also applicable to evaluate the environmental performance of different agricultural production systems, including pest control practices (Nemecek et al. 2016, Weidema 2019). In recent years, LCA has been applied for both, assessing the environmental impacts of pesticide field applications (e.g. Peña et al. 2018, Gentil et al. 2020a) as well as assessing the whole supply chain of inputs involved in pest control of different conventional, integrated pest management (IPM), and organic farming systems (e.g. Cellura et al. 2012, Longo et al. 2017). Furthermore, LCA results have also been combined with simplified monetary valuation approaches to derive external cost estimates, which is costs associated with certain considered environmental impacts related to pest control practices (e.g. Steingrimsdottir et al. 2018, Mankong et al. 2022). With that, LCA is generally applicable to evaluate the environmental impact performance of pest control options along their life cycle and is hence applied in the present deliverable as main methodological approach followed for assessing environmental impacts.

LCA consists of four main phases. The first phase is to define the goal and scope of a study. The second phase is to quantify the emission and resource use flows of the assessed technological system as part of the life cycle inventory analysis (LCI). The third phase is to characterize these emission and resource use flows in terms of their impact on human health, ecosystem quality and natural resources in the life cycle impact assessment (LCIA). The fourth phase is the interpretation of results for one or more assessed technological systems. For details about the different LCA phases see e.g. Hauschild et al. (2018).

Given the broad scope of LCA (e.g. considering international or even global life cycles and supply chains as well as a wide range of environmental impact categories in the LCIA phase), LCA is generally much less detailed as compared to, for example, local and receptor-focused risk assessment approaches (Olsen et al. 2001, Bare 2006). Furthermore, LCA by definition aims to be comprehensive in considering all potentially relevant emissions and resource use flows and related impacts on human health, ecosystem quality and natural resources, in order to avoid overlooking relevant trade-offs and impact contributors. However, current widely adopted LCIA methods are still missing impact aspects that are relevant for pest control. This includes currently missing operational methods for assessing impacts of agricultural field workers, bystanders and residential households near agricultural fields, as well as impacts on terrestrial soil ecosystems, pollinating insects, marine aquatic ecosystems and other potentially relevant organisms and ecosystems. Detailed discussions of the methodological advancements for these aspects can be found elsewhere (Crenna et al. 2017, Fantke et al. 2018a, Fantke et al. 2018b, Ryberg et al. 2018, Fantke 2019, Crenna et al. 2020, Nemecek et al. 2022, Owsianiak et al. 2023).

An overview of relevant aspects related to evaluating direct human toxicity and ecotoxicity impacts associated with pesticides applied in agricultural fields is provided in Figure 2, including where appropriate and operational LCIA methods are currently missing and, hence, preventing us from providing a comprehensive environmental impact performance picture of assessed pest control options. This *indicates that the environmental* *sustainability impacts quantified in the present deliverable for the SPRINT case study sites are currently largely underestimated*.



	(eco-)toxicity-related impacts [relevant receptors to be considered]	**impacts addressed in WP2-5** [measured/risk modelling]	**impacts addressed in WP6** [life cycle impact modelling]
Humans	**workers** (pesticide production, agricultural field workers applying pesticides)	**partly** (inhalation during pesticide application, food intake)	**no***
	bystanders (residents/households near fields, persons walking/passing by fields)	**partly** (indoor air inhalation, dust ingestion, food intake)	**no***
	general population (pesticide residues in field crops, emissions from agricultural fields)	**partly** (residues in food crops, inhalation, food/water intake)	**yes** (residues in field crops, field-level emissions**)
Ecosystems	**freshwater aquatic ecosystems** (all potentially affected species across trophic levels)	**yes** (concentrations in field-adjacent rivers and species)	**yes** (freshwater aquatic species with available data)
	terrestrial soil ecosystems (all potentially affected species across trophic levels)	**yes** (concentrations in field/off-fiel soils and species)	**no***
	pollinating insects (all potentially affected species contributing to pollination)	**yes** (concentrations in outdoor air and dust)	**no***
	other relevant ecosystems*** (e.g. marine aquatic, groundwater, sediment, predatory birds, etc.)	**no**	**no***

Ideally, all receptors are considered in the life cycle impact modelling to be comprehensive, but current methods are still lacking models for various receptors

Figure 2. Receptors relevant for human toxicity and ecotoxicity impacts associated with agricultural pest control (left side), and whether they are considered in the SPRINT project work package 6 (WP6, right side) for quantifying environmental sustainability impacts based on the life cycle impact assessment (LCIA) methodology. For comparison, aspects covered in other SPRINT WPs are shown for comparison (middle), illustrating that various receptors are currently missing in LCIA that are relevant for comprehensively evaluating the environmental impact performance of different pest control. *Receptors currently not included in our assessment of environmental sustainability impacts of pest control due to methodological limitations in widely adopted LCIA methods. **Emissions to air, field crops (and related exposure to pesticide residues in harvested crops), field soil and off-field surfaces (and related transport to adjacent freshwater ecosystems) are considered. For further details about the assessment methods applied in the present deliverable, see Chapter 2. ***These receptors are considered less relevant for the SPRINT project.

Despite the methodological limitations of current LCIA methods, it is crucial to understand the wider farm-level life cycle impacts of different pest control options with respect to environmental sustainability. Initial attempts exist to assess environmental sustainability impacts at farm level (Gentil et al. 2020a, Mathis et al. 2022). However, a systematic comparison of the environmental impact performance of different pest control options based on actual farm-level data, putting a special emphasis on direct impacts of field-applied pesticides, is currently still missing. Hence, such a novel approach is being presented in the current deliverable as part of the work conducted in the SPRINT WP6.

The main goal of the present deliverable is to *evaluate farm-level environmental sustainability impacts of pest control practices in Europe*, based on coupling data collected from 169 SPRINT case study site farms across 10 European countries with widely adopted LCIA methods for characterizing environmental impacts. Outcome of this works is to provide initial recommendations for improving pest control at farm level from the perspective of environmental impact performance.

2 Methods

2.1 Overall followed approach

To evaluate farm-level environmental sustainability impacts of pest control practices across SPRINT case study sites, we followed the general LCA framework according to ISO 14040 and 14044 (ISO International Organization for Standardization 2006b, a), in line with the boundary conditions for comparing different practices on a functional basis. As widely adopted LCA software, in which all life cycle processes related to the technological pest control systems are implemented (such as resource use flows), we used SimaPro, version 9.4.0.2 (https://simapro.com, Goedkoop et al. 2016).

Two different yet consistent approaches for assessing environmental life cycle sustainability impacts were applied in the present deliverable to capture different aspects of the pest control options of the considered SPRINT case study site farms:

(1) *Farm-level emissions of chemical pesticides*: Since the SPRINT project focuses on a more sustainable pest control, a specific emphasis is put in the present deliverable on the evaluation of human toxicity and ecotoxicity impacts of pesticide emissions associated with farm-level pesticide use at SPRINT case study sites. For this pest control aspect, we applied the pesticide emission model PestLCI Consensus (https://pestlciweb.man.dtu.dk, Dijkman et al. 2012, Nemecek et al. 2022). This emission model was on the one hand coupled with the global scientific consensus model USEtox (https://usetox.org, Rosenbaum et al. 2008, Fantke et al. 2021, Owsianiak et al. 2023) for characterizing emission-related impacts on humans and freshwater ecosystems. Emissions from the emission model to air, field soil and field crop were on the other hand coupled with the dynamic plant-uptake model dynamiCROP (https://dynamicrop.org, Fantke et al. 2011b, Fantke & Jolliet 2016) for characterizing pesticide residues in crops-related impacts on humans. Details about the considered scenarios and pesticide application information are found in Section 2.2. Details about the applied models, input data used and pathways and effects considered are found in Section 2.3.

(2) *Life cycle emissions and resource uses associated with farm-level pest control*: Environmental impacts of pest control also include other aspects than direct pesticide field emissions. This includes agricultural machinery required to apply pesticides (e.g. related diesel fuel consumption and tire abrasion), and manufacturing and related market activities (e.g. transportation of packaged pesticide-related plant protection products) of chemical active ingredients. Environmental impacts associated with emissions and resource uses of life cycle aspects of pest control are assessed by applying the globally applicable state-of-the-art LCIA method ImpactWorld+ that considers a consistent set of impact categories (https://www.impactworldplus.org, Bulle et al. 2019). This LCIA method is implemented in the used LCA software SimaPro. Details about the considered scenarios and pesticide application information are found in Section 2.2. Details about the applied LCIA method, input data used and pathways and effects considered are found in Section 2.4.

Mass emitted (output of emission and resource flow inventory analysis phase) can be combined with impact characterization factors per inventory flow and impact category, such as climate change or human toxicity (output of impact assessment phase), to derive an impact score expressed in impact per functional unit (see Section 2.2). Impact scores can be aggregated across inventory flows per pest control system to yield an overall *impact score per system, which is the main output of LCA* to compare environmental impacts of different product or technology life cycles. In the present deliverable, we aim at enabling to use environmental impact results in combination with economic impact estimates (e.g. farmer costs for pest control). For that, impact scores across inventory flows per area of protection (i.e. human health, ecosystem quality, natural resources) may first be combined with monetary values to arrive at damage costs or external costs (i.e. costs associated with environmental impacts that are not included in market prices of agricultural production, i.e. costs that are "external" to the product market). The set of governing equations for deriving environmental impacts for pest control options across SPRINT case study sites based on emissions and related environmental impacts across considered impact categories is provided in Table 1.

Table 1. Governing equations for calculating environmental life cycle impacts of pest control options across considered SPRINT case study site farms in the present deliverable. The equations are consistent with widely used LCA approaches to quantify environmental impacts of products and technologies across relevant impact categories and life cycle stages. Note that monetary valuation is not a part of classical LCA, but can be coupled with LCA outputs to derive damage or external cost estimates where needed, yet in a very much simplified way by using, for example, generic valuation factors for human health (see e.g. Pizzol et al. 2015).

Equation	Description	Remarks
$m_{\mathrm{emi},c} = m_{\mathrm{appl}} \times f_c$	For field-applied pesticides, the product of pesticide mass applied, m_{appl} [kg applied/ha] and emission fraction to a given compartment	Output of life cycle

Equation	Description	Remarks
	c (air, field crop, field soil, off-field surface), f_c [kg emitted/kg applied] yield emitted mass to that compartment, $m_{\text{emi},c}$ [kg emitted/ha]. For other emission and resource flows, mass emitted or resource used is provided by LCI databases.	inventory (LCI) analysis
$CF_c^I = FF_c \times XF \times DRF \times SF$	Impact characterization factors for impact category I (e.g. climate change, human toxicity) and emission compartment c, CF_c^I [damage/kg emitted] are the product of factors for environmental fate, FF_c [time-integrated kg in environment/kg emitted], human or ecosystem exposure, XF [kg exposure/kg in environment], dose-response for the relevant effects, DRF [impact/kg exposure], and effect severity on human lifetime or species loss, SF [damage/impact]. For impacts on natural resources, characterization factors are typically a product of resource extracted and resource stock available.	Output of life cycle impact assessment (LCIA)
$IS^I = m_{\text{emi},c} \times \sum_c CF_c^I$	For a given inventory flow (e.g. specific field-applied pesticide), the product of emission mass, $m_{\text{emi},c}$ [kg emitted/ha] and respective characterization factor, CF_c^I [damage/kg emitted], summed over all emission compartments c for that inventory flow yield an impact score for a given impact category I that the inventory flow belongs to (e.g. human toxicity or ecotoxicity for field-applied pesticides), IS^I [damage/ha].	Combined LCI and LCIA outputs per inventory flow
$IS^{AoP} = \sum_I IS^I$	For a specific area of protection AoP (i.e. human health, ecosystem quality, natural resources), related impact scores, IS^{AoP} [damage/ha] are derived by aggregating impact scores across all inventory flows and impact categories (e.g. climate change, human toxicity) that contribute to this area of protection, IS^I [damage/ha]. With that, we derive impact scores for three areas of protection, with units of damage expressed as population-level disability-adjusted life years (DALY) lost for human health, potentially disappeared fraction of species (PDF) over a given area and year for ecosystem quality, and MJ as energy-related unit for natural resources.	Aggregating impacts at the level of areas of protection, main output of LCA
$DC^{AoP} = IS^{AoP} \times DF^{AoP}$	When LCA results are to be combined with economic sustainability aspects, impact scores per area of protection, IS^{AoP} [damage/ha] can be combined with monetary valuation factors, DF^{AoP} [costs/damage] to derive damage costs (or external costs), DC^{AoP} [costs/ha]. As generic monetary valuation factors for the three areas of protection, we used 74,000 Euro/DALY for human health damage expressed in DALY, 0.14 Euro/PDF-m²-year for ecosystem quality damage expressed in PDF-m²-years, and 0.0043 Euro/MJ for natural resource damage expressed in MJ. With these generic factors, the loss of 1 DALY would correspond to the loss of ~530,000 PDF-m²-years. The generic monetary valuation factors were derived from Jolliet et al. (2016).	Monetary valuation of impacts per area of protection

2.2 Pest control scenarios and emission/resource use inventory

The goal for the environmental sustainability assessment in the present deliverable was defined as determining the environmental impact profile of different pest control scenarios across various case study cite farms in 10 European countries. Environmental sustainability impact results were compared across scenarios on a functional basis of *one ha of farm area that is used for agricultural crop production*. The life cycle of all inputs (i.e. inputs related to the supply chain and on-farm use of agricultural pesticides) relevant in the considered pest control practices was considered, and related emission and resource use flows were quantified as well as related impacts on human health, ecosystem quality and natural resources were characterized.

Pest control systems considered in the present deliverable were classified according to three main farming system categories: conventional farming, integrated pest management (IPM), and organic farming. In conventional farming systems, chemical pesticides are widely used to increase crop yield, but with potential negative effects of these pesticides on humans and ecosystems via toxicity-related effects associated with the direct application of the chemical pesticides at farm level. IPM systems focus on optimizing the use of chemical pesticides to achieve sustainability in production (Nemecek et al. 2011). As an example, the use of herbicides has been substantially decreased in IPM systems as compared to conventional farming systems, and substituted by, for example, mechanical weeding methods. In IPM systems, sulfur-based fungicides are dominant as compared to a wide range of organic pesticides applied in conventional farming. Reduced toxicity-related impacts of sulfur-based pesticides (as compared to the wider range of organic pesticides applied in conventional farming) might come, however, at the expense of higher energy consumption (and related impacts on e.g. climate change) for mechanical weeding—one of several possible tradeoffs that can be suitably evaluated using LCA as applied in the present deliverable.

Organic farming systems are characterized by using pest control options other than applying organic pesticides, but instead use a wide range of biological pesticides and to some extent also inorganic pesticides, such as copper-based fungicides. Based on the obtained data from different SPRINT case study sites, copper-based fungicides are the predominating pesticides used in several organic farming systems, especially in French and Portuguese vineyards, while *Bacillus*-based biological insecticides and fungicides are predominantly used in organic farming systems on vegetable crops in Spain and Italy. Pest control processes in organic farming systems can cause lower toxicity-related impacts as compared to organic pesticide use in conventional farming. However, organic farming can on the one hand results in reduced crop yields and hence a higher demand for crop land for some crop types (e.g. Ponisio et al. 2015) while on the other hand can also have substantial toxicity-related impacts where copper-based fungicides are extensively used (e.g. Peña & Antón 2017). These and potential other tradeoffs (i.e. reduced toxicity from organic pesticides versus increased land use impacts and high toxicity from copper-based fungicides) can again be suitably evaluated using LCA as applied in the present deliverable.

In the present deliverable, 169 farms associated with SPRINT case study sites in 10 European countries were considered, including farms in Spain, Portugal, France, Switzerland, Italy, Croatia, Slovenia, Czech Republic, The Netherlands, and Denmark. An overview of case study cites, as well as related pest control systems, pesticide applications and treated crops per case study site are provided in Table 2.

Table 2. General information on pest control systems, pesticide applications and crops treated at the different SPRINT case study sites considered in the present deliverable. Data

related to pest control system, crops, and pesticides used, including machinery information related to pest control operations at case study site farms were directly collected from farmers via questionnaires within the SPRINT project. IPM: Integrated pest management.

Case study site	Pest control system count			Pesticide application count per case study site			Treated crops at the different case study sites
	Conventional	IPM	Organic*	Herbicide	Fungicide	Insecticide	
Spain	10	-	7	3	31	91	Broccoli
Portugal	-	10	8	8	325	15	Vineyard
France	5	-	9	2	501	13	Vineyard
Switzerland	6	5	8	5	234	32	Apple, Cherry, Pear, Plum, Strawberry
Italy	-	8	10	7	14	35	Broccoli, Cabbage, Cauliflower, Lettuce, Pepper, Radish
Croatia	6	5	8	2	38	36	Olive
Slovenia	12	-	12	38	-	-	Maize, Winter Barley
Czech Republic	11	-	6	30	22	15	Oilseed rape, Poppy, Sunflower
Netherlands	5	3	6	27	86	59	Potato
Denmark	10	-	10	27	14	-	Barley, Oats, Rye

*Some farms are stated to be "in transition to organic farming"

All data around pest control in these farms, such as the specification of farming system, type, magnitude and date of applied pesticides, biological agents, and machinery used for pest control operations were collected through designed questionnaires within the SPRINT project. The related data collection protocol is described in Silva et al. (2021), and a related structured database containing all the farm-level data of the considered SPRINT case study sites is available via the SPRINT project repository (https://sprint-h2020.eu).

Based on the collected data, 125 pesticides were used across SPRINT case study sites applying different pest control systems. The highest number of pesticide applications is found in France ($n = 501$), followed by Portugal ($n = 325$) and Switzerland ($n = 234$). Note that the selected case study sites are not necessarily a representation of average pest-control practices in the related countries or for the considered crop, nor are the pesticides applied, be it chemical or biological pesticides. However, the considered selection of SPRINT case study sites still allows for comparing pest control practices across related specific farms for the year 2022. Results from the questionnaires are used to derive input data for the toxicity-related LCIA environmental impact characterization of field-applied pesticides as detailed in Section 2.3.

While pesticide application data along with selected information on the use of machinery for pest control operation on the farms were provided directly as primary data by the relevant farmers (so-called "foreground system information"), supply chain data were not collected via farmer questionnaires. Instead, data related to the supply chain of the applied pesticides as well as related to the machinery related to pest control operation were collected from the most widely used life cycle inventory (LCI) database ecoinvent, version 3 (https://www.ecoinvent.org, Wernet et al. 2016). For illustration purposes, an excerpt of the emission-related inventory data for the example process of diesel consumption of agricultural machinery for applying pesticides at case study sites are presented in Table 3. Results from the background data collection in LCI databases are used to derive input data for the LCIA environmental impact characterization across the various relevant impact categories of pest control life cycle related processes as detailed in Section 2.4.

Table 3. Selected life cycle emission inventory data (i.e. emissions of greenhouse gases, air pollutants, and other chemicals from industrial processes, not from pesticides applied to agricultural fields) for processes related to the production of 1 kg diesel consumed by agricultural machinery involved in pest control operations as illustrative process of LCI data for the background system in the present deliverable.

Crop protection process	Substance name emitted to rural air	kg emitted
Diesel consumption of agricultural machinery used in farm-level pest control operations (e.g. pesticide application, mechanical weeding)	Ammonia	2.0×10^{-5}
	Benzene	7.3×10^{-6}
	Benzo(a)pyrene	3.0×10^{-8}
	Cadmium	1.0×10^{-8}
	Carbon dioxide, fossil	3.1
	Particulates, ≤2.5 µm	2.6×10^{-3}

2.3 Toxicity impacts of farm-level emissions of chemical pesticides

Chemical pesticides, including organic and copper-based chemical compounds, are associated with human toxicity and ecotoxicity impacts in LCIA. For characterizing environmental emissions at field-level and related human toxicity and ecotoxicity impacts of chemical pesticides applied at farms of considered SPRINT case study sites, we applied a set of models that are consistently coupled at the emission level. This means we have coupled a model linking applied mass to emissions into different environmental compartments, which match the emission input compartments of the related fate models on the impact assessment side. A general scheme of the model suite applied in the present deliverable for evaluating the toxicity-related impacts of farm-level applied pesticides is provided in Figure 3.

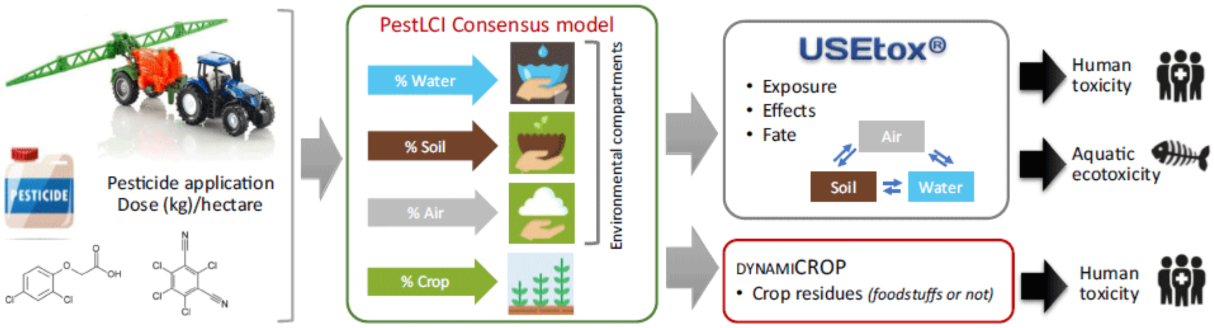


Figure 3. Conceptual illustration of how direct impacts of chemical pesticides on humans and ecosystems are assessed in the current deliverable for SPRINT case study sites, based on state-of-the-art LCIA emission and impact modelling approaches. Information on pesticide application at farm-level (left-side part) is based on SPRINT farmer surveys. Pesticide field emissions are estimated using the PestLCI Consensus model (middle part) that derives initial emission distribution fractions to air, field-soil, field-crop and off-field surfaces (Dijkman et al. 2012, Nemecek et al. 2022). Human toxicity and freshwater ecotoxicity impacts related to pesticide emissions from field applications are estimated using the USEtox model (upper right-side part), based on environmental fate, exposure and effect assessment for chemical emissions (Rosenbaum et al. 2008, Fantke et al. 2021, Owsianiak et al. 2023). Human toxicity impacts related to pesticide residues in harvested field crops are estimated using the dynamiCROP model (lower right-side part), based on plant uptake, human intake and effect assessment (Fantke et al. 2011b, Fantke & Jolliet 2016). Source: adapted from Nemecek et al. (2022).

For linking applied pesticide mass to environmental emissions, we applied the pesticide emission model PestLCI Consensus, version 1.0 (https://pestlciweb.man.dtu.dk, Dijkman et al. 2012, Nemecek et al. 2022). The spatial unit of this model is a single field. Processes considered in this emission model are air emissions (generic emission fractions), drift deposition to off-field surfaces (using drift functions), and partitioning between field crop and field soil surfaces (using crop-specific interception fractions derived from crop growth information and crop type). Input data of this emission model are the application method and crop (to determine the relevant drift deposition function), and the crop growth stage derived from the pesticide application time relative to crop plantation (relevant for the fraction of pesticide intercepted by the treated crop on the field versus the fraction reaching the field soil). The time frame for these processes is set to be within several minutes after pesticide application, which is why other processes have been assumed not to be relevant during this short time (e.g. degradation, runoff, leaching) but are handled in the subsequent environmental fate model as part of the impact assessment. Emission model output are a set of emission fractions (kg emitted into a specific compartment per kg applied of a certain pesticide in a given scenario). Details of the different emission fractions can be found elsewhere (Dijkman et al. 2012, Gentil-Sergent et al. 2021).

To characterize impacts on humans and freshwater ecosystems associated with emissions into environmental compartments other than field crops, emission model results were coupled with the global scientific consensus model USEtox, version 2.12 (https://usetox.org, Rosenbaum et al. 2008, Fantke et al. 2021, Owsianiak et al. 2023). USEtox is a nested model (i.e. not a spatialized model) where a generic urban environment is nested within a continent that is itself nested within a generic global environment. While the generic urban environment consist only of an outdoor air compartment, the continental and global environments each consist of an agricultural soil, a natural soil, a freshwater and a marine water compartment, of which only the continental-level compartments are used as emission compartments (to receive the output from the emission model). USEtox is a steady-state model, which means it builds, for example, on time-integrated mass of a pesticide in the environment per unit mass of the pesticide emitted to a given compartment. Environmental fate processes considered in USEtox include phase partitioning (e.g. between air and water), degradation (based on half-lives), intermedia transport processes, such as diffusion (e.g. volatilization) and advection (e.g. water flow) and other processes, such as run-off, leaching, sedimentation, resuspension, and deposition. All processes are modelled at the level of average conditions per continental and global level compartment, which introduces simplifying assumptions for processes that are strongly varying among sites with different environmental conditions.

Input data of USEtox are chemical physicochemical properties (molecular weight, partition coefficients, dissociation constants, environmental half-lives, and bioaccumulation factors) to derive environmental fate and human/ecological exposure factors, as well as human toxicity and ecotoxicity test data to derive related effect factors. Details about the environmental fate and exposure processes considered in USEtox along with related input data requirements are found elsewhere (Rosenbaum et al. 2008, Henderson et al. 2011, Fantke et al. 2017). Output of USEtox are a set of factors describing environmental fate, human and ecological exposure, and human toxicity and ecotoxicity effects, and combining these into impact characterization factors for human health and ecosystem quality via toxicity effects. The impact pathways included in USEtox for assessing ecotoxicity impacts and human toxicity impacts are respectively illustrated in Figure 4 and Figure 5.

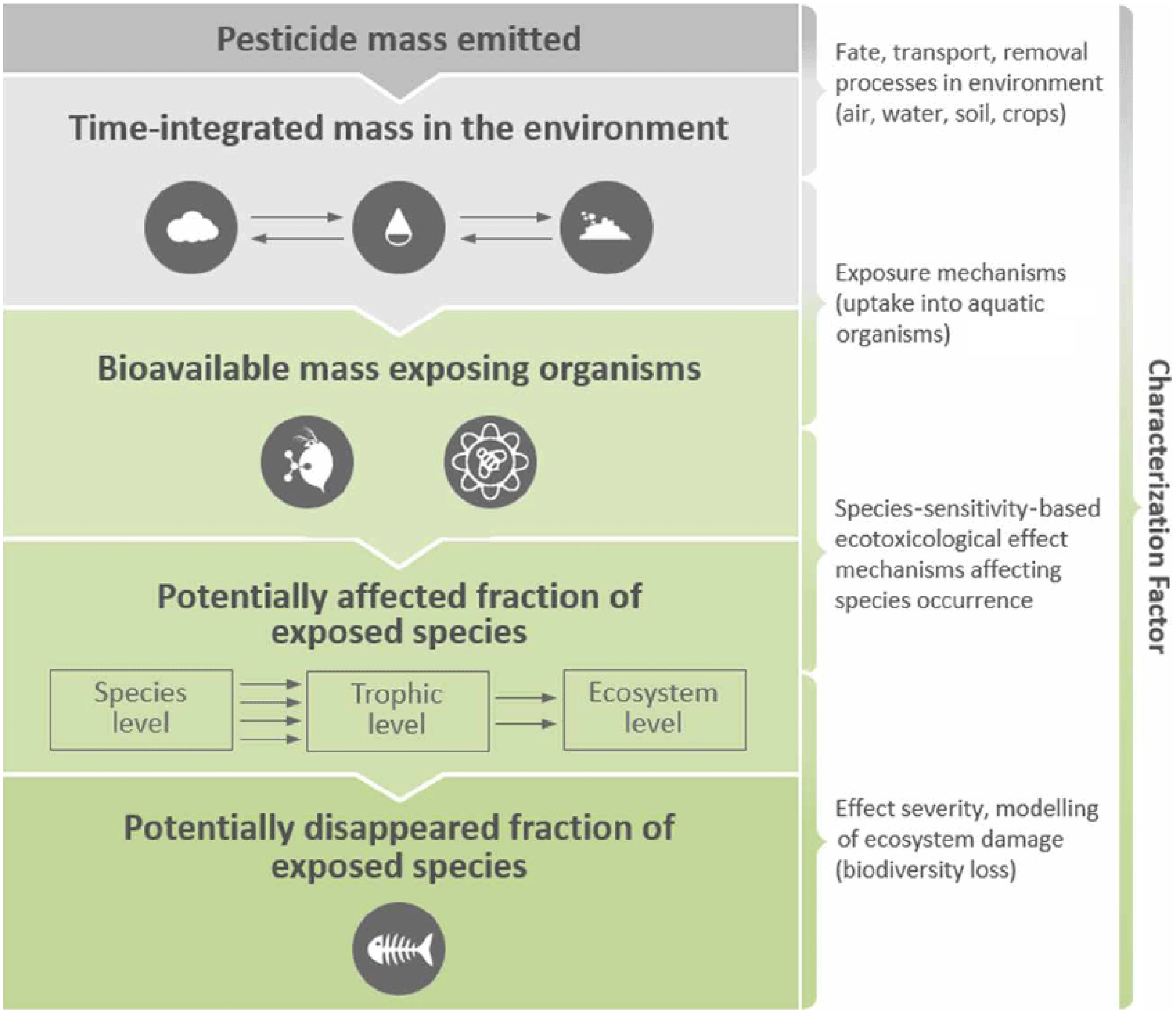


Figure 4. Conceptual representation of how ecotoxicity impacts are assessed in the present deliverable for direct pesticide field emissions, based on the state-of-the-art LCIA model USEtox (Rosenbaum et al. 2008, Owsianiak et al. 2023). Note that only ecotoxicity impacts of freshwater ecosystems are considered as characterization methods for other ecosystems (e.g. soil terrestrial ecotoxicity, ecotoxicity of pollinating insects) that are likely more relevant for agricultural pesticide applications are currently not considered mature enough for inclusion into USEtox. Field emissions are linked to emission compartments relevant for freshwater ecotoxicity assessment in USEtox based on the approach described in Nemecek et al. (2022) (see also Figure 3). Source: adapted from Fantke et al. (2018a).

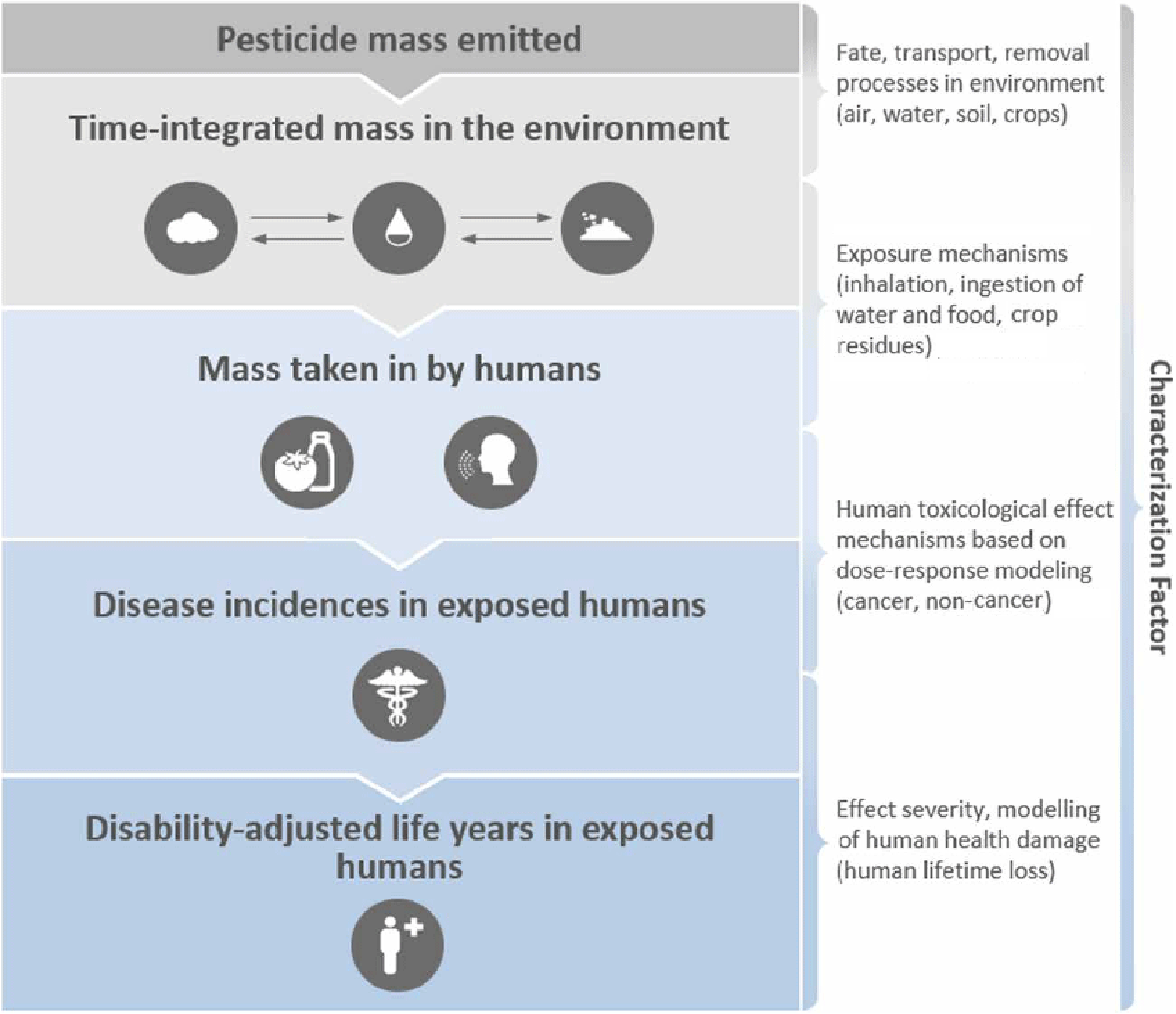


Figure 5. Conceptual representation of how human toxicity impacts are assessed in the present deliverable for direct pesticide field emissions, based on the state-of-the-art LCIA model USEtox (Rosenbaum et al. 2008, Fantke et al. 2021). Note that only generic cancer and non-cancer effects are considered as characterization methods for other or more specific health endpoints (e.g. neurotoxicity, endocrine effects) that are likely relevant for agricultural pesticide applications are currently not considered mature enough for inclusion into USEtox. Field emissions are linked to emission compartments relevant for human toxicity assessment in USEtox based on the approach described in Nemecek et al. (2022) (see also Figure 3). Source: adapted from Fantke et al. (2018b).

For deriving ecotoxicity effect factors in USEtox for freshwater ecosystems, effect test data across all available species per chemical were collected from Posthuma et al. (2019). The slope at the 50% level of species response over their chronic EC50 was then used and defined as effect factor (Henderson et al. 2011). This introduces simplifying assumptions as for most chemicals, test data for only three species (typically an algae, a daphnia, and a tropical fish embryo) are available. Since these three species are only very poorly reflecting actual ecosystems, ecotoxicity effect factors come with considerable uncertainty, which is propagated into final impact results for ecotoxicity. Detailed information on how ecotoxicity effect factors are derived in USEtox are found in Huijbregts et al. (2010) and Fantke et al. (2017).

For deriving human toxicity effect factors in USEtox, all possible effects were aggregated into a cancer and a non-cancer effect, as more specific information is usually lacking for the data that are used as starting point, namely animal test studies, such as from rats and mice. Such data are used in USEtox (as compared to e.g. human toxicity or epidemiological studies, which are not available for most chemicals, including the majority of pesticides), as animal *in vivo* test study data are avaialble for many chemicals included in product and technology life cycles. Simplifying assumptions are then introduced to convert animal data into human lifetime doses. The smallest human lifetime dose derived from all available animal test data (extracted from e.g. the U.S. EPA Chemistry Dashboard, https://comptox.epa.gov/dashboard) is then used and the slope taken at the 50% effect dose level, to define human toxicity effect factors (Rosenbaum et al. 2011). With that, a considerable uncertainty is introduced in human toxicity factors, which is propagated into final impact results for human toxicity. Detailed information on how human toxicity effect factors are derived in USEtox are found in Huijbregts et al. (2010) and Fantke et al. (2017).

To characterize impacts on humans associated with residues related to pesticide emissions to field crops, emission model results were coupled with the dynamic plant-uptake model dynamiCROP, version 3.12 (https://dynamicrop.org, Fantke et al. 2011b, Fantke & Jolliet 2016). Environmental compartments considered in dynamiCROP are air, soil, paddy water (only for paddy rice) and a set of crop components, namely root, stem, fruit, leaf, fruit surface and leaf surface. The spatial unit of this model is a square metre. Six crop archetypes are considered (wheat, paddy rice, apple tree, tomato, lettuce and potato) that are matched to emission model crops to link emission fractions to field crops (output of emission model) consistently to related exposure and impacts from residues in these crops (Gentil et al. 2020a). Processes considered in dynamiCROP are phase partitioning (e.g. between air and water), degradation (based on half-lives), and intermedia transport processes, such as diffusion (e.g. volatilization), advection (e.g. root uptake) and other processes, such as xylem flow, run-off, leaching, deposition, and crop growth dilution. Details about the environmental fate processes considered in USEtox are found elsewhere (Fantke et al. 2011a, Fantke et al. 2013). The model provides a dynamic solution of the mass balance between pesticide application and crop harvest to account for dynamics of pesticide residues in the harvested crop components (see e.g. Fantke et al. 2013). Generic food processing factors are then used to link pesticide residues in harvested crop components to human intake. Such factors represent a reduction of pesticide residues due to food processing, such as washing of fruits or baking of bread from wheat. Input data of dynamiCROP are the same as for USEtox, since the same type of environmental fate processes is simulated. In addition, crop-internal processes require additional information about degradation within crops, which are derived from e.g. Fantke and Juraske (2013). Human intake is then based on the harvested crop components that are available for human consumption (e.g. for wheat only the grain without the grainsurrounding husk) and the modelled pesticide residues in each of these crop components. Related human toxicity effect factors that are combined with the resulting human intake estimates are derived the same way as for USEtox (see previous paragraph).

2.4 Impacts of life cycle emissions and resource uses from farm-level pest control

Impacts associated with pest control life cycle emissions and resource use are characterized for a wider set of environmental impact categories as shown in Figure 6.

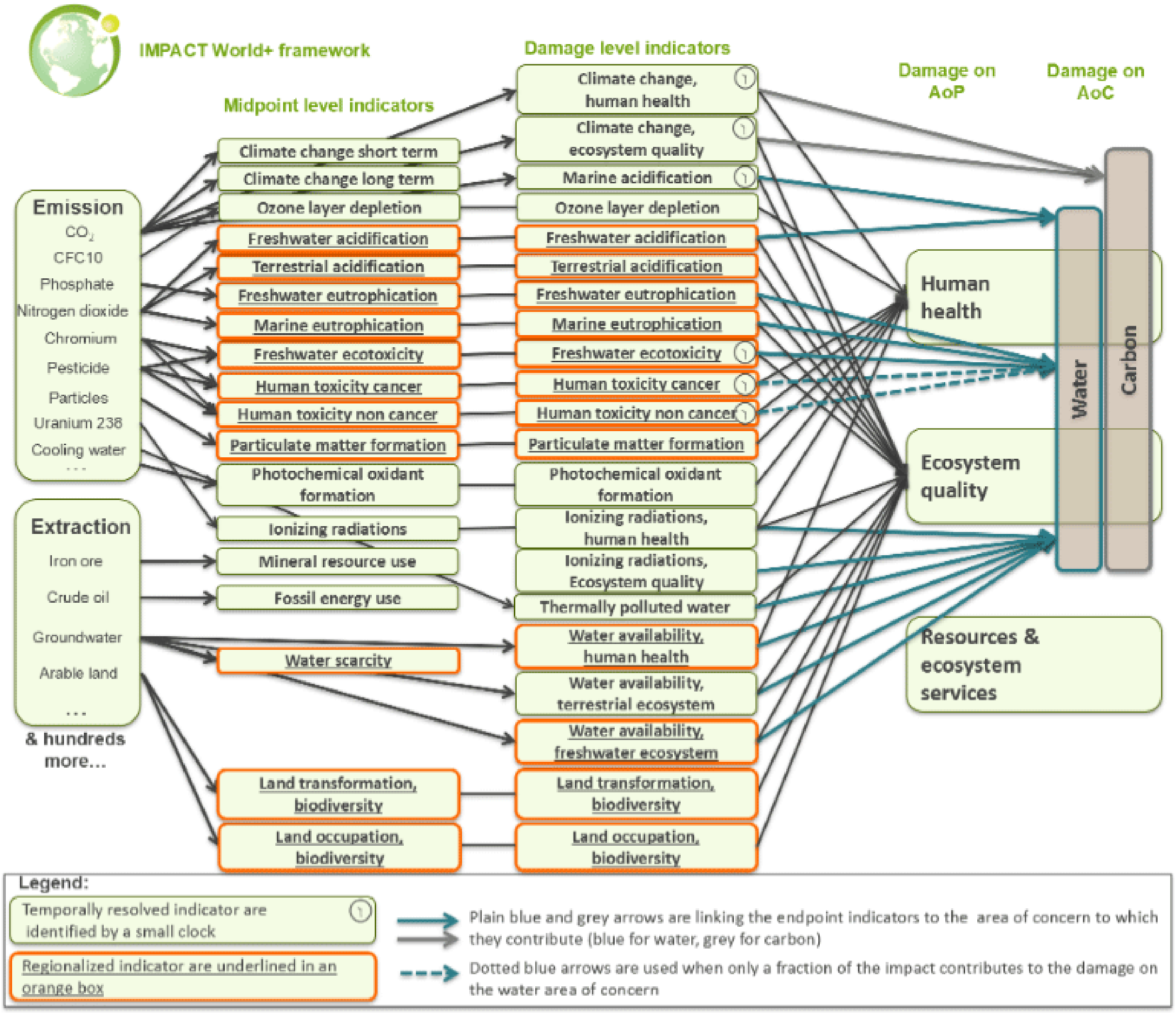


Figure 6. Overview of environmental impact categories that are included in the assessment of supply chain related emissions and resource use flows for the considered pest control options of the SPRINT case study sites in the present deliverable, based on the ImpactWorld+ global LCIA method. The model behind freshwater ecotoxicity and human toxicity impacts is USEtox (Rosenbaum et al. 2008, Fantke et al. 2021, Owsianiak et al. 2023), consistent with assessing impacts of direct pesticide field applications (see Figure 4 and Figure 5). "Midpoint level indicators" are used to identify the contribution of different emission and resource use flows to each impact category. "Damage level indicators" can be aggregated per area of protection (AoP, e.g. human health) or per area of concern (AoC,

not relevant for the present study) and are used to identify the contribution of different impact categories to damage on each area of protection. Impacts on natural resources are currently not included in ImpactWorld+ and, hence, impacts related to non-renewable energy for energy carriers and mineral extraction processes were derived from Impact2002+ as described in Jolliet et al. (2003). Source: Bulle et al. (2019).

Environmental life cycle impacts other than those directly associated with human toxicity and ecotoxicity of the pesticides applied at farms contribute likewise to overall environmental impacts of pest control. This includes impacts associated with agricultural machinery required to apply pesticides (e.g. related diesel fuel consumption and tire abrasion, mechanical weeding), and manufacturing and related market activities (e.g. transportation of packaged pesticide-related plant protection products) of chemical active ingredients. Environmental impacts associated with emissions and resource uses of these aspects of pest control are assessed by applying the globally applicable state-of-the-art LCIA method ImpactWorld+ that considers a consistent set of impact categories (https://www.impactworldplus.org, Bulle et al. 2019). Impacts on natural resources are currently not included in this LCIA method and, hence, were derived from Impact2002+ (Jolliet et al. 2003) in a way that is consistent with ImpactWorld+. Both LCIA methods are implemented in the used LCA software SimaPro.

In ImpactWorld+, several environmental impact categories are included that contribute to damage on human health (i.e. climate change, ozone layer depletion, human toxicity via cancer and non-cancer effects, particulate matter formation, photochemical oxidant formation, ionizing radiation, water availability) and ecosystem quality (i.e. climate change, acidification, eutrophication, freshwater ecotoxicity, ionizing radiation, thermally polluted water and water availability, land transformation and occupation). In Impact2002+, we considered impacts related to non-renewable energy for energy carriers and mineral extraction processes. Environmental impacts in these LCIA methods are quantified based on a consistent set of indicators that can be aggregated at damage level. For impacts contributing to damage on human health, the common damage unit is the disability-adjusted life year (DALY), which is widely accepted in public health (e.g. Forouzanfar et al. 2016). For impacts contributing to damage on ecosystem quality, the common damage unit is potentially disappeared fraction of species (PDF) over a unit area and year (PDF m² year). MJ is a common energy-related unit that is used for impacts contributing to damage on natural resources.

3 Results and Discussion

3.1 Applied pesticides at farm and case study site level

Across the 169 farms of the considered SPRINT case study sites in 10 European countries, plant protection products containing 189 distinct pesticides were applied, which includes organic chemical pesticides, inorganic pesticides (e.g. sulfur), copper-based pesticides, and biological pesticides. Across farms considered in each of the countries

Portugal, Switzerland and France, applications of more than 40 distinct pesticides have been reported, closely followed by applications of more than 30 distinct pesticides across farms in each of the countries Czech Republic, Italy, Spain and The Netherlands. In contrast, applications of only 17, 11 and 8 distinct pesticides across farms have been reported for Croatia, Denmark and Slovenia, respectively. An overview of the pesticide count across farm per considered case study site country is show in Figure 7, with a detailed overview of individual pesticides applied per country and farming system provided in the Appendix, Table A 1.

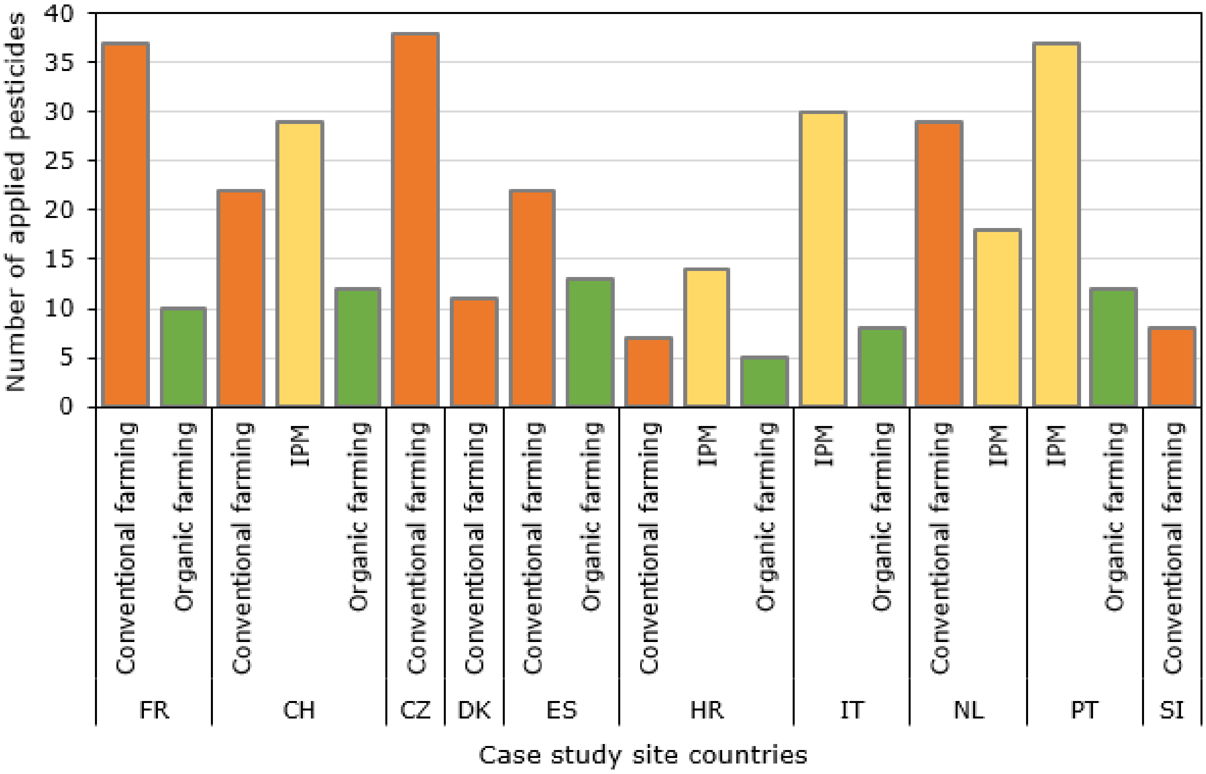


Figure 7. Number of distinct pesticides used per considered SPRINT case study site country in the present deliverable, differentiated according to farming system type within each country. Note that some pesticides are used in different farming systems within the same country. Hence, the number of pesticides across farming systems per country (e.g. 37 pesticides applied on farms with conventional farming plus 10 pesticides applied on farms with organic farming in France) can be higher than the overall number of pesticides used in that country (e.g. 42 pesticides applied on considered farms in France across farming systems; see Appendix, Table A 1). Farms reported to be "in transition to organic farming" have been allocated to "Organic farming".

The highest number of pesticides is applied in conventional farming across considered case study sites where several farming systems were reported, with the exception of Switzerland, where the highest number of pesticides is applied in IPM farming systems. In terms of reported dose applied per pesticide, only chemical pesticides and copper-based pesticides were considered, since they can currently not be evaluated in terms of direct effects on humans and ecosystems, and since data on applied dose of the actual active ingredients in biological pesticides have usually not been reported. An overview of the ranges across reported applied doses for all considered pesticides across farms per case study site are provided in the Appendix, Table A 2.

Highest applied doses were reported for chemical substances that can currently not be characterized in terms of human toxicity or ecotoxicity impacts, or that come with large uncertainties in the impact results. This includes reported doses of more than 10 kg of active ingredient applied per ha of treated crop area for kaolin, manganese, and paraffin oil. These were followed by reported doses of more than 2 kg of active ingredient applied per ha of treated crop area for some chemical pesticides, including copper (II) hydroxide, paraquat, and glyphosate. Most other chemical pesticides are applied in the range of 10 to 100 g of active ingredient applied per ha of treated crop area.

3.2 Human toxicity and ecotoxicity impacts of applied pesticides

Environmental impacts associated with the direct application of pesticides at farms across considered SPRINT case study sites were only evaluated for chemical pesticides, including organic substances and copper-based substances. This is on the one hand because applied doses of the actual active ingredients in biological pesticides were usually not reported, while on the other hand currently no LCIA methods are available for assessing direct effects of biological pesticides on humans and ecosystems.

As first step, emission fractions for each pesticide application scenario have been compiled, which depend on application method (e.g. boom sprayer) and crop growth stage (influencing crop interception on the field). For illustrative purposes, a set of emission fractions into the considered compartments has been compiled in Table 4, differentiated by crop type (determining what drift function is applied), and using the dominating application method as reference and average field crop interception fractions. From this illustrative overview, we can see that certain combinations of application method and crop growth stage (influencing the interception fraction on the field) lead to high emission fractions to field soil of around 50% or more of the applied pesticide mass. An example for that are pesticides applied to vegetable crops via a boom sprayer with standard flat fan at early crop stages (Table 4, red shaded cells in the respective column). In contrast, certain combinations of application method and crop growth stage lead to emission fractions going beyond the treated field area and reaching off-field surfaces that are higher than 2% of the applied mass, such as air blast sprayers applying pesticides to vineyards at late crop stages (Table 4, red shaded cells in the respective column). Both contribute to ecotoxicity impacts in the present approach followed as they lead to mass of applied pesticides that reaches freshwater aquatic environments.

In contrast, certain combinations of application method and crop growth stage may lead to higher air emissions of more than 10% of the applied pesticide mass, influencing inhalation exposure of field workers and residential bystanders and households. An example are pesticides applied via air blast sprayers in vineyards at early and late crop growth stages (Table 4, red shaded cells in the respective column.

Table 4. Typical initial emission distribution fractions for 10 crop groups used in the considered SPRINT case study sites for emission modelling. Four emission compartments are implemented in the PestLCI Consensus emission model (Dijkman et al. 2012, Nemecek et al. 2022), namely field crop, field soil, air, and off-field surfaces via drift deposition (run-off, leaching and other long-term processes are not considered on the emission side, but on the subsequent fate side of the LCIA). Air emissions and initial deposition fractions emitted to off-field surfaces are based on drift functions, while the distribution of initial deposition fractions between field crop and field soil surfaces is modeled based on leaf area interception as a function of crop growth stage. Initial distribution fractions to field crop and field soil can hence vary, depending on crop growth stage during pesticide application.

Crop group	Reference application method	Average crop interception fraction	Field crop surface deposition fraction	Field soil surface deposition fraction	Air emission fraction	Off-field surface deposition fraction
Fruit Orchards	Hand operated sprayer and Air blast sprayer	0.7	65.9%	25.6%	6.2%	2.3%
Broccoli	Air blast sprayer	0.8	65.3%	24.6%	7.5%	2.6%
Vineyard	Air blast sprayer	0.7	57.3%	28.2%	11.3%	3.1%
Potato	Conventional boom sprayer	0.6	55.0%	33.9%	10.0%	1.2%
Olive	Air blast sprayer	0.6	53.8%	34.9%	8.0%	3.3%
Cereals	Conventional boom sprayer with drift reduction nozzles	0.4	48.0%	48.9%	2.4%	0.7%
Oilseeds	Boom sprayer - standard flat fan	0.4	36.8%	55.9%	6.5%	0.8%
Vineyard	Air blast sprayer	0.3	25.3%	59.0%	12.5%	3.2%
Maize	Boom sprayer - standard flat fan	0.25	23.0%	69.6%	6.6%	0.8%
Vegetable crops	Boom sprayer - standard flat fan	0.2	17.8%	74.3%	7.1%	0.8%

Applied pesticide mass combined with environmental emission fractions was characterized in terms of toxicity-related impacts on humans and freshwater ecosystems, based on state-of-the-art LCIA impact assessment methods. Results for human toxicity are shown in Figure 8, and results for ecotoxicity are shown in Figure 9. Impacts of pesticide use including pesticide supply chain for each considered farm are provided in the Appendix, Table A 3.

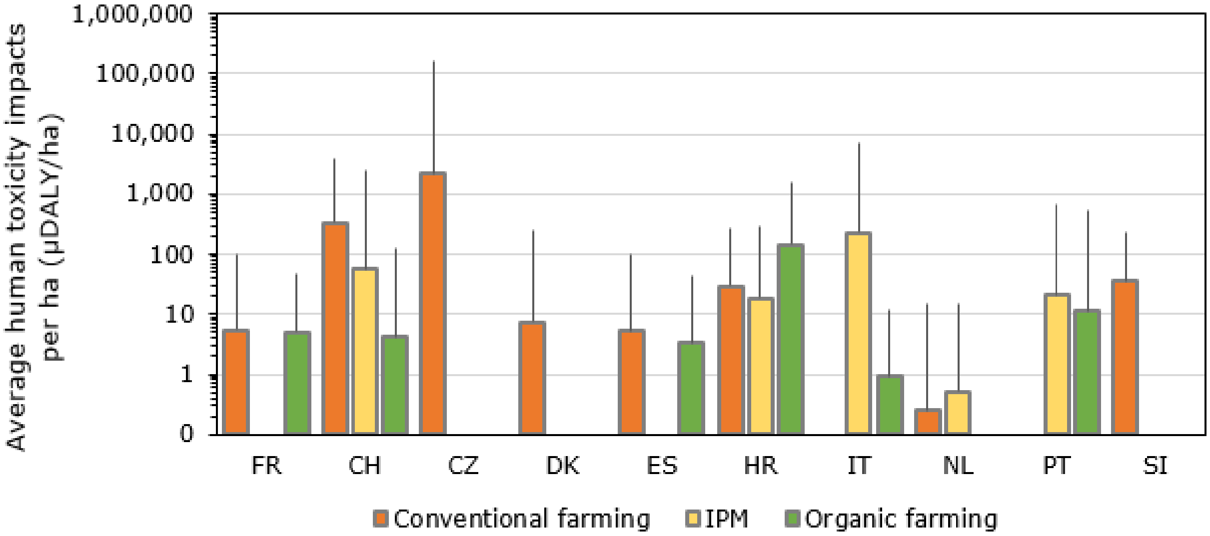


Figure 8. Average human toxicity-related impacts (for the considered cancer and generic non-cancer effects in the general human population via inhalation and ingestion – see also Figure 2) and high-end uncertainty bounds of pesticide use across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in micro-disability-adjusted life years (µDALY) per ha treated crop area. One DALY represents a lost healthy human life across the human population, and one µDALY corresponds to ~0.52 minutes of healthy life lost. Uncertainty bars reflect the maximum impacts per ha per case study site and farming system.

Highest average human toxicity impacts of pesticide application across farms per considered SPRINT case study site are found for conventional farming across most case study sites. The exception is Croatia, where extensive copper-based fungicide application leads to higher average per ha human toxicity impacts as compared to conventional farming (see Figure 8). Highest average per ha impacts are found in Czech Republic, with a total of more than 2000 µDALY average human toxicity impacts per ha. Overall, human toxicity impact per ha across farms and farming system ranges between 0.2 and more than 2000 µDALY, with considerable uncertainty. Considering uncertainty, estimated human toxicity impacts can reach beyond 100,000 µDALY per ha in Czech Republic, which corresponds to 0.1 DALY (i.e. 1 tenth of a healthy life year lost) per ha treated crop area, constituting a substantial health burden from pesticide exposure.

Highest average ecotoxicity impacts of pesticide application across farms per considered SPRINT case study site are found for both conventional farming in The Netherlands, and for IPM in Switzerland, Croatia and Portugal. In France, Spain and Portugal, also organic farming related impacts are of similar magnitude as impacts from conventional farming systems, which is again due to the extensive use of copper-based fungicides in both organic farming and IPM. Highest average per ha impacts are found in Croatia, with a total of more than 2 PDF m²yr average ecotoxicity impacts per ha. Overall, ecotoxicity impact per ha across farms and farming system ranges between 0.002 and more than 2 PDF m² yr, with considerable uncertainty. Considering uncertainty, estimated ecotoxicity impacts can reach more than 75 PDF m² yr per ha in Croatia.

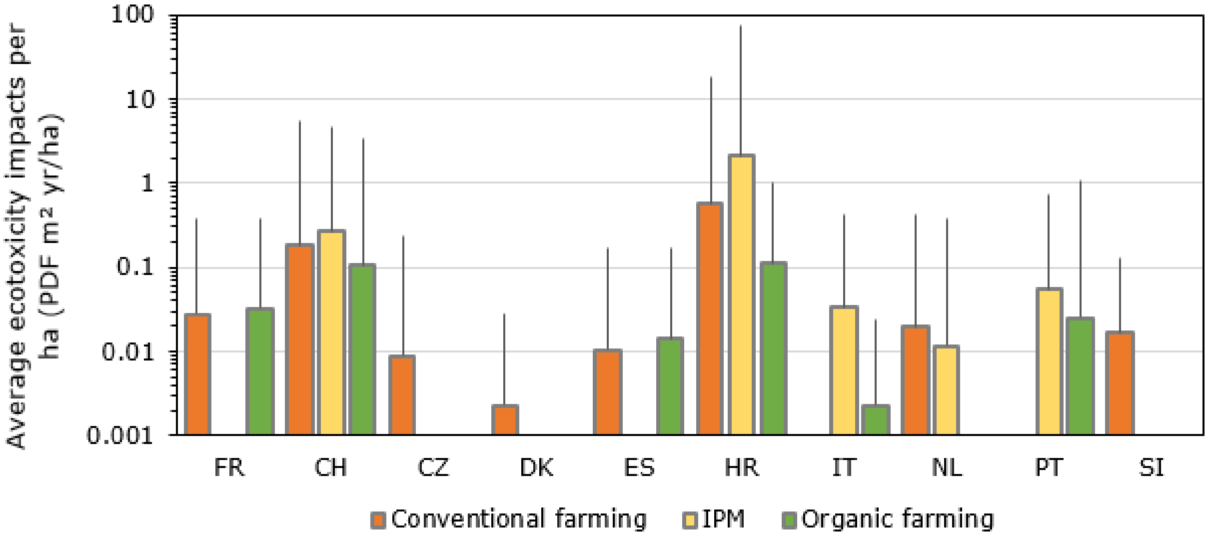


Figure 9. Average ecotoxicity-related impacts and high-end uncertainty bounds of pesticide use across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in potentially disappeared fraction of ecosystem species (PDF) integrated over 1 m² of exposed water area and one year per ha treated crop area. Uncertainty bars reflect the maximum impacts per ha per case study site and farming system.

3.3 Overall environmental impacts of pest control and related damage costs

Different life cycle aspects of pest control contribute to overall environmental impacts pf pest control across the different farming systems. Contributions include on the one hand impacts related to pesticides via field application and their respective supply chain impacts of pesticide manufacturing and marketing. Contributions furthermore include impacts from pest control related processes.

Here, we considered impacts associated with tire abrasion (tires of tractors and other machines wearing down due to friction with soil surfaces), sprayer (supply chain of pesticide applicator), total fuel direct (emissions from using fuel on farms) and indirect (supply chain of fuel), tractor (supply chain of tractor), and weeder (supply chain of mechanical weeding). Contributions of the different life cycle aspects to environmental impacts of pest control across areas of protection (human health, ecosystem quality, natural resources) and farming systems is provided in Figure 10.

In conventional farming, IPM and organic farming, pesticide related impacts dominate across areas of protection, with highest contributions of more than 80% in conventional farming and IPM. In organic farming, pesticide related impacts are less dominating, contributing between 55% to impacts on natural resources and ~70% to impacts on human health and ecosystem quality, mainly due to the use of copper-based fungicides. For natural resources, indirect fuel-related impacts are an additional substantial contributor, with up to 40% contribution across farming systems.

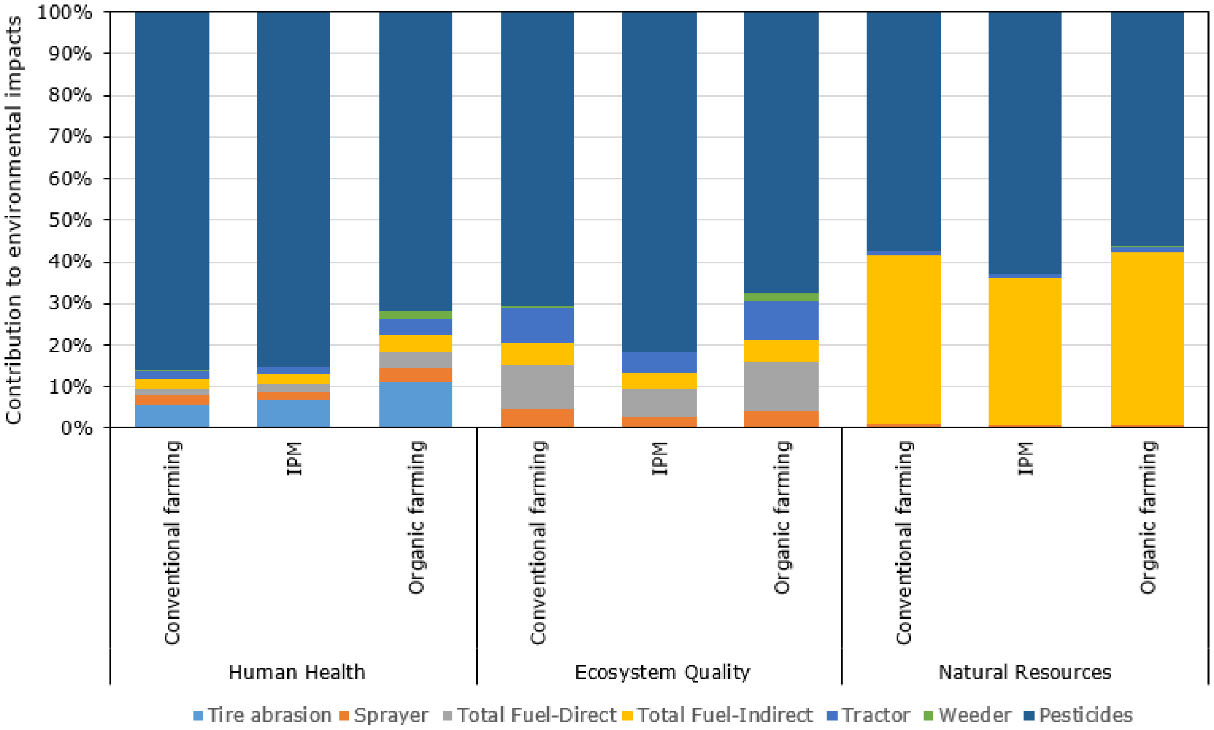


Figure 10. Contribution of human health, ecosystem quality and natural resources impacts of pesticides applied to crop fields versus pest control related processes. Pesticides include direct field application related impacts and supply chain impacts of pesticide manufacturing and marketing. Pest control related processes include impacts associated with tire abrasion (tires of tractors and other machines wearing down due to friction with soil surfaces), sprayer (supply chain of pesticide applicator), total fuel direct (emissions from using fuel on farms) and indirect (supply chain of fuel), tractor (supply chain of tractor), and weeder (supply chain of mechanical weeding).

Combining impacts from pesticide use and all other pest control related life cycle impacts yields overall environmental impacts of pest control. Total average environmental impacts are shown for human health in Figure 11, for ecosystem quality in Figure 12, and for natural resources in Figure 13.

Consistently, impact results show that pesticide related aspects (direct field application and pesticide supply chain) dominate overall impact estimates across farming systems and areas of protection. This effect is most prominent for impacts of pest control on human health and on ecosystem quality. For impacts on human health, pesticides dominate with average impacts per ha of more than 10,000 µDALY for conventional farming and IPM, and with more than 5,000 µDALY for organic farming. Other pest control related impacts on human health contribute typically with less than 1,000 µDALY per ha, mainly driven by impacts related to emissions from tire abrasion, followed by impacts related to fuel consumption and supply chain processes (see Figure 11). Again, considerable uncertainty is associated with these impacts. Considering uncertainty, impacts on human health can reach more than 300,000 µDALY, which constitutes a substantial health burden.

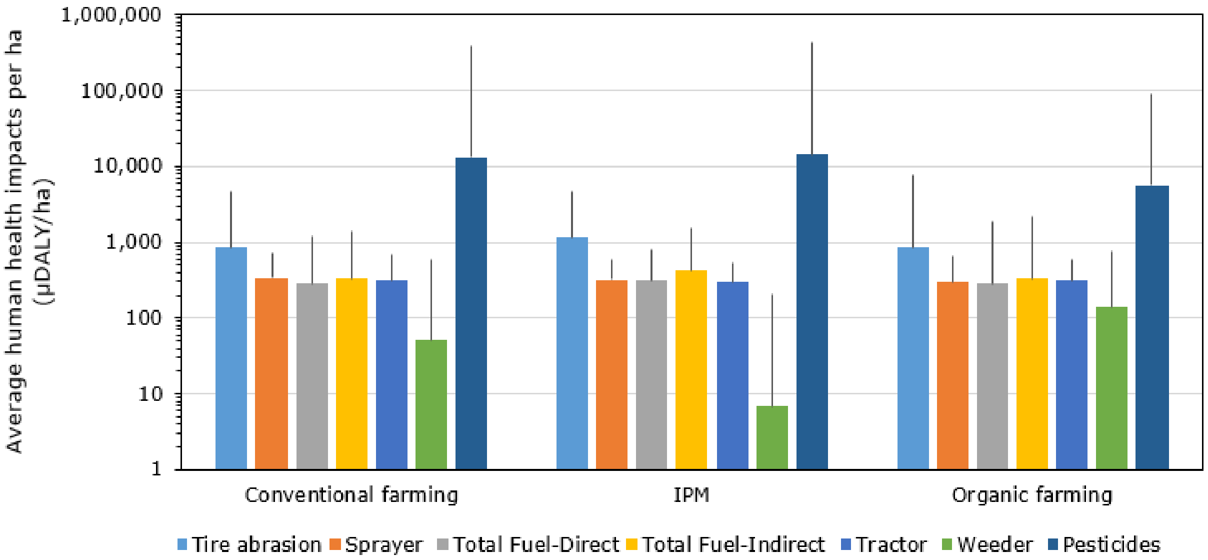


Figure 11. Total average and high-end uncertainty bounds of environmental impacts on human health associated with pest control across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in micro-disability-adjusted life years (µDALY) per ha treated crop area. One DALY represents a lost healthy human life across the human population, and one µDALY corresponds to ~0.52 minutes of healthy life lost. Uncertainty bars reflect the maximum costs per ha per case study site and farming system. Pesticides include direct field application related impacts and supply chain impacts of pesticide manufacturing and marketing. Pest control related processes include impacts associated with tire abrasion (tires of tractors and other machines wearing down due to friction with soil surfaces), sprayer (supply chain of pesticide applicator), total fuel direct (emissions from using fuel on farms) and indirect (supply chain of fuel), tractor (supply chain of tractor), and weeder (supply chain of mechanical weeding).

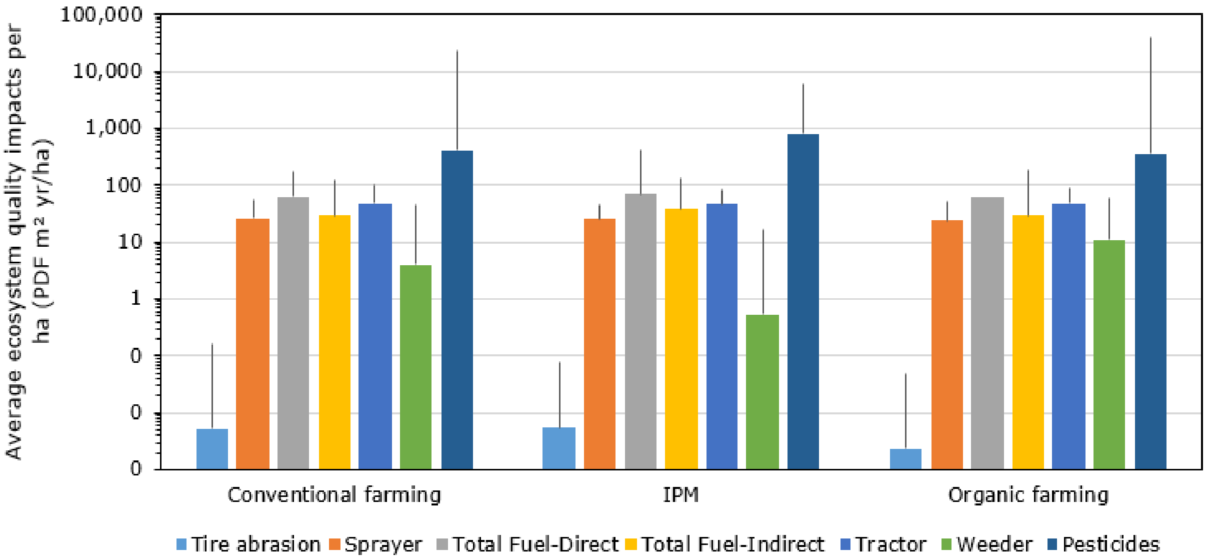


Figure 12. Total average and high-end uncertainty bounds of environmental impacts on ecosystem quality associated with pest control across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in potentially disappeared fraction of ecosystem species (PDF) integrated over 1 m² of exposed water area and one year per ha treated crop area. Uncertainty bars reflect the maximum costs per ha per case study site and farming system. Pesticides include direct field application related impacts and supply chain impacts of pesticide manufacturing and marketing. Pest control related processes include impacts associated with tire abrasion (tires of tractors and other machines wearing down due to friction with soil surfaces), sprayer (supply chain of pesticide applicator), total fuel direct (emissions from using fuel on farms) and indirect (supply chain of fuel), tractor (supply chain of tractor), and weeder (supply chain of mechanical weeding).

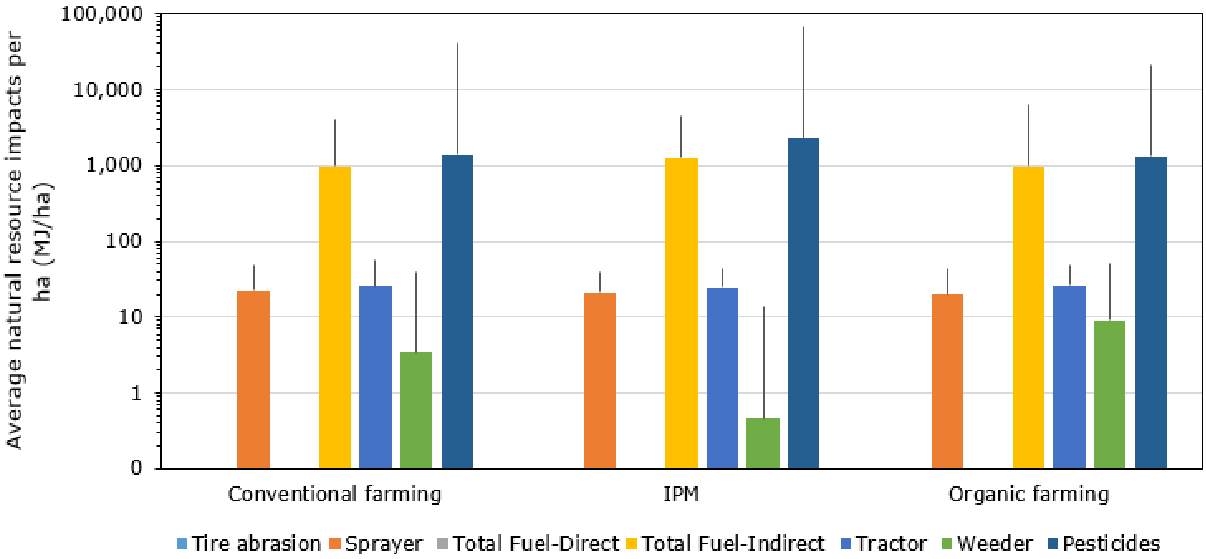


Figure 13. Total average and high-end uncertainty bounds of environmental impacts on natural resources associated with pest control across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in mega joule (MJ) per ha treated crop area. Uncertainty bars reflect the maximum costs per ha per case study site and farming system. Pesticides include direct field application related impacts and supply chain impacts of pesticide manufacturing and marketing. Pest control related processes include impacts associated with tire abrasion (tires of tractors and other machines wearing down due to friction with soil surfaces), sprayer (supply chain of pesticide applicator), total fuel direct (emissions from using fuel on farms) and indirect (supply chain of fuel), tractor (supply chain of tractor), and weeder (supply chain of mechanical weeding).

For impacts on ecosystem quality, pesticides again dominate with average impacts per ha of more than 400 PDF m yr for conventional farming and IPM, and with more than 300 PDF m² yr for organic farming. Other pest control related impacts on ecosystem quality contribute typically with less than 70 PDF m² yr per ha, mainly driven by impacts related to fuel consumption and supply chain processes as well as tractor operations (see Figure 12). Considerable uncertainty is associated also with these impacts. Considering uncertainty, impacts on ecosystem quality can reach more than 23,000 PDF m² yr for IPM.

For impacts on natural resources, pesticides together with indirect fuel-related processes dominate across farming systems, with values around 1,000 MJ each per ha. Considering uncertainty, impacts on natural resources can reach more than 66,000 MJ from pesticide use in IPM.

Translating the combined environmental impacts on human health, ecosystem quality and natural resources into damage costs allows for an overall economic picture of environmental burden related to pest control. However, we note that translating LCA environmental impact results into monetary terms should be interpreted with caution as very rough simplifying assumptions are applied on the monetary valuation side. Monetized environmental impact results related to pest control across farming systems are summarized in Figure 14, and follow the trends described in the previous figures describing environmental impacts of pest control across considered case study sites. Costs are not systematically higher for any given farming system based on the currently considered impacts. This is mainly due to the fact that while impacts in conventional farming are driven by the use of chemical pesticides, copper-based fungicides widely used in both IPM and organic farming drive high impacts for these farming systems. However, considerable uncertainty are associated with the initial findings in the present deliverable in terms of damage costs. Considering these uncertainties, we can reach costs as high as >10,000 Euro per ha treated crop area in Czech Republic.

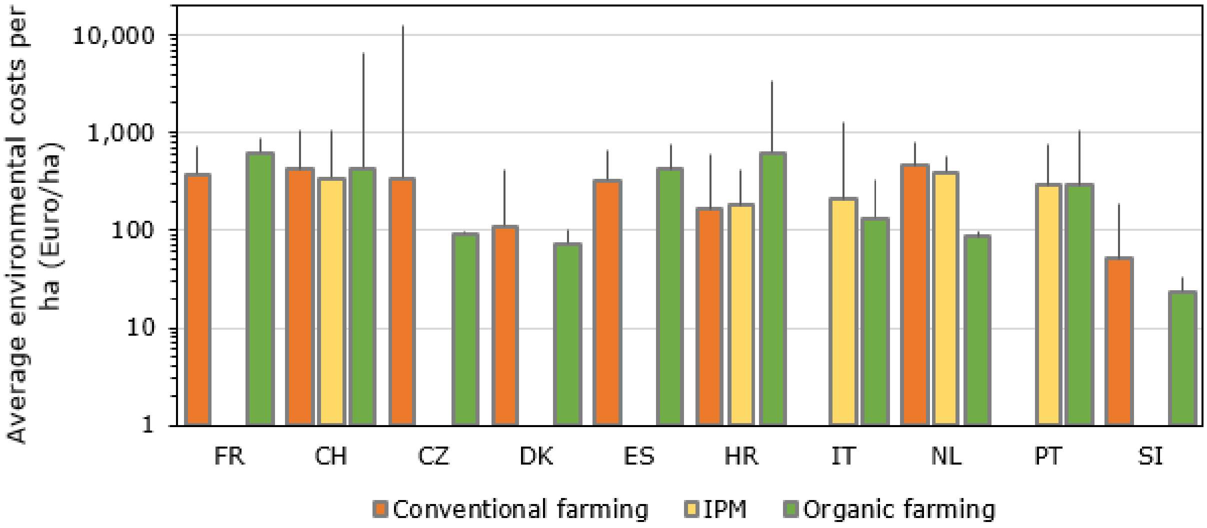


Figure 14. Total average and high-end uncertainty bounds of environmental damage or external costs of pest control across farms per considered SPRINT case study sites, differentiated according to farming system, and expressed in annual Euro 2022 per ha treated crop area. Uncertainty bars reflect the maximum costs per ha per case study site and farming system.

3.4 Applicability and limitations of the followed approach

The presented results are generally in line with results from other studies where crop protection was considered in assessing environmental sustainability impacts. This includes assessment aspects covered, a strong focus on actually applied pesticides, some organic and copper-based pesticides dominating human toxicity and ecotoxicity impacts, and impact distributions across the three considered farming systems (e.g. Perrin et al. 2014, Renaud-Gentié et al. 2015, Peña et al. 2018, Gentil et al. 2020a, Mathis et al. 2022, Nemecek et al. 2022). More specifically, chemical pesticides are consistently identified an important contributor to human toxicity and ecotoxicity impacts in conventional farming systems in our present as well as in other studies. Moreover, copper-based fungicides have likewise been identified as an important contributor to human toxicity and ecotoxicity impacts when applied in organic (or other) farming systems. This supports the call for an improved assessment of practices where copper-based fungicides are applied, to consider spatial characteristics influencing copper speciation and related effect magnitudes and to understand whether copper-based fungicides should be allowed from a sustainability perspective in organic farming at all (see e.g. discussions in Peña & Antón 2017, Peña et al. 2018).

Our presented approach has many limitations. On the one hand, our applied LCA methodology generally aims at being comprehensive in covering life cycle stages and environmental impact categories relevant for pest control. On the other hand, we apply our approach at the farm level, for which LCA typically is not well suited as it has for most impact categories a much more coarse resolution. For example, human toxicity and ecotoxicity impacts in LCA are typically not spatially differentiated, and factors are available only at the global (generic) or sub-continental level (Rosenbaum et al. 2008, Kounina et al. 2014). Based on that, not considering spatial aspects from pesticide application to damage on human and ecological health is a strong limitation of the present approach. This includes spatial differences in field settings, climate and soil conditions, human population density and vulnerability toward pesticide exposure and ecological species richness and composition, which all influence emission, fate, exposure and effect results. Based on that limitation, we recommend advancing spatial modelling approaches in pesticide emission and impact assessment, based on initial approaches for modeling chemical fate and exposure in a spatially explicit way (e.g. Wannaz et al. 2018a, Wannaz et al. 2018b, Jolliet et al. 2020).

One of the strongest limitations of the presented approach is most likely that many of the receptors that are actually relevant for pest control operations are currently not operationally included in available state-of-the-art LCIA methods (see also Figure 2), such as ImpactWorld+ (Bulle et al. 2019), LC-Impact (Verones et al. 2020), ReCiPe (Huijbregts et al. 2017), or TRACI (Bare 2011). This includes the lack of considering impacts on agricultural field workers, residential and other bystanders near agricultural fields, related indoor air and dust exposure in near-field residences on the human health side, along with supply chain-related worker impacts (e.g. associated with exposure to occupational injuries and emissions into worker environments for manufacturing pesticides). This further includes the lack of considering impacts on terrestrial soil ecosystems (mainly relevant for agricultural soil) and on pollinating insects (e.g. honey bees, wild bees). To some extent, this may also concern other types or ecosystems that might, however, be of less relevance for pesticide-related impacts (e.g. marine aquatic ecosystems – relevant for pest control near coastal areas, groundwater ecosystems – relevant for strong leaching areas, or predatory birds – relevant where they feed mainly on pollinators that are exposed to pesticides). The lack of considering these receptors in LCIA has been acknowledged also in other studies and is further discussed elsewhere (Kijko et al. 2015, Rosenbaum et al. 2015, Kijko et al. 2016, Crenna et al. 2017, Fantke et al. 2018a, Fantke et al. 2018b, Ryberg et al. 2018, Fantke 2019, Crenna et al. 2020, Nemecek et al. 2022). Overall, this limitation is the main contributor to a large underestimation of the presented environmental impacts for the pest control scenarios of the considered SPRINT case study sites. Based on that limitation, we strongly recommend developing new methods for including the above-mentioned receptor impacts into operational LCIA frameworks that are in line with the boundary conditions of LCA (Fantke et al. 2018a), in support of a more comprehensive assessment of environmental sustainability impacts of pest control practices.

Another limitation of our presented approach is that operational LCIA methods can currently not assess human toxicity, ecotoxicity or other direct effects on humans and ecosystems of any biological or inorganic substances. This is a known gap in LCIA (see e.g. Kirchhübel & Fantke 2019, Nemecek et al. 2022, Owsianiak et al. 2023). This might lead to underestimating overall environmental impacts of pest control, especially where such pesticides are used (e.g. biological pesticide use in organic farming, or sulfur fungicides used in different farming practices). Based on that limitation, we recommend expanding current approaches for assessing direct impacts of chemical pesticides on humans and ecosystems to cover biological and inorganic pesticides.

Finally, the many simplifications along the impact pathway for pesticides in LCIA models is a strong limitation of our presented approach. This includes to only consider initial partitioning for estimating emissions, instead of considering field-related aspects (e.g. slope, field shape), chemical and environmental characteristics that also influence emission distributions (Rosenbaum et al. 2015, Gentil et al. 2020b, Gentil-Sergent et al. 2021, Nemecek et al. 2022). This further includes simplifications mainly on the effect assessment side. On the one hand, only a certain set of species usually has available effect test data that are supposed to represent (spatial differences in) real ecosystems, while on the other hand animal *in vivo* data are used to estimate human population-level toxicity effects (Henderson et al. 2011, Rosenbaum et al. 2011, Fantke et al. 2018a, Fantke et al. 2018b). In addition, mixture toxicity effects and transformation products that can be more or less toxic or ecotoxic are currently not considered in LCIA models for human toxicity and ecotoxicity impact characterization. This moreover includes generic monetary valuation factors for human health, ecosystem quality and natural resources. This limitation is a dominating contributor to uncertainty in the presented environmental impact estimates. Based on that limitation, we recommend developing approaches that increase the specificity of toxicity and ecotoxicity effect estimates for use in LCIA, to reduce the uncertainty of toxicity and ecotoxicity impact results related to pesticides and other chemicals.

Many of the urgently needed methodological advances in LCIA to improve the quantification of environmental impacts of pest control in a life cycle perspectives can benefit from increased interaction with researchers from adjacent fields, including soil scientists, agronomists, environmental chemists, toxicologists, ecologists, human behavior and social scientists, and environmental economists. Researchers from these fields can provide targeted data from measurement and monitoring programs, from mechanistic environmental modelling of chemical-human-ecosystem interactions, from generation of knowledge related to optimizing pest control practices, and from the prediction of relevant data to fill relevant input data in LCIA models. Such information and data are also generated in other work packages of the SPRINT project, and we suggest making use of such generated information and data to evaluate presented environmental impact results as well as to identify starting points for further improving and extending existing methods that are applied in WP6 and in LCA studies beyond the SPRINT project.

4 Conclusions

In the present deliverable, pest control related impacts from 169 farms across 10 SPRINT project case study sites in 10 European countries. The different farms considered different pest control operations based on three main farming systems, namely conventional farming, IPM and organic farming. To understand the wider environmental sustainability implications of the different considered pest control systems, we quantified related environmental life cycle impacts, which includes human toxicity and ecotoxicity impacts of pesticides applied at farm level, but also the life cycle emissions and resource use of the applied pesticides as well as of the machinery involved in pest control operations.

In line with widely adopted methods for evaluating environmental sustainability impacts in LCA, we applied life cycle inventory (LCI) analysis to estimate emissions and resource for each pest control scenario, and applied life cycle impact assessment (LCIA) models for characterizing related environmental impacts on human health, ecosystem quality and natural resources. Given the broad scope of life cycles and various considered environmental impact categories from climate change to human toxicity and energy use, both LCI and LCIA methodologies come with simplifying assumptions and large uncertainties. In addition, while LCA aims at being comprehensive, many receptors that are negatively affected by pest control are currently not considered in operational LCIA method. This indicates that the *environmental sustainability impacts quantified in the present document are largely underestimated*, presuming that currently missing quantified *impacts on workers, residential bystanders, terrestrial (agricultural) soil ecosystems and pollinating insects are likely exceeding the presented impacts by several orders of magnitude*.

We found that environmental impacts of pest control are dominated by direct impacts associated with pesticide field applications across various considered case study sites and farming systems. High impacts in a given case study site are often driven by few compounds, such as in copper-based fungicides applied in vineyards.

Life cycle environmental impacts associated with agricultural machinery and pesticide manufacturing and related market processes contribute between 15% and 40% to overall environmental impacts from pest control across farming systems, the rest being associated with pesticide field application. For conventional farming, human toxicity and ecotoxicity impacts associated with the applied pesticides typically dominate overall human toxicity and ecotoxicity impacts per pest control scenario at farm level. This is in contrast to IPM and organic farming scenarios, where human toxicity and ecotoxicity impacts associated with the applied pesticides are typically contributing less to overall human toxicity and ecotoxicity impacts of pest control, but are still substantial, mostly from copper-based fungicides. With that, pesticide-related impacts are an important contributor to overall human toxicity (where we currently only consider generic cancer and non-cancer effects) and ecotoxicity impacts, predominantly in conventional farming but also in other farming systems, where cooper-based fungicides are applied.

Overall, environmental life cycle impacts of pest control options across various farms and farming systems in Europe have been quantified, following LCA methodology. However, we identified that currently, perhaps the most relevant receptors (e.g. human field workers applying pesticides and residents living near agricultural fields, as well as ecosystems in agricultural soil and pollinating insects) are missing in current LCIA methods. This likely leads to large underestimations of overall impacts of pest control, which has also wider implications on the reliability of other LCA-based studies of products and technologies where pest control is an important contributor to the environmental sustainability performance.

Based on the presented work, we strongly recommend developing quantitative impact assessment methods that cover receptors (e.g. workers, pollinating insects), pathways (e.g. dust ingestion of residential bystanders) and pest control agents (e.g. inorganic substances like sulfur and biological pesticides). With that, related LCAs will be able to compare different product and technology life cycles that are driven by pesticides in a comprehensive manner. Hence, the presented results should not be interpreted as actual environmental impacts of pest control under SPRINT. Instead, the presented results should be interpreted to be a first component in the overall environmental impact picture of pest control in Europe and elsewhere, which should moreover be combined with economic sustainability indicators to provide a full picture of sustainability-related impacts of pest control and to identify possible ways forward to reduce these impacts.

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Appendix

Table A 1. Reported count of applications per pesticide across farms under different farming systems (conventional farming, integrated pest management (IPM), and organic farming) within the considered SPRINT case study sites in 10 European countries. Pesticides include organic pesticides, copper-based fungicides, and biological pesticides. Farms reported to be "in transition to organic farming" have been allocated to "Organic farming".

Pesticide name	Conventional	IPM	Organic	Total
FR	**172**		**376**	**548**
Alpha-cypermethrin	1			1
Ametoctradin	4			4
Benthiavalicarb	1			1
Carfentrazone-ethyl	1			1
Copper			3	3
Copper	18		89	107
Copper (1) oxide			23	23
Copper (II) hydroxide	13		87	100
Copper oxychloride	1			1
Copper sulphate	9		17	26

Pesticide name	Conventional	IPM	Organic	Total
Cyazofamid	1			1
Cyflufenamid	4			4
Cymoxanil	1			1
Cypermethrin	1			1
Deltamethrin	1			1
Difenoconazole	5			5
Dimethomorph	4			4
Disodium phosphonate	2			2
Ethoxylated triglyceride 10 OE	1			1
Fenbuconazole	3			3
Fluopicolide	4			4
Fluopyram	1			1
Fosetyl-aluminium	15			15
Glyphosate	1			1
Indoxacarb	3			3
Lambda-cyhalothrin	1			1
Mandipropamid	1			1
Metiram	12			12
Metrafenone	4			4
Oxathiapiprolin	1			1
Potassium phosphate	3			3
potassium phosphonates	9			9
Pyrethrin	1		6	7
Spinosad			1	1
Sulphur	30		132	162
Sweet orange essential oil			8	8
Tau-fluvalinate	1			1
Terpene Alcohols			10	10
Tetraconazole	3			3
Trifloxystrobin	2			2
Trifloxystrobin	4			4
Zoxamide	5			5
CH	**63**	**122**	**158**	**343**
Acetamiprid	1	6		7
Alumina Sulfuric			36	36
Azadirachtin		2	5	7
Azoxystrobin	3			3
Bacillus amyloliquefaciens plantarum		1		1
Bacillus thuringiensis sp. kurstaki		1		1
Calcium hydroxyde		2		2
Calcium Oxide		2		2
Calcium polysulfide			5	5
Captan	5	11		16
Codling moth granulosis virus			9	9
Copper (II) hydroxide	3	7	3	13
Copper oxychloride		9	3	12
Cyflufenamid	1	2		3
Difenoconazole	8	8		16
Dithianon	10	7		17
Dried spores/mycelium of Gliocladium catenulatum		1		1
Emamectin benzoate		2		2
Fluazinam	2			2
Glufosinate-ammonium	1	1		2
Glyphosate	2	4		6
Granulosis virus				
Indoxacarb	1	1		2
Kaolin			1	1
Laminarin	4	2		6
Mancozeb	2			2
Mepanipyrim	2			2
Metalaxyl-M	2			2
Myclobutanil	1			1
Paraffin oil	3	4	3	10
Penconazole	2			2
Pheromone			1	1
Pirimicarb	1			1

Pesticide name	Conventional	IPM	Organic	Total
Potassium bicarbonate		14	12	26
potassium phosphonates		2		2
Shell moth granulosis virus		3		3
Specially prepared horsetail extract			36	36
Spinosad		2		2
Spirotetramat		4		4
Sulphur	3	17	44	64
Thiacloprid		1		1
Thiophanate-methyl	3	2		5
Trifloxystrobin	3	4		7
CZ	**87**			**87**
Acetamiprid	8			8
Aminopyralid	1			1
Azoxystrobin	3			3
Boscalid	3			3
Chlorotoluron	2			2
Clethodim	1			1
Clomazone	3			3
Clopyralid	2			2
Deltamethrin	1			1
Dimethenamid-P	1			1
Dimoxystrobin	2			2
Fluazifop-P-butyl	1			1
Fluopyram	1			1
Flupyradifurone	1			1
Flurochloridone	1			1
Fluroxypyr	4			4
Gamma-cyhalothrin	6			6
Halauxifen-methyl	3			3
Haloxyfop-R-Methyl Ester	2			2
Imazamox	1			1
Isofetamid	1			1
isoxadifen-ethyl	2			2
Lambda-cyhalothrin	1			1
Mancozeb	2			2
Mepiquat chloride	1			1
Mesotrione	4			4
Metaldehyde	1			1
Metconazole	6			6
Pethoxamid	1			1
Picloram	3			3
Propaquizafop	1			1
Prothioconazole	3			3
Quizalofop-P-ethyl	1			1
Tau-fluvalinate	1			1
Tebuconazole	5			5
Tembotrione	4			4
Thiophanate-methyl	1			1
Tribenuron-methyl	2			2
DK	**41**			**41**
Aclonifen	3			3
Diflufenican	7			7
Florasulam	4			4
Fluopyram	4			4
Fluroxypyr	4			4
Glyphosate	2			2
Mefentrifluconazole	1			1
Prothioconazole	6			6
Pyraclostrobin	4			4
Tebuconazole	2			2
Tribenuron-methyl	4			4
ES	**93**		**42**	**135**
Acetamiprid	6			6
Azadirachtin			4	4
Azoxystrobin	3			3
Bacillus amyloliquefaciens			2	2

Pesticide name	Conventional	IPM	Organic	Total
bacillus thuringiensis	1		8	9
Bacillus thuringiensis sp. kurstaki			1	1
Chlorantraniliprole	11			11
Chlorantraniliprole	4			4
Citric acid	4			4
Copper			4	4
Copper oxychloride			3	3
Deltamethrin	10			10
Difenoconazole	6			6
Fluopicolide	3			3
Fluxapyroxad	4			4
Helicoverpa armigera			1	1
Indoxacarb	2			2
Lambda-cyhalothrin	9			9
Mancozeb	2			2
Metalaxyl	4			4
Metazachlor	1			1
Natural nettle extract			5	5
Pendimethalin	2			2
phosphorus salts formulated with surfactants	1			1
Piretrinas naturales			1	1
Propamocarb hydrochloride	3			3
Pyrethrin			6	6
Sabadilla Alkaloids			3	3
Spinetoram	2			2
Spinosad			2	2
Spirotetramat	9			9
Sulfoxaflor	5			5
Sweet orange essential oil			2	2
Tau-fluvalinate	1			1
HR	**34**	**38**	**9**	**81**
Acetamiprid		1		1
Alpha-cypermethrin		2		2
Bacillus thurigiensis	2	1		3
Copper		1		1
Copper (1) oxide		2		2
Copper (II) hydroxide			1	1
Copper oxychloride	7	4	3	14
Deltamethrin	10	8	1	19
Dodine		1		1
Flazasulfuron		2		2
Imidacloprid		4		4
Kaolin			3	3
Kresoxim-methyl	3	5		8
Paraffin oil			1	1
Phosmet	2	5		7
Tebuconazole	5	1		6
Trifloxystrobin	5	1		6
IT		**43**	**13**	**56**
Abamectin		2		2
Acetamiprid		1		1
Azadirachtin			1	1
Azoxystrobin		1		1
Bacillus			1	1
Bacillus thuringiensis Berliner g 50			2	2
Bacillus thuringiensis var. kurstaki, SA12 g 18		1		1
Bacillus thuringiensis var. kurstaki, SA12 g 19		1		1
Bacillus thuringiensis var. kurstaki, SA12 g 20		1		1
Bacillus thuringiensis var. kurstaki, SA12 g 21		1		1
Bacillus thuringiensis var. kurstaki, SA12 g 22		1		1
Benfluralin		1		1
Boscalid		1		1
Chlorantraniliprole		1		1
Copper sulphate			2	2
Cypermethrin		1		1
Deltamethrin		1		1

Pesticide name	Conventional	IPM	Organic	Total
Fosetyl		1		1
Hexythiazox		2		2
Indoxacarb		1		1
Lambda-cyhalothrin		4		4
Mancozeb		1		1
Metalaxyl-M		1		1
Metazachlor		1		1
Penconazole		2		2
Pendimethalin		2		2
Potassium bicarbonate		2		2
Propamocarb		1		1
Propyzamide		3		3
Pyraclostrobin		1		1
Pyrethrin			2	2
Spinosad		2	2	4
Spirotetramat		2		2
Sulfoxaflor		1		1
Sulphur			1	1
Sweet orange essential oil		2	2	4
NL	**132**	**55**		**187**
Acetamiprid	12	5		17
Alcohol ethoxylate	5			5
Amisulbrom	1			1
Azoxystrobin	2	2		4
Bacillus subtilis GB03	3			3
Benthiavalicarb	3			3
Carfentrazone-ethyl	3	3		6
Cyazofamid	10	12		22
Cymoxanil	5	7		12
Difenoconazole	1	1		2
Esfenvalerate	20	3		23
Esterified rapeseed oil	2	2		4
Ethoxylates, C18-C20 Fatty Acids, Alkanolamides	1			1
Flonicamid	3			3
Florasulam	2			2
Fluazifop-P-butyl	1			1
Fluopicolide	8	1		9
Glyphosate	1			1
Lambda-cyhalothrin	8	4		12
Mancozeb	1	1		2
Mandipropamid	17	2		19
Manganese	1			1
Metobromuron	2	2		4
Metribuzin	2	2		4
Oxamyl	1			1
Oxathiapiprolin	3			3
Pirimicarb	1			1
Propamocarb		2		2
Propamocarb hydrochloride	8	1		9
Pyraflufen	5	4		9
Sulfoxaflor		1		1
PT		**234**	**118**	**352**
Alpha-cypermethrin		8		8
Azoxystrobin		6		6
Boscalid		13		13
Copper			12	12
Copper (II) hydroxide		2	28	30
Copper oxychloride		8		8
Copper sulphate		7	6	13
Cymoxanil		7		7
Cypermethrin		2		2
Deltamethrin		2		2
Dimethomorph		10	2	12
Dithianon		7		7
Eugenol			2	2
Fluopyram		1		1

Pesticide name	Conventional	IPM	Organic	Total
Fluxapyroxad		2		2
Folpet		20	4	24
Fosetyl-aluminium		10		10
Geraniol			2	2
Glyphosate		2		2
Kresoxim-methyl		13		13
Mancozeb		16		16
Mandipropamid		7		7
Meptyldinocap		2		2
Metalaxyl		4	2	6
Metalaxyl-M		13		13
Metazachlor		3		3
Metiram		3		3
Metrafenone		1		1
Penconazole		10		10
potassium phosphonates		3		3
Pyraclostrobin		2		2
Pyrimethanil		1		1
Pyriofenone		2		2
Quinmerac		3		3
Saccharomyces cerevisiae LAS117			2	2
Sodium hydrogen carbonate			10	10
Spirotetramat		3		3
Spiroxamine		1		1
Sulphur		19	46	65
Tebuconazole		12		12
Thymol			2	2
Trichoderma atroviride (Bio)		2		2
Zoxamide		7		7
SI	**38**			**38**
2,4 D	2			2
Cyprosulfamide	8			8
Foramsulfuron	4			4
Isoxaflutole	4			4
Mesotrione	4			4
Metolachlor	4			4
Terbuthylazine	4			4
Thiencarbazone-methyl	8			8

Table A 2. Reported applied doses [gram active ingredient per ha of treated crop area] of individual pesticides (organic, inorganic and copper-based substances) per case study site country considered in the present deliverable. Note that average, minimum and maximum dose are the same when only a single applied dose was originally reported.

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
FR			
Alpha-cypermethrin	9.9	9.9	9.9
Ametoctradin	248.0	133.8	300.0
Benthiavalicarb	14.0	14.0	14.0
Carfentrazone-ethyl	10.5	10.5	10.5
Copper	68.0	68.0	68.0
Copper	216.0	50.0	500.0
Copper (1) oxide	107.4	15.0	300.0
Copper (II) hydroxide	148.7	21.5	644.9
Copper oxychloride	999.0	999.0	999.0
Copper sulphate	204.1	12.0	746.5
Cyazofamid	109.4	109.4	109.4
Cyflufenamid	17.0	14.1	23.9
Cymoxanil	99.9	99.9	99.9
Cypermethrin	29.2	29.2	29.2
Deltamethrin	7.4	7.4	7.4
Difenoconazole	33.3	28.2	46.5

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
Dimethomorph	193.8	100.4	225.0
Disodium phosphonate	1110.0	1085.0	1135.0
Ethoxylated triglyceride 10 OE	118.5	118.5	118.5
Fenbuconazole	37.5	37.5	37.5
Fluopicolide	110.8	88.8	133.2
Fluopyram	36.5	36.5	36.5
Fosetyl-aluminium	1444.3	752.0	2000.1
Glyphosate	537.1	537.1	537.1
Indoxacarb	37.4	37.2	37.5
Lambda-cyhalothrin	12.4	12.4	12.4
Mandipropamid	125.0	125.0	125.0
Metiram	1038.0	574.0	1400.0
Metrafenone	99.4	97.5	100.0
Oxathiapiprolin	6.0	6.0	6.0
Potassium phosphate	2109.0	2018.5	2169.6
potassium phosphonates	2055.3	1510.0	2265.0
Pyrethrin	15.8	2.4	27.9
Spinosad	4.8	4.8	4.8
Sulphur	2316.1	168.0	8000.0
Sweet orange essential oil	64.4	61.8	72.0
Tau-fluvalinate	48.0	48.0	48.0
Terpene Alcohols	94.4	79.8	113.1
Tetraconazole	20.6	9.9	30.0
Trifloxystrobin	41.3	20.0	62.5
Trifloxystrobin	56.0	36.5	62.5
Zoxamide	109.4	96.0	120.0
CH			
Acetamiprid	61.7	48.0	64.0
Alumina Sulfuric	4400.0	2400.0	5400.0
Azadirachtin	157.7	96.0	200.0
Azoxystrobin	250.0	250.0	250.0
Calcium hydroxyde	1940.0	1940.0	1940.0
Calcium Oxide	300.0	300.0	300.0
Calcium polysulfide	6840.0	6840.0	6840.0
Captan	1408.5	100.0	1920.0
Copper (II) hydroxide	782.1	208.3	2100.0
Copper oxychloride	578.7	175.0	1393.0
Cyflufenamid	26.1	25.0	26.6
Difenoconazole	70.1	6.3	125.0
Dithianon	489.2	280.0	840.0
Emamectin benzoate	30.4	30.4	30.4
Fluazinam	375.0	250.0	500.0
Glufosinate-ammonium	875.0	750.0	1000.0
Glyphosate	823.8	191.5	1920.0
Indoxacarb	60.8	40.5	81.0
Kaolin	34200.0	34200.0	34200.0
Laminarin	33.8	33.8	33.8
Mancozeb	1600.0	1600.0	1600.0
Mepanipyrim	179.8	134.8	224.7
Metalaxyl-M	100.0	100.0	100.0
Myclobutanil	84.0	84.0	84.0
Paraffin oil	40596.0	26560.0	59460.0
Penconazole	3.0	3.0	3.0
Pirimicarb	75.0	75.0	75.0
Potassium bicarbonate	3258.1	2031.5	4974.5
potassium phosphonates	2416.0	2416.0	2416.0
Specially prepared horsetail extract	146.7	80.0	180.0
Spinosad	153.6	153.6	153.6
Spirotetramat	146.0	96.0	200.0
Sulphur	2639.1	640.0	4000.0
Thiacloprid	76.8	76.8	76.8
Thiophanate-methyl	1000.0	1000.0	1000.0
Trifloxystrobin	178.6	150.0	200.0
CZ			
Acetamiprid	34.0	24.0	50.0
Aminopyralid	12.0	12.0	12.0

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
Azoxystrobin	173.3	120.0	250.0
Boscalid	93.3	79.8	100.0
Chlorotoluron	375.0	350.0	400.0
Clethodim	96.0	96.0	96.0
Clomazone	33.6	28.8	36.0
Clopyralid	96.0	72.0	120.0
Deltamethrin	5.0	5.0	5.0
Dimethenamid-P	720.0	720.0	720.0
Dimoxystrobin	100.0	100.0	100.0
Fluazifop-P-butyl	150.0	150.0	150.0
Fluopyram	100.0	100.0	100.0
Flurochloridone	425.0	425.0	425.0
Fluroxypyr	46.9	37.5	75.0
Gamma-cyhalothrin	4.8	4.8	4.8
Halauxifen-methyl	3.3	2.5	5.0
Haloxyfop-R-Methyl Ester	64.8	54.0	75.6
Imazamox	46.4	46.4	46.4
Isofetamid	160.0	160.0	160.0
isoxadifen-ethyl	22.0	22.0	22.0
Lambda-cyhalothrin	7.5	7.5	7.5
Mancozeb	1500.0	1500.0	1500.0
Mepiquat chloride	233.1	233.1	233.1
Mesotrione	75.6	38.4	120.0
Metaldehyde	142.8	142.8	142.8
Metconazole	44.1	30.0	75.0
Pethoxamid	1200.0	1200.0	1200.0
Picloram	16.0	12.0	24.0
Propaquizafop	100.0	100.0	100.0
Prothioconazole	86.5	65.6	100.0
Quizalofop-P-ethyl	100.0	100.0	100.0
Tau-fluvalinate	48.0	48.0	48.0
Tebuconazole	175.0	93.8	250.0
Tembotrione	44.0	44.0	44.0
Thiophanate-methyl	500.0	500.0	500.0
Tribenuron-methyl	13.1	11.3	15.0
DK			
Aclonifen	166.7	150.0	200.0
Diflufenican	57.1	30.0	120.0
Florasulam	46.9	37.5	50.0
Fluopyram	44.7	31.3	50.0
Fluroxypyr	116.6	99.9	166.5
Glyphosate	1080.0	1080.0	1080.0
Mefentrifluconazole	50.0	50.0	50.0
Prothioconazole	43.5	20.0	62.5
Pyraclostrobin	56.3	50.0	75.0
Tebuconazole	51.3	40.0	62.5
Tribenuron-methyl	3.9	3.8	4.0
ES			
Acetamiprid	100.0	100.0	100.0
Azadirachtin	68.0	32.0	80.0
Azoxystrobin	216.7	200.0	250.0
Chlorantraniliprole	35.0	35.0	35.0
Chlorantraniliprole	40.0	40.0	40.0
Copper	480.0	480.0	480.0
Deltamethrin	17.5	12.5	25.0
Difenoconazole	75.0	50.0	125.0
Fluopicolide	100.0	100.0	100.0
Fluxapyroxad	75.0	75.0	75.0
Indoxacarb	60.0	60.0	60.0
Lambda-cyhalothrin	21.7	12.5	65.0
Mancozeb	640.0	640.0	640.0
Metalaxyl	140.0	80.0	200.0
Metazachlor	1000.0	1000.0	1000.0
Pendimethalin	1365.0	1365.0	1365.0
Propamocarb hydrochloride	1000.0	1000.0	1000.0
Pyrethrin	53.3	40.0	60.0

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
Spinetoram	150.0	150.0	150.0
Spinosad	101.3	90.0	112.5
Spirotetramat	89.2	60.0	112.5
Sulfoxaflor	57.6	48.0	60.0
Sweet orange essential oil	180.0	180.0	180.0
Tau-fluvalinate	72.0	72.0	72.0
HR			
Acetamiprid	25.0	25.0	25.0
Alpha-cypermethrin	50.0	50.0	50.0
Bacillus thurigiensis	117.3	80.0	192.0
Copper	102.0	102.0	102.0
Copper (1) oxide	1125.0	1125.0	1125.0
Copper (II) hydroxide	3000.0	3000.0	3000.0
Copper oxychloride	747.4	250.9	2250.0
Deltamethrin	26.7	4.0	75.0
Dodine	816.0	816.0	816.0
Flazasulfuron	15.0	15.0	15.0
Imidacloprid	40.0	40.0	40.0
Kaolin	11866.7	7800.0	20000.0
Kresoxim-methyl	132.5	60.0	300.0
Paraffin oil	16500.0	16500.0	16500.0
Phosmet	525.7	180.0	750.0
Tebuconazole	141.7	60.0	240.0
Trifloxystrobin	70.8	30.0	120.0
IT			
Abamectin	18.9	18.0	19.8
Acetamiprid	320.0	320.0	320.0
Azadirachtin	20.8	20.8	20.8
Azoxystrobin	172.5	172.5	172.5
Benfluralin	1080.0	1080.0	1080.0
Boscalid	400.5	400.5	400.5
Chlorantraniliprole	43.8	43.8	43.8
Copper sulphate	480.0	160.0	800.0
Cypermethrin	50.0	50.0	50.0
Deltamethrin	4.7	4.7	4.7
Fosetyl	620.0	620.0	620.0
Hexythiazox	50.0	50.0	50.0
Indoxacarb	12.8	12.8	12.8
Lambda-cyhalothrin	20.9	3.8	50.0
Mancozeb	1920.0	1920.0	1920.0
Metalaxyl-M	120.0	120.0	120.0
Metazachlor	750.0	750.0	750.0
Penconazole	47.0	47.0	47.0
Pendimethalin	910.0	910.0	910.0
Potassium bicarbonate	2390.2	2390.2	2390.2
Propamocarb	1060.0	1060.0	1060.0
Propyzamide	1466.7	1400.0	1600.0
Pyraclostrobin	100.5	100.5	100.5
Pyrethrin	15.0	15.0	15.0
Spinosad	132.0	96.0	144.0
Spirotetramat	150.0	150.0	150.0
Sulfoxaflor	48.0	48.0	48.0
Sulphur	2400.0	2400.0	2400.0
Sweet orange essential oil	123.6	56.4	240.0
NL			
Acetamiprid	42.0	30.0	50.0
Alcohol ethoxylate	62.6	50.5	66.9
Amisulbrom	100.0	100.0	100.0
Azoxystrobin	718.8	625.0	750.0
Benthiavalicarb	28.0	28.0	28.0
Carfentrazone-ethyl	49.5	39.0	60.0
Cyazofamid	78.5	64.0	80.0
Cymoxanil	109.1	60.0	120.0
Difenoconazole	125.0	100.0	150.0
Esfenvalerate	38.6	5.0	750.0
Esterified rapeseed oil	1263.0	842.0	1684.0

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
Flonicamid	78.3	75.0	80.0
Florasulam	125.0	100.0	150.0
Fluazifop-P-butyl	250.0	250.0	250.0
Fluopicolide	79.9	62.5	100.0
Glyphosate	920.9	920.9	920.9
Lambda-cyhalothrin	2.5	2.5	2.5
Mancozeb	813.8	811.5	816.0
Mandipropamid	125.3	100.0	150.0
Manganese	11205.0	11205.0	11205.0
Metobromuron	912.9	750.0	1000.0
Metribuzin	183.8	120.0	300.0
Oxamyl	1500.0	1500.0	1500.0
Oxathiapiprolin	12.0	12.0	12.0
Pirimicarb	250.0	250.0	250.0
Propamocarb	800.0	800.0	800.0
Propamocarb hydrochloride	798.6	625.0	1000.0
Pyraflufen	19.1	16.9	19.4
Sulfoxaflor	48.0	48.0	48.0
PT			
Alpha-cypermethrin	10.0	10.0	10.0
Azoxystrobin	171.4	140.3	187.0
Boscalid	80.0	80.0	80.0
Copper	41.5	24.0	45.0
Copper (II) hydroxide	318.7	75.3	2500.0
Copper oxychloride	2025.0	1200.0	2500.0
Copper sulphate	1070.8	80.0	2000.0
Cymoxanil	107.1	90.0	120.0
Cypermethrin	250.0	250.0	250.0
Deltamethrin	12.5	12.5	12.5
Dimethomorph	252.7	180.0	300.0
Dithianon	932.1	525.0	1500.0
Eugenol	128.0	128.0	128.0
Fluopyram	80.0	80.0	80.0
Fluxapyroxad	45.0	45.0	45.0
Folpet	804.2	250.0	1200.0
Fosetyl-aluminium	1390.0	1050.0	1500.0
Geraniol	256.0	256.0	256.0
Glyphosate	720.0	720.0	720.0
Kresoxim-methyl	40.0	40.0	40.0
Mancozeb	1381.3	1050.0	1600.0
Mandipropamid	375.0	125.0	1000.0
Meptyldinocap	140.0	140.0	140.0
Metalaxyl	466.7	200.0	1000.0
Metalaxyl-M	93.8	80.0	100.0
Metazachlor	1250.0	1125.0	1500.0
Metiram	916.7	825.0	1100.0
Metrafenone	100.0	100.0	100.0
Penconazole	31.2	30.0	35.8
potassium phosphonates	1158.0	1021.8	1226.1
Pyraclostrobin	75.0	75.0	75.0
Pyrimethanil	1000.0	1000.0	1000.0
Pyriofenone	90.0	90.0	90.0
Quinmerac	416.7	375.0	500.0
Sodium hydrogen carbonate	1980.0	1980.0	1980.0
Spirotetramat	76.5	76.5	76.5
Spiroxamine	300.0	300.0	300.0
Sulphur	3189.5	160.0	15000.0
Tebuconazole	83.1	79.2	102.0
Thymol	256.0	256.0	256.0
Zoxamide	360.0	120.0	960.0
SI			
2,4 D	150.0	150.0	150.0
Cyprosulfamide	45.6	25.5	75.0
Foramsulfuron	55.1	53.6	56.7
Isoxaflutole	97.3	74.3	112.5
Mesotrione	121.9	112.5	131.3

Pesticide name	Average of applied dose (g/ha)	Minimum of applied dose (g/ha)	Maximum of applied dose (g/ha)
Metolachlor	1218.8	1125.0	1312.5
Terbuthylazine	406.3	375.0	437.5
Thiencarbazone-methyl	28.2	17.0	45.0

Table A 3. Sum of environmental impacts of pesticide application including supply chain of pesticides on three areas of protection (human health, ecosystem quality, natural resources) across farms considered in the present deliverable.

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
CH10_1	**26684**	**1399.7**	**206.52**
Captan	11263	665.9	98.97
Copper (II) hydroxide	996	52.4	7.70
Cyflufenamid	139	7.8	1.14
Difenoconazole	571	31.7	4.65
Dithianon	5147	271.6	39.82
Emamectin benzoate	0	0.0	0.00
Glufosinate-ammonium	1627	72.2	10.55
Glyphosate	5774	232.2	34.03
Laminarin	139	7.9	1.15
Spinosad	316	17.9	2.63
Spirotetramat	711	40.1	5.88
CH11_1	**23086**	**940.4**	**137.92**
Acetamiprid	396	22.4	3.28
Captan	2490	128.1	19.03
Copper (II) hydroxide	1852	104.9	15.39
Difenoconazole	446	15.9	2.33
Dithianon	5864	127.3	18.67
Glyphosate	5805	232.2	34.03
Spinosad	333	17.9	2.63
Spirotetramat	633	28.0	4.10
Thiophanate-methyl	5267	263.9	38.46
CH22_1	**4137**	**227.1**	**32.44**
Azadirachtin	659	37.3	5.47
Copper (II) hydroxide	1659	90.4	12.82
Copper oxychloride	1819	99.4	14.15
CH23_1	**2609**	**142.3**	**20.23**
Copper (II) hydroxide	1244	67.8	9.62
Copper oxychloride	1364	74.6	10.61
CH26_1	**70364**	**3986.1**	**584.88**
Kaolin	70364	3986.1	584.88
CH27_1	**4688**	**257.5**	**36.81**
Azadirachtin	823	46.6	6.84
Copper (II) hydroxide	1843	100.4	14.25
Copper oxychloride	2021	110.5	15.72
CH28_1	**9645**	**525.3**	**75.04**
Azadirachtin	790	44.8	6.57
Copper (II) hydroxide	2189	118.5	16.85
Copper oxychloride	6666	362.1	51.63
CH29_1	**1816**	**96.1**	**13.48**
Copper (II) hydroxide	483	25.5	3.56
Copper oxychloride	1332	70.6	9.92
CH3_1	**24935**	**940.7**	**137.03**
Acetamiprid	109	5.6	0.82
Captan	1824	96.0	14.25
Copper (II) hydroxide	5236	286.0	41.04
Cyflufenamid	192	3.7	0.54
Difenoconazole	242	6.0	0.87
Dithianon	11334	288.6	42.31
Glyphosate	1094	43.5	6.38
Laminarin	289	15.7	2.31
Mepanipyrim	1512	45.4	6.62

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Myclobutanil	159	8.3	1.22
Pirimicarb	177	9.9	1.44
Thiophanate-methyl	2765	131.9	19.23
CH4_1	**34279**	**1085.6**	**158.14**
Copper (II) hydroxide	4581	250.3	35.91
Difenoconazole	590	13.9	2.04
Dithianon	22572	509.3	74.66
Glyphosate	1091	43.5	6.38
Indoxacarb	107	4.7	0.69
Thiophanate-methyl	5338	263.8	38.46
CH5_1	**269**	**15.7**	**2.33**
Captan	203	12.0	1.78
Difenoconazole	56	3.1	0.45
Penconazole	11	0.6	0.09
CH6_1	**9988**	**642.2**	**93.46**
Azoxystrobin	1544	87.6	12.83
Difenoconazole	446	24.8	3.64
Fluazinam	689	44.6	6.61
Glufosinate-ammonium	2017	96.2	14.07
Mancozeb	3954	313.2	45.20
Metalaxyl-M	412	23.3	3.42
Trifloxystrobin	926	52.4	7.70
CH7_1	**4341**	**222.3**	**31.43**
Acetamiprid	396	22.4	3.28
Copper (II) hydroxide	1211	61.3	8.37
Copper oxychloride	1193	60.9	8.37
Difenoconazole	143	7.9	1.16
Glyphosate	576	23.2	3.39
Trifloxystrobin	823	46.6	6.84
CH8_1	**5477**	**282.0**	**40.18**
Copper (II) hydroxide	1211	61.3	8.37
Copper oxychloride	1193	60.9	8.37
Difenoconazole	143	7.9	1.16
Dithianon	1206	63.7	9.33
Glyphosate	576	23.2	3.39
Indoxacarb	167	9.4	1.39
Thiacloprid	158	9.0	1.31
Trifloxystrobin	823	46.6	6.84
CZ1_1	**1329**	**70.7**	**10.36**
Acetamiprid	103	5.8	0.86
Aminopyralid	32	1.5	0.22
Boscalid	267	12.6	1.84
Clopyralid	192	9.1	1.32
Deltamethrin	11	0.8	0.11
Gamma-cyhalothrin	11	0.7	0.11
Haloxyfop-R-Methyl Ester	79	3.9	0.58
Lambda-cyhalothrin	17	1.2	0.17
Picloram	64	3.0	0.44
Tau-fluvalinate	109	7.3	1.08
Tebuconazole	442	24.8	3.64
CZ10_1	**4111**	**240.9**	**35.30**
Acetamiprid	125	7.0	1.03
Azoxystrobin	247	14.0	2.05
Halauxifen-methyl	7	0.3	0.05
Metconazole	138	7.4	1.09
Pethoxamid	2902	176.3	25.81
Picloram	32	1.5	0.22
Propaquizafop	159	7.3	1.07
Quizalofop-P-ethyl	148	7.3	1.07
Tebuconazole	354	19.8	2.91
CZ11_1	**1418**	**76.1**	**11.17**
Chlorotoluron	511	30.2	4.42
Clomazone	83	4.4	0.64
Fluazifop-P-butyl	221	10.9	1.61
Gamma-cyhalothrin	11	0.7	0.11
Mesotrione	79	4.5	0.66

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Metconazole	133	5.9	0.87
Prothioconazole	149	6.5	0.95
Tebuconazole	232	13.0	1.91
CZ2_1	**96**	**5.4**	**0.79**
Imazamox	96	5.4	0.79
CZ3_1	**2236**	**118.0**	**17.26**
Acetamiprid	130	7.2	1.06
Azoxystrobin	517	29.3	4.28
Clethodim	280	14.5	2.13
Clopyralid	320	15.1	2.21
Fluopyram	274	12.6	1.84
Gamma-cyhalothrin	22	1.5	0.22
Halauxifen-methyl	20	0.9	0.14
Haloxyfop-R-Methyl Ester	111	5.5	0.81
Picloram	32	1.5	0.22
Prothioconazole	177	9.9	1.45
Tebuconazole	354	19.8	2.91
CZ4_1	**1149**	**73.1**	**10.66**
Acetamiprid	64	3.5	0.51
Thiophanate-methyl	1020	66.0	9.61
Tribenuron-methyl	65	3.7	0.53
CZ5_1	**191720**	**57.6**	**8.44**
Clomazone	104	5.5	0.80
Fluroxypyr	331	14.2	2.07
Gamma-cyhalothrin	13	0.7	0.11
Mesotrione	148	8.4	1.23
Prothioconazole	207	9.3	1.36
Tebuconazole	166	9.3	1.36
Tembotrione	190752	10.3	1.50
CZ6_1	**2920**	**167.9**	**24.59**
Boscalid	267	12.6	1.84
Dimethenamid-P	1741	105.8	15.49
Flurochloridone	912	49.5	7.27
CZ7_1	**3435**	**212.9**	**30.85**
Chlorotoluron	441	26.4	3.87
Clomazone	104	5.5	0.80
Fluroxypyr	220	9.5	1.38
Mancozeb	1855	147.0	21.19
Mesotrione	148	8.4	1.23
Metconazole	186	5.9	0.87
Tembotrione	480	10.3	1.50
CZ8_1	**1704**	**93.9**	**13.76**
Acetamiprid	145	8.2	1.20
Azoxystrobin	309	17.5	2.57
Boscalid	213	10.1	1.47
Gamma-cyhalothrin	11	0.7	0.11
Isofetamid	329	18.6	2.74
Mepiquat chloride	508	28.6	4.17
Metaldehyde	51	3.3	0.51
Metconazole	137	6.9	1.01
CZ9_1	**2101**	**160.8**	**23.24**
Mancozeb	1854	146.9	21.19
Mesotrione	247	14.0	2.05
DK1_1	**696**	**35.1**	**5.12**
Diflufenican	70	4.1	0.60
Fluopyram	138	6.3	0.92
Fluroxypyr	278	12.6	1.84
Prothioconazole	98	5.0	0.73
Pyraclostrobin	102	6.6	0.96
Tribenuron-methyl	10	0.6	0.08
DK1_2	**3923**	**166.4**	**24.37**
Diflufenican	234	13.6	1.98
Florasulam	88	5.0	0.73
Fluopyram	137	6.3	0.92
Glyphosate	3248	130.6	19.14
Prothioconazole	145	6.9	1.02

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Tebuconazole	71	4.0	0.58
DK2_1	**427**	**25.5**	**3.74**
Aclonifen	268	16.3	2.40
Diflufenican	94	5.4	0.79
Florasulam	66	3.7	0.55
DK2_2	**281**	**16.3**	**2.38**
Diflufenican	281	16.3	2.38
DK3_1	**3907**	**150.6**	**22.05**
Diflufenican	127	6.8	0.99
Fluroxypyr	522	12.6	1.84
Glyphosate	3248	130.6	19.14
Tribenuron-methyl	10	0.5	0.08
DK4_1	**359**	**21.3**	**3.12**
Aclonifen	200	12.2	1.80
Diflufenican	70	4.1	0.60
Florasulam	88	5.0	0.73
DK4_2	**1518**	**83.7**	**12.25**
Aclonifen	200	12.2	1.80
Diflufenican	70	4.1	0.60
Florasulam	88	5.0	0.73
Fluopyram	84	3.9	0.58
Fluroxypyr	445	21.0	3.06
Mefentrifluconazole	88	5.0	0.73
Prothioconazole	166	9.3	1.36
Pyraclostrobin	255	16.5	2.40
Tebuconazole	111	6.2	0.91
Tribenuron-methyl	10	0.6	0.08
DK5_1	**590**	**30.4**	**4.44**
Fluopyram	127	6.0	0.87
Fluroxypyr	267	12.6	1.84
Prothioconazole	84	4.7	0.69
Pyraclostrobin	102	6.6	0.96
Tribenuron-methyl	9	0.5	0.08
ES1_1	**188**	**10.5**	**1.54**
Spinosad	188	10.5	1.54
ES10_1	**2333**	**146.0**	**21.28**
Acetamiprid	697	35.0	5.13
Chlorantraniliprole	73	4.1	0.60
Deltamethrin	114	7.6	1.12
Difenoconazole	179	9.9	1.45
Fluxapyroxad	309	17.5	2.57
Mancozeb	797	62.6	9.04
Metalaxyl	165	9.3	1.37
ES10_2	**2395**	**146.1**	**21.28**
Acetamiprid	738	35.0	5.13
Chlorantraniliprole	74	4.1	0.60
Deltamethrin	114	7.6	1.12
Difenoconazole	203	9.9	1.45
Fluxapyroxad	309	17.5	2.57
Mancozeb	794	62.7	9.04
Metalaxyl	165	9.3	1.37
ES11_1	**4490**	**265.1**	**38.77**
Chlorantraniliprole	72	4.1	0.60
Fluopicolide	291	12.6	1.84
Indoxacarb	247	14.0	2.05
Metalaxyl	826	46.6	6.84
Propamocarb hydrochloride	2045	131.9	19.23
Spirotetramat	745	39.3	5.77
Sulfoxaflor	99	5.6	0.82
Tau-fluvalinate	164	10.9	1.61
ES12_1	**3093**	**186.1**	**27.24**
Azoxystrobin	515	29.2	4.28
Lambda-cyhalothrin	148	10.0	1.46
Metazachlor	2430	146.9	21.51
ES2_1	**496**	**28.0**	**4.10**
Azadirachtin	496	28.0	4.10

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
ES3_1	**2155**	**118.3**	**17.31**
Copper	2064	112.2	16.42
Pyrethrin	91	6.1	0.90
ES3_2	**2155**	**118.3**	**17.31**
Copper	2064	112.2	16.42
Pyrethrin	91	6.1	0.90
ES4_1	**546**	**36.4**	**5.38**
Copper oxychloride	0	0.0	0.00
Pyrethrin	546	36.4	5.38
ES5_1	**236**	**13.1**	**1.92**
Spinosad	236	13.1	1.92
ES6_1	**66**	**3.7**	**0.55**
Azadirachtin	66	3.7	0.55
ES7_1	**1191**	**65.2**	**9.55**
Azoxystrobin	412	23.4	3.42
Chlorantraniliprole	166	9.3	1.37
Difenoconazole	222	12.4	1.82
Lambda-cyhalothrin	91	6.1	0.90
Sulfoxaflor	301	14.0	2.05
ES7_2	**1228**	**65.2**	**9.55**
Azoxystrobin	412	23.4	3.42
Chlorantraniliprole	166	9.3	1.37
Difenoconazole	222	12.4	1.82
Lambda-cyhalothrin	91	6.1	0.90
Sulfoxaflor	337	14.0	2.05
ES8_1	**748**	**42.6**	**6.25**
Chlorantraniliprole	145	8.2	1.20
Lambda-cyhalothrin	57	3.8	0.56
Spinetoram	309	17.5	2.57
Spirotetramat	237	13.1	1.92
ES8_2	**745**	**42.6**	**6.25**
Chlorantraniliprole	145	8.2	1.20
Lambda-cyhalothrin	57	3.8	0.56
Spinetoram	309	17.5	2.57
Spirotetramat	234	13.1	1.92
ES9_1	**3252**	**220.0**	**32.30**
Chlorantraniliprole	147	8.2	1.20
Deltamethrin	85	5.7	0.84
Fluopicolide	286	12.6	1.84
Pendimethalin	425	47.6	7.15
Propamocarb hydrochloride	2043	131.9	19.23
Spirotetramat	267	14.0	2.05
ES9_2	**3252**	**220.0**	**32.30**
Chlorantraniliprole	147	8.2	1.20
Deltamethrin	85	5.7	0.84
Fluopicolide	286	12.6	1.84
Pendimethalin	425	47.6	7.15
Propamocarb hydrochloride	2043	131.9	19.23
Spirotetramat	267	14.0	2.05
FR10_1	**7396**	**408.5**	**59.83**
Copper	2458	135.5	19.84
Copper (1) oxide	877	48.2	7.05
Copper (II) hydroxide	4061	224.8	32.94
FR11_1	**7396**	**408.5**	**59.83**
Copper	2458	135.5	19.84
Copper (1) oxide	877	48.2	7.05
Copper (II) hydroxide	4061	224.8	32.94
FR12_1	**1666**	**96.3**	**13.54**
Copper (1) oxide	32	1.8	0.26
Copper (II) hydroxide	923	53.4	7.45
Copper sulphate	691	39.7	5.64
Pyrethrin	11	0.7	0.11
Spinosad	10	0.6	0.08
FR13|14_1	**11063**	**609.1**	**89.19**
Copper	5550	303.8	44.46
Copper (II) hydroxide	5513	305.3	44.73

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
FR16_1	**10256**	**561.9**	**82.26**
Copper	10256	561.9	82.26
FR17_1	**10259**	**561.9**	**82.26**
Copper	10259	561.9	82.26
FR2_1	**13123**	**834.6**	**121.11**
Ametoctradin	238	13.3	1.95
Copper	3700	203.7	29.65
Copper (II) hydroxide	3105	173.1	25.28
Cyazofamid	314	16.6	2.43
Cyflufenamid	58	3.5	0.51
Cypermethrin	66	4.5	0.65
Deltamethrin	17	1.1	0.17
Difenoconazole	140	7.8	1.14
Dimethomorph	207	11.7	1.72
Fluopicolide	241	11.4	1.66
Fluopyram	99	4.6	0.67
Fosetyl-aluminium	3022	250.9	36.11
Indoxacarb	77	4.3	0.64
Lambda-cyhalothrin	28	2.0	0.28
Metiram	1518	109.7	15.83
Metrafenone	201	11.4	1.67
Tetraconazole	18	1.0	0.14
Trifloxystrobin	75	4.3	0.62
FR3_1	**18071**	**1210.2**	**175.52**
Ametoctradin	545	29.7	4.36
Copper	1359	70.2	10.26
Copper (II) hydroxide	1708	93.4	13.68
Copper sulphate	3265	180.4	26.45
Dimethomorph	463	26.2	3.85
Fenbuconazole	133	7.4	1.09
Fluopicolide	237	11.2	1.63
Fosetyl-aluminium	5114	424.5	61.11
Indoxacarb	77	4.4	0.64
Metiram	4470	323.0	46.62
Metrafenone	206	11.7	1.71
Pyrethrin	6	0.4	0.06
Trifloxystrobin	257	14.6	2.14
Zoxamide	230	13.1	1.92
FR4_1	**18618**	**1248.1**	**180.78**
Alpha-cypermethrin	23	1.5	0.22
Ametoctradin	1005	55.3	8.11
Carfentrazone-ethyl	19	1.0	0.15
Copper	3250	176.5	25.82
Copper (II) hydroxide	1358	75.3	11.03
Cyflufenamid	34	2.1	0.30
Difenoconazole	50	2.8	0.41
Fluopicolide	350	16.5	2.41
Fosetyl-aluminium	5914	490.8	70.65
Glyphosate	1615	65.0	9.52
Metiram	5000	361.3	52.15
FR6_1	**17372**	**1149.2**	**166.97**
Benthiavalicarb	29	1.8	0.27
Copper oxychloride	2092	116.6	17.08
Copper sulphate	5587	313.1	45.90
Cyflufenamid	73	4.4	0.65
Cymoxanil	242	14.7	2.15
Difenoconazole	107	5.9	0.87
Fluopicolide	356	16.8	2.45
Fosetyl-aluminium	5370	445.7	64.16
Indoxacarb	77	4.4	0.64
Mandipropamid	257	14.6	2.14
Metiram	1925	139.2	20.08
Metrafenone	206	11.7	1.71
Oxathiapiprolin	12	0.7	0.10
Tau-fluvalinate	109	7.3	1.08
Tetraconazole	96	5.2	0.76

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Trifloxystrobin	170	9.6	1.41
Zoxamide	664	37.6	5.52
FR7_1	**13385**	**849.5**	**123.51**
Copper	2595	140.3	20.52
Copper (II) hydroxide	2106	116.7	17.10
Copper sulphate	1554	87.1	12.77
Dimethomorph	926	52.4	7.70
Fenbuconazole	66	3.7	0.55
Fosetyl-aluminium	1355	112.5	16.19
Metiram	4218	304.8	44.00
Metrafenone	206	11.7	1.71
Trifloxystrobin	129	7.3	1.07
Zoxamide	230	13.1	1.92
FR8_1	**10641**	**584.5**	**85.60**
Copper	4484	243.3	35.61
Copper (1) oxide	1095	60.4	8.85
Copper (II) hydroxide	4954	273.6	40.08
Pyrethrin	108	7.2	1.06
FR9_1	**9654**	**532.5**	**77.60**
Copper	442	24.0	3.49
Copper	3135	170.1	24.71
Copper (1) oxide	2360	130.6	19.05
Copper (II) hydroxide	3591	199.3	29.10
Pyrethrin	127	8.5	1.25
HR1_1	**4935**	**366.9**	**42.40**
Copper (1) oxide	2613	206.9	19.24
Deltamethrin	85	6.0	0.84
Dodine	725	79.8	11.77
Phosmet	1513	74.3	10.55
HR10_1	**7209**	**390.7**	**57.28**
Copper oxychloride	4759	262.6	38.48
Deltamethrin	109	7.3	1.08
Kresoxim-methyl	494	28.0	4.10
Phosmet	363	17.3	2.53
Tebuconazole	990	47.6	6.98
Trifloxystrobin	494	28.0	4.10
HR11_1	**2798**	**153.9**	**22.56**
Alpha-cypermethrin	228	15.2	2.24
Copper oxychloride	1202	65.6	9.62
Imidacloprid	247	14.0	2.05
Kresoxim-methyl	617	35.0	5.13
Phosmet	504	24.1	3.52
HR15_1	**1842**	**97.3**	**14.25**
Acetamiprid	52	2.9	0.43
Copper oxychloride	1203	65.6	9.62
Imidacloprid	82	4.7	0.68
Phosmet	504	24.1	3.52
HR16_1	**4007**	**207.2**	**30.33**
Copper oxychloride	2046	109.4	16.03
Deltamethrin	28	1.9	0.28
Phosmet	1513	72.3	10.55
Tebuconazole	265	14.9	2.18
Trifloxystrobin	154	8.7	1.28
HR17_1	**32691**	**1847.5**	**271.08**
Copper oxychloride	595	29.3	4.29
Kaolin	32096	1818.2	266.79
HR2_1	**41148**	**2331.0**	**342.03**
Kaolin	41148	2331.0	342.03
HR20_1	**706**	**40.6**	**5.97**
Deltamethrin	85	5.7	0.84
Kresoxim-methyl	620	35.0	5.13
HR20_2	**10325**	**542.0**	**79.34**
Copper	222	11.9	1.74
Copper (1) oxide	2433	131.4	19.24
Copper oxychloride	4028	218.8	32.07
Deltamethrin	57	3.8	0.56

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Flazasulfuron	74	4.2	0.61
Kresoxim-methyl	206	11.7	1.71
Phosmet	3025	144.5	21.10
Tebuconazole	177	9.9	1.45
Trifloxystrobin	103	5.8	0.86
HR3_1	**3176**	**175.1**	**25.65**
Copper oxychloride	3176	175.1	25.65
HR4_1	**0**	**0.0**	**0.00**
Deltamethrin	0	0.0	0.00
HR5_1	**1739**	**95.4**	**14.01**
Copper oxychloride	1274	65.7	9.62
Deltamethrin	341	22.7	3.36
Kresoxim-methyl	123	7.0	1.03
HR6_1	**1867**	**101.8**	**14.92**
Copper oxychloride	1513	81.7	11.97
Deltamethrin	18	1.2	0.18
Tebuconazole	212	11.9	1.74
Trifloxystrobin	123	7.0	1.03
HR7_1	**7708**	**350.7**	**51.31**
Copper (II) hydroxide	7708	350.7	51.31
HR8_1	**1747**	**101.9**	**12.25**
Copper oxychloride	1718	100.0	11.97
Deltamethrin	28	1.9	0.28
HR9_1	**1762**	**95.4**	**14.01**
Copper oxychloride	1297	65.7	9.62
Deltamethrin	341	22.7	3.36
Kresoxim-methyl	123	7.0	1.03
IT1_1	**544**	**29.9**	**4.38**
Copper sulphate	341	18.7	2.74
Spinosad	203	11.2	1.64
IT13_1	**17644**	**631.9**	**92.02**
Abamectin	42	2.1	0.31
Boscalid	1075	50.5	7.37
Deltamethrin	11	0.7	0.11
Fosetyl	1250	59.7	8.72
Lambda-cyhalothrin	9	0.6	0.08
Mancozeb	2536	188.0	27.12
Metalaxyl-M	259	14.0	2.05
Propamocarb	2165	139.8	20.38
Propyzamide	10092	163.2	23.94
Pyraclostrobin	206	13.3	1.93
IT14_1	**5356**	**227.4**	**33.46**
Benfluralin	993	64.2	9.51
Propyzamide	4363	163.2	23.94
IT15_1	**2097**	**141.9**	**20.90**
Metazachlor	1814	110.2	16.13
Pendimethalin	283	31.8	4.76
IT17_1	**960**	**41.2**	**6.03**
Acetamiprid	899	37.3	5.47
Indoxacarb	26	1.5	0.22
Lambda-cyhalothrin	34	2.4	0.34
IT18_1	**3887**	**186.5**	**27.36**
Propyzamide	3887	186.5	27.36
IT19_1	**431**	**41.8**	**6.22**
Cypermethrin	114	7.7	1.12
Lambda-cyhalothrin	34	2.3	0.34
Pendimethalin	283	31.7	4.76
IT20_1	**3112**	**130.8**	**19.11**
Abamectin	53	2.3	0.34
Azoxystrobin	359	20.3	2.95
Chlorantraniliprole	94	5.1	0.75
Hexythiazox	259	11.7	1.71
Lambda-cyhalothrin	114	8.0	1.12
Penconazole	209	9.3	1.37
Spinosad	1246	33.6	4.93
Spirotetramat	622	35.0	5.13

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Sulfoxaflor	156	5.6	0.82
IT3_1	**1646**	**93.2**	**13.68**
Copper sulphate	1646	93.2	13.68
IT7_1	**34**	**2.3**	**0.34**
Pyrethrin	34	2.3	0.34
IT8_1	**373**	**21.5**	**3.15**
Azadirachtin	43	2.4	0.36
Pyrethrin	34	2.3	0.34
Spinosad	296	16.8	2.46
NL10_1	**10211**	**617.6**	**90.10**
Cyazofamid	1102	58.2	8.53
Cymoxanil	1280	77.7	11.38
Fluopicolide	234	11.0	1.61
Metobromuron	2464	139.6	20.32
Propamocarb	3266	211.1	30.76
Propamocarb hydrochloride	1786	115.4	16.82
Pyraflufen	80	4.5	0.66
NL11_1	**7368**	**437.7**	**63.81**
Acetamiprid	289	16.3	2.39
Azoxystrobin	1288	73.2	10.69
Carfentrazone-ethyl	69	3.9	0.57
Cyazofamid	1378	72.7	10.67
Cymoxanil	580	35.3	5.16
Esfenvalerate	34	2.3	0.34
Lambda-cyhalothrin	23	1.5	0.22
Mancozeb	1003	79.5	11.46
Metobromuron	2221	125.9	18.32
Metribuzin	345	19.3	2.84
Pyraflufen	40	2.3	0.33
Sulfoxaflor	99	5.6	0.82
NL12_1	**3209**	**180.7**	**26.46**
Acetamiprid	165	9.3	1.37
Azoxystrobin	1545	87.8	12.83
Carfentrazone-ethyl	175	9.8	1.44
Cyazofamid	230	12.1	1.78
Difenoconazole	267	14.9	2.18
Mandipropamid	576	32.6	4.79
Metribuzin	212	11.9	1.74
Pyraflufen	40	2.3	0.33
NL13_1	**8276**	**485.5**	**70.79**
Acetamiprid	309	17.5	2.57
Carfentrazone-ethyl	106	6.0	0.87
Cyazofamid	459	24.3	3.56
Flonicamid	214	10.1	1.47
Florasulam	177	9.9	1.45
Fluazifop-P-butyl	370	18.2	2.68
Fluopicolide	434	20.6	2.99
Lambda-cyhalothrin	17	1.6	0.17
Mandipropamid	1029	58.3	8.55
Metobromuron	1845	104.7	15.24
Propamocarb hydrochloride	3317	214.4	31.25
NL14_1	**16583**	**1001.9**	**146.20**
Acetamiprid	103	5.8	0.86
Amisulbrom	177	9.9	1.45
Azoxystrobin	1545	87.8	12.83
Carfentrazone-ethyl	106	5.9	0.87
Cyazofamid	459	24.2	3.56
Cymoxanil	580	35.3	5.16
Esfenvalerate	91	6.1	0.90
Fluopicolide	634	30.0	4.37
Mandipropamid	1389	78.7	11.54
Metobromuron	2464	139.6	20.32
Metribuzin	531	29.7	4.36
Oxamyl	3066	198.0	28.84
Pirimicarb	510	33.0	4.81
Propamocarb hydrochloride	4847	313.3	45.67

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Pyraflufen	80	4.5	0.66
NL15_1	**9185**	**589.9**	**86.10**
Acetamiprid	194	11.0	1.61
Carfentrazone-ethyl	69	3.9	0.57
Cyazofamid	413	21.8	3.20
Cymoxanil	145	8.8	1.29
Esfenvalerate	1760	117.3	17.30
Flonicamid	200	9.5	1.38
Fluopicolide	617	29.2	4.26
Lambda-cyhalothrin	17	1.1	0.17
Mancozeb	1009	79.9	11.53
Propamocarb hydrochloride	4720	305.1	44.46
Pyraflufen	40	2.3	0.33
NL16_1	**3395**	**194.5**	**28.35**
Acetamiprid	247	14.0	2.05
Benthiavalicarb	171	11.1	1.62
Cyazofamid	689	36.4	5.33
Cymoxanil	290	17.6	2.58
Esfenvalerate	137	10.2	1.34
Florasulam	265	14.9	2.18
Mandipropamid	1235	70.0	10.26
Metribuzin	212	11.9	1.74
Oxathiapiprolin	74	4.2	0.62
Pyraflufen	75	4.2	0.62
NL8_1	**6071**	**297.0**	**43.47**
Acetamiprid	165	9.3	1.37
Azoxystrobin	1545	87.8	12.83
Cyazofamid	230	12.1	1.78
Cymoxanil	290	17.6	2.58
Difenoconazole	178	9.9	1.45
Flonicamid	214	10.1	1.47
Glyphosate	2770	111.4	16.32
Lambda-cyhalothrin	11	0.8	0.11
Mandipropamid	669	37.9	5.56
PT1_1	**24465**	**1544.9**	**224.93**
Boscalid	213	10.1	1.47
Copper oxychloride	4362	233.6	34.20
Cymoxanil	218	13.2	1.94
Dimethomorph	463	26.2	3.85
Dithianon	3591	189.5	27.78
Fluopyram	219	10.1	1.47
Folpet	1057	58.5	8.67
Fosetyl-aluminium	2877	238.8	34.37
Kresoxim-methyl	82	4.7	0.68
Mancozeb	3659	289.9	41.81
Mandipropamid	257	14.6	2.14
Metalaxyl-M	206	11.7	1.71
Metazachlor	3627	220.3	32.26
Metiram	1513	109.3	15.78
Quinmerac	1435	75.8	11.11
Spirotetramat	157	8.9	1.31
Tebuconazole	282	15.8	2.32
Zoxamide	247	14.0	2.05
PT10_1	**2286**	**127.6**	**18.85**
Dimethomorph	465	26.3	3.86
Folpet	1410	78.0	11.56
Metalaxyl	412	23.3	3.42
PT10_2	**2286**	**127.6**	**18.85**
Dimethomorph	465	26.3	3.86
Folpet	1410	78.0	11.56
Metalaxyl	412	23.3	3.42
PT11_1	**980**	**52.8**	**7.73**
Copper (II) hydroxide	980	52.8	7.73
PT11_2	**980**	**52.8**	**7.73**
Copper (II) hydroxide	980	52.8	7.73
PT2_1	**29710**	**1694.0**	**247.40**

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Azoxystrobin	289	16.4	2.40
Copper oxychloride	5800	292.0	42.75
Copper sulphate	8932	466.9	68.41
Cymoxanil	218	13.2	1.94
Cypermethrin	569	38.1	5.60
Deltamethrin	28	1.9	0.28
Fluxapyroxad	93	5.2	0.77
Folpet	529	29.2	4.34
Glyphosate	2166	87.1	12.76
Mancozeb	4847	383.8	55.38
Mandipropamid	514	29.1	4.28
Meptyldinocap	288	16.3	2.39
Metalaxyl-M	330	18.6	2.74
Metazachlor	2720	165.3	24.20
Penconazole	53	3.0	0.44
Pyriofenone	185	10.5	1.54
Quinmerac	1077	56.8	8.33
Spirotetramat	157	8.9	1.31
Tebuconazole	420	23.5	3.46
Zoxamide	494	28.0	4.10
PT2_2	**28948**	**1694.0**	**247.40**
Azoxystrobin	289	16.4	2.40
Copper oxychloride	5433	292.0	42.75
Copper sulphate	8540	466.9	68.41
Cymoxanil	218	13.2	1.94
Cypermethrin	569	38.1	5.60
Deltamethrin	28	1.9	0.28
Fluxapyroxad	93	5.2	0.77
Folpet	529	29.2	4.34
Glyphosate	2165	87.1	12.76
Mancozeb	4845	383.9	55.38
Mandipropamid	514	29.1	4.28
Meptyldinocap	288	16.3	2.39
Metalaxyl-M	330	18.6	2.74
Metazachlor	2720	165.3	24.20
Penconazole	53	3.0	0.44
Pyriofenone	185	10.5	1.54
Quinmerac	1077	56.8	8.33
Spirotetramat	157	8.9	1.31
Tebuconazole	420	23.5	3.46
Zoxamide	494	28.0	4.10
PT3_1	**15710**	**956.3**	**139.62**
Alpha-cypermethrin	46	3.0	0.45
Boscalid	427	20.2	2.94
Copper sulphate	3409	186.8	27.36
Cymoxanil	290	17.6	2.58
Dimethomorph	463	26.2	3.85
Dithianon	1508	79.6	11.67
Folpet	1092	60.4	8.96
Fosetyl-aluminium	1438	119.4	17.19
Kresoxim-methyl	165	9.3	1.37
Mancozeb	1978	156.7	22.60
Mandipropamid	2058	116.6	17.10
Metalaxyl	412	23.3	3.42
Metalaxyl-M	206	11.7	1.71
Penconazole	63	3.5	0.52
Tebuconazole	180	10.1	1.48
Zoxamide	1975	111.9	16.42
PT3_2	**15710**	**956.3**	**139.62**
Alpha-cypermethrin	46	3.0	0.45
Boscalid	427	20.2	2.94
Copper sulphate	3409	186.8	27.36
Cymoxanil	290	17.6	2.58
Dimethomorph	463	26.2	3.85
Dithianon	1508	79.6	11.67
Folpet	1092	60.4	8.96

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Fosetyl-aluminium	1438	119.4	17.19
Kresoxim-methyl	165	9.3	1.37
Mancozeb	1978	156.7	22.60
Mandipropamid	2058	116.6	17.10
Metalaxyl	412	23.3	3.42
Metalaxyl-M	206	11.7	1.71
Penconazole	63	3.5	0.52
Tebuconazole	180	10.1	1.48
Zoxamide	1975	111.9	16.42
PT4_1	**24975**	**1513.4**	**220.49**
Alpha-cypermethrin	46	3.0	0.45
Boscalid	640	30.3	4.42
Copper (II) hydroxide	5532	292.1	42.75
Copper oxychloride	8797	467.2	68.41
Cymoxanil	291	17.6	2.58
Dimethomorph	1235	69.9	10.26
Folpet	1092	60.4	8.96
Fosetyl-aluminium	2781	230.8	33.23
Kresoxim-methyl	247	14.0	2.05
Mancozeb	3708	293.8	42.38
Metalaxyl-M	412	23.3	3.42
Penconazole	53	3.0	0.44
Tebuconazole	140	7.8	1.15
PT4_2	**25157**	**1513.4**	**220.49**
Alpha-cypermethrin	46	3.0	0.45
Boscalid	640	30.3	4.42
Copper (II) hydroxide	5606	292.1	42.75
Copper oxychloride	8905	467.3	68.41
Cymoxanil	291	17.6	2.58
Dimethomorph	1235	69.9	10.26
Folpet	1092	60.4	8.96
Fosetyl-aluminium	2781	230.8	33.23
Kresoxim-methyl	247	14.0	2.05
Mancozeb	3709	293.8	42.38
Metalaxyl-M	412	23.3	3.42
Penconazole	53	3.0	0.44
Tebuconazole	140	7.8	1.15
PT5_1	**25670**	**1406.1**	**205.62**
Copper oxychloride	2603	140.2	20.52
Copper sulphate	3411	186.8	27.36
Dimethomorph	1451	82.2	12.06
Dithianon	12136	640.5	93.88
Metiram	2269	164.0	23.67
Metrafenone	206	11.7	1.71
Pyraclostrobin	306	19.8	2.88
Pyrimethanil	2669	126.2	18.40
Spiroxamine	618	35.0	5.13
PT6_1	**7892**	**498.0**	**72.73**
Azoxystrobin	771	43.8	6.40
Boscalid	213	10.1	1.47
Folpet	2150	118.9	17.63
Fosetyl-aluminium	1007	83.6	12.03
Kresoxim-methyl	82	4.7	0.68
Mancozeb	1298	102.8	14.83
Metalaxyl	2058	116.6	17.10
Metalaxyl-M	206	11.7	1.71
Penconazole	106	5.9	0.87
PT6_2	**7892**	**498.0**	**72.73**
Azoxystrobin	771	43.8	6.40
Boscalid	213	10.1	1.47
Folpet	2150	118.9	17.63
Fosetyl-aluminium	1007	83.6	12.03
Kresoxim-methyl	82	4.7	0.68
Mancozeb	1298	102.8	14.83
Metalaxyl	2058	116.6	17.10
Metalaxyl-M	206	11.7	1.71

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
Penconazole	106	5.9	0.87
PT7_1	**3465**	**186.6**	**27.35**
Copper (II) hydroxide	1792	94.3	13.80
Copper sulphate	431	23.3	3.42
Eugenol	188	9.3	1.37
Geraniol	527	29.8	4.38
Thymol	527	29.8	4.38
PT7_2	**3465**	**186.6**	**27.35**
Copper (II) hydroxide	1792	94.3	13.80
Copper sulphate	431	23.3	3.42
Eugenol	188	9.3	1.37
Geraniol	527	29.8	4.38
Thymol	527	29.8	4.38
PT9_1	**3589**	**190.6**	**27.90**
Copper	567	29.1	4.26
Copper (II) hydroxide	2249	119.4	17.48
Copper sulphate	772	42.0	6.16
PT9_2	**3589**	**190.6**	**27.90**
Copper	567	29.1	4.26
Copper (II) hydroxide	2249	119.4	17.48
Copper sulphate	772	42.0	6.16
SI10_1	**2709**	**148.8**	**22.05**
Mesotrione	236	13.1	1.92
Metolachlor	1613	98.4	14.67
Terbuthylazine	859	37.3	5.45
SI10_2	**2704**	**148.8**	**22.05**
Mesotrione	236	13.1	1.92
Metolachlor	1613	98.4	14.67
Terbuthylazine	855	37.3	5.45
SI12_1	**3168**	**173.6**	**25.72**
Mesotrione	275	15.3	2.24
Metolachlor	1882	114.8	17.12
Terbuthylazine	1011	43.5	6.36
SI12_2	**3168**	**173.6**	**25.72**
Mesotrione	275	15.3	2.24
Metolachlor	1882	114.8	17.12
Terbuthylazine	1011	43.5	6.36
SI2_1	**284**	**12.8**	**1.88**
Cyprosulfamide	60	3.1	0.46
Foramsulfuron	189	7.9	1.15
Thiencarbazone-methyl	35	1.8	0.26
SI2_2	**284**	**12.8**	**1.88**
Cyprosulfamide	60	3.1	0.46
Foramsulfuron	189	7.9	1.15
Thiencarbazone-methyl	35	1.8	0.26
SI4_1	**525**	**26.3**	**3.86**
Cyprosulfamide	166	8.7	1.28
Isoxaflutole	272	13.1	1.92
Thiencarbazone-methyl	86	4.5	0.65
SI4_2	**346**	**17.4**	**2.55**
Cyprosulfamide	109	5.8	0.85
Isoxaflutole	180	8.7	1.27
Thiencarbazone-methyl	57	2.9	0.43
SI6_1	**479**	**23.7**	**3.47**
Cyprosulfamide	150	7.9	1.15
Isoxaflutole	251	11.8	1.73
Thiencarbazone-methyl	77	4.0	0.59
SI6_2	**479**	**23.7**	**3.47**
Cyprosulfamide	150	7.9	1.15
Isoxaflutole	251	11.8	1.73
Thiencarbazone-methyl	77	4.0	0.59
SI8_1	**489**	**23.0**	**3.38**
2,4 D	221	10.9	1.61
Cyprosulfamide	56	3.0	0.44
Foramsulfuron	179	7.5	1.09
Thiencarbazone-methyl	33	1.7	0.25

Farm	Human Health (DALY/ha)	Ecosystem Quality (PDF.m2.yr/ha)	Natural Resources (MJ/ha)
SI8_2	**489**	**23.0**	**3.38**
2,4 D	221	10.9	1.61
Cyprosulfamide	56	3.0	0.44
Foramsulfuron	179	7.5	1.09
Thiencarbazone-methyl	33	1.7	0.25