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Assessing life cycle impacts from toxic substance emissions in major crop production systems in Thailand

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ABSTRACT

Toxicity-related impacts are often omitted or poorly represented in environmental performance assessments of agricultural production systems. Existing studies usually focus on selected aspects, such as pesticides, and rely on the wider range of relevant emissions and life cycle operations, hampering decision support that considers trade-offs and regional characteristics. The present study comprehensively assesses life cycle toxicity impacts of major crop production systems in Thailand, considering all relevant supply chain operations, farm-level field operations, and downstream crop residue burning. Impact characterization factors for farm-level and downstream processes have been specifically parameterized for Thai conditions. All impacts were translated into damage costs for different scenarios based on Thailand's action plans for agricultural production, air pollution control and energy consumption, to facilitate targeted decision support at the national level. Toxicity-related impacts vary considerably across Thai crop production systems, ranging from a few hours (cassava, sugarcane, palm oil) to 1.5 months (rice) of average individual human lifetime loss, and from 15 (sugarcane) to 147 (rice) million species fraction lost over time and water volume. Combined, these crop systems caused damage equivalent to >3.5 trillion Thai Baht in 2019, dominated by pesticide and manure/fertilizer-related farm-level emissions due to human health damage, and by fertilizer and fuel-related supply chain operations due to ecosystem quality damage. The scenarios could substantially reduce toxicity-related impacts on humans and ecosystems across almost all considered crop production systems, mainly through adopting integrated approaches, including optimal use of crop residues and swine manure, and reducing pesticide use and diesel consumption for field operations. Our results demonstrate that including all life cycle operations and regionalized impact factors is crucial to respectively identify major trade-offs across production scenarios and account for country-specific characteristics. The proposed approach is suitable to inform national strategies supporting more sustainable crop production, and can be adapted to consider other production systems and regions.

1. Introduction

Demand for food will rise steadily as the world's population approaches 10 billion in 2050 (FAO, 2017). Sugarcane, maize, wheat, rice, oil palm fruit, and potatoes are considered as major crops, accounting for approximately 60 % of annual global production (FAO,

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2021). Thailand is a significant contributor to the global market of major crop products such as rice, cassava, sugarcane, and oil palm, ranking among the top six countries for global producing and exporting countries (USDA, 2022; USDA, 2021; FAO, 2018). Approximately 66 % of Thailand's agricultural land was planted with major crops in 2019, including rice, cassava, sugarcane, and oil palm, on 11.6, 1.4, 1.9, and 1.0 million hectares (ha), respectively (OAE, 2021).

A major challenge to the Thai agricultural sector in striving for sustainability is responding to global demands while dealing with environmental concerns. The amount of pesticides imported to Thailand ranges from 100 to 198 thousand tonnes per year (DGA, 2022b). Pesticides applied in agricultural areas contaminate land and water resources (Jaipieam et al., 2009; Kruawal et al., 2005). Furthermore, chemical fertilizers ranging from 4.7 to 5.8 million tonnes per year are imported into Thailand (DGA, 2022a). Excess nutrients from manure and fertilizer use enter lakes and waterways through runoff, and enter soil and groundwater through leaching (Inthasan et al., 2010; Wongsanit et al., 2015). Heavy metals are known to contaminate fertilizers, manure, and pesticides and then are released through their application (Alengebawy et al., 2021; Amlinger et al., 2004; Dorca-Preda et al., 2022). Heavy metal residues are therefore found in agricultural soil, surface water, crops, and in the blood of residents (Kladsomboon et al., 2020) as well as in groundwater and tap water (Wongsasuluk et al., 2021). Furthermore, harmful chemicals are released on farms from fuels used in agricultural machines (Steiner et al., 2016). In addition, the burning of crop residues is identified as a main source of air pollution in Thailand (PCD, 2019). Consequently, the emissions of numerous toxic substances from different parts of agricultural production systems in Thailand lead to a wide range of adverse health effects (Nankongnab et al., 2020; Sapbamrer et al., 2020; Wongsasuluk et al., 2021), as well as to negative impacts on the environment (Wongsanit et al., 2015; Chagnon et al., 2015; Kladsomboon et al., 2020).

Life cycle assessment (LCA), a widely standardized methodology, evaluates the environmental sustainability impacts of products and activities throughout their life cycle (ISO 14040, 2006a). The life cycle inventory (LCI) phase in LCA quantifies a system's interactions (resource inputs and emissions) with the environment throughout its life cycle. Life cycle impact assessment (LCIA) translates the LCI results into environmental impacts. Based on human toxicity (Fantke et al., 2021) and ecotoxicity (Owsianiak et al., 2023; Fantke et al., 2018) impact pathways for chemical emissions in LCA, the geographic location can have a significant impact on the environmental fate, as it is linked to the exposure and effects on humans and other living organisms (Wannaz et al., 2018b; Peña et al., 2018). However, assessing impacts with spatial details in local or regional dimensions can be challenging in LCA (Verones et al., 2020). USEtox (https://usetox.org) as a scientific consensus model developed under the UNEP-SETAC Life Cycle Initiative is widely used for characterizing the human toxicity and ecotoxicity impacts of chemicals in LCA (Rosenbaum et al., 2008; Westh et al., 2015). USEtox can be parameterized based on country-specific environmental conditions to derive particular characterization factors (CFs), such as Thai-specific CFs of pesticide emissions in Thailand (Mankong et al., 2022), where more specific spatial emission details or models are not available. The official USEtox version takes into account freshwater ecotoxicity in the area of protection of ecosystem quality as currently the only mature ecotoxicity-related indicator. To cover additional indicators, the LC-IMPACT version of USEtox was developed that also includes marine and terrestrial ecotoxicity impacts of chemicals (Verones et al., 2020), where terrestrial species constitute a dominating contributor to toxicity-related impacts on ecosystems from agricultural emissions.

Based on these considerations, the main goals of the present study are 1) to investigate the potential life cycle toxicity impacts on human and ecosystem health and associated costs caused by chemical emissions in major crop production systems in Thailand, and 2) to recommend approaches to potentially mitigate these impacts. In particular, the following specific questions are addressed: (a) What are the predominant toxic substances emitted from major crop production systems in Thailand? (b) What is the contribution of direct (on-farm) and indirect (relevant supply chain) impacts of pesticides/fertilizers, manure (containing heavy metals)/fuels, and crop residue burning to the total impacts?

This study performs an in-depth analysis that allows (a) considering all life cycle operations to identify trade-offs along the life cycle, and (b) using regionalized impact factors to more adequately capture national environmental characteristics. Toxic substance emissions throughout the production of major crops rice, cassava, sugarcane, and oil palm are quantified and divided into upstream (supply chain operations), field (on-farm operations), and downstream (crop residue burning) emissions. Consequential modelling approaches are applied to assess the supply chain effects of increase in demand of agricultural production in Thailand. Application of pesticides and fertilizer/manure (containing heavy metals), and downstream emissions of heavy metals and polycyclic aromatic hydrocarbons (PAHs) are quantified using specific approaches. Associated impacts of upstream emissions are based on global impact CFs while field/downstream emissions are quantified by Thai-specific CFs. USEtox and LC-IMPACT version of USEtox are applied to derive respective human toxicity and ecotoxicity impact characterization. The aggregated impacts from upstream, field, and downstream emissions yield total impact scores that are translated into damage costs derived for the national context. Alternative scenarios based on Thailand's action plans for agricultural production, air pollution control, and energy consumption are developed and examined for their potential to reduce the quantified impacts.

2. Review of existing toxicity characterization approaches for agricultural systems

Conducting LCAs of agricultural systems is challenging as they are open systems influenced by soil, climate, and farm management (Caffrey and Veal, 2013; Nemecek et al., 2023). Emissions of various toxic substances into different environmental compartments are difficult to measure in real-field situations due to high variation and require a large sample size to obtain reliable results (Nemecek et al., 2023). Various methods or models are key to comprehensively quantifying specific substance emissions in agricultural LCAs. Also, complex calculations are needed, which are not easy to be carried out by users without additional training (e.g., regulators and policymakers). This could be a reason that agricultural LCA studies traditionally rely on available background LCI databases such as ecoinvent (Corrado et al., 2018), combined with characterizing impacts based on global average factors (Foteinis and Chatzisymeon, 2016; Selvaraj et al., 2021; Brito et al., 2023). However, until now, assessing toxicity-related impacts of agricultural production using the LCA framework has mainly focused on toxicity impacts from pesticide application on farms (Juraske and Sanjuán, 2011; Xue et al., 2015; Peña et al., 2019). In contrast, other toxic substance emissions such as heavy metals and PAHs are not commonly considered. Heavy metal emissions from the use of pig manure in fields are quantified using the Swiss Agricultural Life Cycle Assessment (SALCA) method and are identified as a hotspot for metal-based substances in the study of Dorca-Preda et al. (2022). Considering all life cycle operations to identify trade-offs along the life cycle and to present a holistic toxicity assessment of agricultural production is currently missing for various production systems.

Furthermore, toxic substances emitted on farms require local or regional impact characterization in LCA to consider substantial differences in environmental conditions. Evaluating environmental impacts with spatial details in LCA will allow for more accurate and realistic results, capturing the consequences of local or regional emissions. In recent years, there has been a greater focus on developing geographically differentiated LCIA methods such as LC-IMPACT (Verones et al., 2020) and IMPACT World+ (Bulle et al., 2019). Recent studies illustrate the significance of more accurate and realistic evaluations of environmental impact results when regionalized characteristics are applied (Henderson et al., 2017; Anton et al., 2014). Spatial differentiation is hence identified as important for aggregated human health damage, being up to five times higher when compared to generic assessment scores (Owsianiak et al., 2018). The environmental burden (i.e., via land use, water use, ozone formation, terrestrial acidification) varies by up to one order of magnitude for the individual impact categories (Owsianiak et al., 2018; Heidari et al., 2017). Therefore, spatial differentiation is crucial when applied to agricultural systems, such as in tropical countries like Thailand. For example, in tropical agricultural systems, high temperatures increase the degradation and volatilization rates of chemical emissions, while heavy rains and loose soils increase runoff and leaching behavior (Daam et al., 2019).

Nevertheless, up-to-date emission and characterization models are not fully appropriate for crop cultivation in tropical regions (e.g., Thailand) (Gentil et al., 2020). USEtox, a globally recommended model for characterizing human toxicity and ecotoxicity in LCA, is based on default or generic global/continent-level inputs. Alternatively, the geospatial Pangea model provides impact scores with high spatial resolutions (Wannaz et al., 2018a; Wannaz et al., 2018b). However, this model is currently not available as a user-friendly version and requires complex calculations performed by experts. A study by Mankong et al. (2022) showed that the USEtox consensus model can be parameterized for Thailand-specific conditions by adjusting default parameters such as landscape, temperature, population, and food consumption. Differences ranging from 1 to 169 % for human toxicity and from 0.1 to 3587 % for ecotoxicity of pesticide-related toxicity impacts were observed. This parameterized model can be further applied to derive country-specific CFs for characterizing human toxicity and ecotoxicity of other substances available or not available in USEtox, and be further applied to other tropical countries. However, only freshwater ecotoxicity is currently considered to be mature enough for inclusion in the official USEtox version. The LC-IMPACT version of USEtox includes additional ecotoxicity impacts on marine and terrestrial species, which is also recommended for ecotoxicity modelling of metals (Owsianiak et al., 2023). All in all, existing approaches for characterizing toxicity impacts in LCA for agricultural systems lack regional specificity and coverage of relevant emissions - research gaps that we address in the present study.

3. Methodology

The life cycle toxicity assessment on human health and ecosystem quality has been carried out following ISO 14040 (2006a) and ISO 14044 (2006b), and the guidelines of Weidema (2003).

3.1. Scope of the study

Key agricultural materials (i.e., pesticides, fertilizers, manure, fuels, and electricity) required for rice, cassava, sugarcane, and oil palm cultivation in Thailand, and related crop residue managements are investigated for any toxic substance emissions causing potential toxicity impacts on human health and ecosystem quality. The functional unit

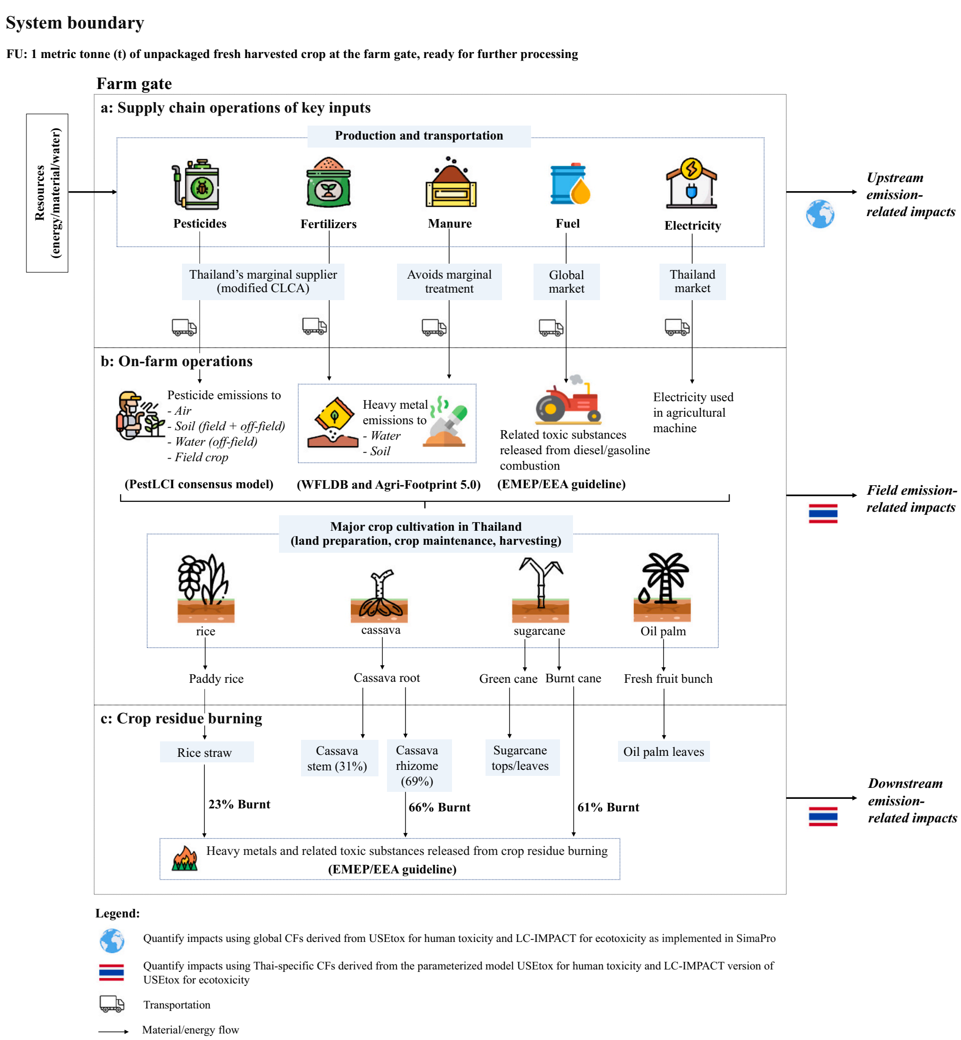

Fig. 1. System boundary considered for life cycle toxicity assessment for major crop production systems in Thailand according to different emission sources (a, b, c).

(FU) is defined as 1 metric tonne (t) of unpackaged fresh harvested crop at the farm gate, ready for further processing (hereafter referred to as "tonne of crop"). The system boundary considered in this study is "cradle-to-farm gate", and the life cycle toxicity assessment is carried out based on Fig. 1.

3.2. Base case and scenario development

Base cases are adopted as the business-as-usual (BAU) scenario to reflect the current agricultural practices or conventional farming without modifications in different major crop production systems in Thailand. Alternative scenarios (S1 to S5) and related sub-scenarios are developed based on Thailand's action plans to mitigate potential impacts on human health and ecosystem quality as summarized in Table 1. Thailand's current and future action plans related to agricultural production, air pollution control, and energy consumption include 1) Action Plan of the Department of Agricultural Extension for 5 years (2023–2027) (DOAE, 2021), 2) Organic Agriculture Action Plan 2023–2027 (MOAC, 2022), 3) National Roadmap to Solve Particulate Matter Pollution Report (PCD, 2019), and 4) Paris Agreement (ONEP, 2021). More details on scenario development and associated strategies/approaches of Thailand's action plans are described in Electronic Supplementary Material-1 (ESM1), Tables S1 and S2.

3.3. Inventory analysis

The LCI of major crops produced in Thailand is obtained from the field survey of rice (Arunrat et al., 2021), cassava (Pingmuanglek, 2016), sugarcane (Pongpat et al., 2017), and oil palm (Gheewala, 2014; Silalertruksa et al., 2017). The inventories are provided based on the defined FU for input materials and agricultural activities on farms, as documented in the Electronic Supplementary Material-2 (ESM2), Section S1. Current crop residue management of Thailand's major crops is identified and detailed in the ESM2, Section S2. Quantifying toxic substance emissions across major crop production systems are structured into the upstream, field, and downstream emissions as described in Sections 3.3.1 to 3.3.3.

Table 1
The summary of developed scenarios and description.

Scenario (S)	Description
Business as usual (BAU)	Conventional farming of major crop production systems in Thailand
S1_alternative fertilizer + no burning	Chemical fertilizer and manure reduction along with no crop burning on farms responding to Thailand action plans No. 1 and No.3.
S1a_R + cattle S1b_R + swine S1c_R + poultry S1d_R + chemicals	The share of crop residues (R) considered as a source of organic fertilizers is applied to avoid crop burning and replace chemical fertilizers and/or manure based on nutrient Nitrogen (N), Phosphorus (P), and Potassium (K) requirements. Different systems according to defined scenarios, S1a) cattle manure, S1b) swine manure, S1c) poultry manure, and S1d) chemical fertilizers are added to complete the BAU system.
S2_modified pesticide	Modification of pesticide application doses to meet Good Agricultural Practices (GAP) and compensation of banned pesticides responding to Thailand action plan No.1.
S3_organic farming + no burning	Organic farming along with no crop burning on farms responding to Thailand action plans No.1, No.2, and No.3.
S3a_R + cattle + no pesticide S3b_R + swine + no pesticide S3c_R + poultry + no pesticide	Sub-scenarios 'S1a_R + cattle, S1b_R + swine, and S1c_R + poultry' are applied. All pesticides used in crop cultivation are excluded and integrated techniques are defined to manage the pests.
S4_diesel reduction	Biodiesel is used instead of diesel used in agricultural machines at 30 % responding to Thailand action plan No.4.
S5_integrated approach	Selection of effective scenarios for impact reduction in conventional and organic farming
S5a_conventional farming	Scenarios S1b_R + swine and S2_modified pesticide combined with S4_diesel reduction
S5b_organic farming	Scenarios S3b_R + swine + no pesticide combined with S4_diesel reduction

3.3.1. Quantifying toxic substance emissions of upstream processes

Upstream emissions consider processes and toxic substance emissions related to the input supply chain activities including their production and market activities. Based on statistics on major crop cultivation in Thailand during the crop year 2010 to 2019 (ESM1, Fig. S1), there is a trend of increasing crop cultivation. An increase in demand to produce major crops is therefore expected in Thailand, which will consequently lead to an increase in demand for agricultural inputs. The consequential ecoinvent database v3.8 available under SimaPro v9.4.0.3 (Moreno et al., 2020) is applied as background data. The ecoinvent processes of all input materials required to produce the major crops are identified and documented in ESM2, Section S3.1.

Consequential modelling approaches quantify the global environmental impacts due to a change in demand for a product/service based on marginal data on suppliers, and to avoid co-product allocation by system expansion (Weidema, 2003; Ekvall, 2019). Markets connect users and suppliers of products and services; hence market demands are key in determining which users and suppliers are involved in certain decisions. Marginal suppliers are those suppliers able to increase (or decrease) their supply when demand for their product or commodity rises (or drops). Marginal suppliers of key inputs (i.e., pesticides and fertilizers) used in considered crop production systems are identified based on the guidelines of Weidema et al. (2009) as illustrated in the ESM2, Sections S3.2 and S3.3. The long-term market trends for 10 years are applied to specify the long-term marginal suppliers of pesticides and fertilizers used in Thailand, which are mainly imported and documented by the Office of Agricultural Regulation, Department of Agriculture (DOA), Thailand (DGA, 2022a; DGA, 2022b). The increasing trend and the share of suppliers are considered to define the marginal suppliers. China is identified as the long-term marginal supplier of pesticides applied in Thailand with a contribution of 63 to 78 % to the total pesticide imports in the period of 2012 to 2021. China and Saudi Arabia are the main suppliers of chemical fertilizers used in Thailand, contributing approximately 35 % to total imports from 2012 to 2021. The supply chain processes related to pesticides and fertilizers are modified with the source of materials from identified marginal suppliers, and electricity supply from the Asia market at medium voltage (see the process modification in ESM2, Section S3.1). The weighted average of market share is applied when more than one marginal supplier is considered.

3.3.2. Quantifying toxic substance emissions from field operations

Field emissions include related toxic substances that are applied and then directly emitted on farms. Pesticide fractions distributed across environmental compartments (i.e., air, soil, water, and crop) after field application are estimated using the PestLCI consensus web tool (Nemecek et al., 2022). Model variables such as the fraction of pesticide intercepted by leaves, application method, crop seasons, time of application, region climate, and soil types are defined as shown in ESM2, Section S4.1. The application of fertilizers and manure causes the emissions of heavy metals to water via leaching and emission to soil via a balance between heavy metals emitted into soil (fertilizers, manure, and deposition), and the fraction which is either transfered from soil to other media such as water through leaching, or converted to the biomass (Nemecek et al., 2019; Van Paassen et al., 2019). Heavy metal emissions are derived from the World Food LCA Database (WFLDB) (Nemecek et al., 2019) and Agri-Footprint 5.0 (Van Paassen et al., 2019) guidelines as demonstrated in ESM2, Section S4.2. Emissions to air caused by on-farm fuel combustion (i.e., diesel and gasoline) due to applying agricultural machinery and transport of inputs are quantified using the emission factors guided by EMEP/EEA (EEA, 2019a; EEA, 2021), as shown in ESM2, Section S4.3.

3.3.3. Quantifying toxic substance emissions of downstream processes

Downstream emissions consider related toxic substances that occur during crop residue burning on farms, including burning before sugarcane harvesting. Based on the current crop residue management in Thailand (see ESM2, Section S2), on-farm burning is used to quickly eliminate rice straw (23 %), cassava rhizome (66 %), and sugarcane tops/leaves (61 %). The burning of crop residues in the open field is a source of toxic substance emissions (e.g., heavy metals) into the atmosphere (Oanh et al., 2018; Yao et al., 2023). The emission mass of toxic substances is quantified using emission factors from EMEP/EEA (EEA, 2019a, 2019b). The mass of burnt residues (i.e., activity rate) (kg dry matter) is derived through multiplying five parameters, namely, residue-to-product ratio, dry-matter-to-crop residue ratio, fraction burned in the field, crop-specific burning efficiency based on literature, and crop production of 1 tonne FU as detailed in ESM2, Section S5.1.

3.4. Quantifying impact scores of toxic chemical emissions

Potential toxicity impacts on human health and ecosystem quality caused by major crop production systems in Thailand are quantified in terms of impact scores (*IS*) for an impact category as:

$$IS = \sum_{c,i} \left(M_{c,i} \times CF_{c,i} \right)$$

where $M_{c,i}$ is the emission mass of identified toxic substance *i* from crop systems into an environmental compartment *c* per tonne of crop produced ($kg_{emitted}$/t), and $CF_{c,i}$ is the respective characterization factors for human health damages (DALY/$kg_{emitted}$) or for ecosystem quality damages (PDF m^3 d/$kg_{emitted}$). The human toxicity characterization factors (cancer and non-cancer) at damage level are expressed as disability-adjusted life years (DALY) per kg of emitted toxic substance. The ecotoxicity characterization factors at the damage level are expressed as a potentially disappeared fraction (PDF) of ecosystem species integrated over the exposed environmental compartment volume and time per kg of emitted toxic substance. Impact scores (DALY for human health and PDF m^3 d for ecosystem quality per tonne of crop produced) resulting from all identified toxic substances emitted throughout a crop production system are quantified from the summation about a tonne of crop.

Based on the defined boundary, impacts are assessed on the upstream, field, and downstream emissions across the crop systems. USEtox considers the toxicity impacts of chemicals on humans in the area of protection of human health. The LC-IMPACT incorporates the ecotoxicity impacts of chemicals on freshwater, marine, and terrestrial (soil) species in the area of protection of ecosystem quality. The impact scores of upstream emissions are quantified using global characterization factors obtained from USEtox v2.12 and LC-IMPACT v1.01 as implemented in SimaPro v9.4.0.3 (PRé Sustainability bv, Amersfoort, the Netherlands). Field and downstream emissions-related impacts are quantified by Thai-specific characterization factors derived from the formal USEtox consensus model v2.12 and from the LC-IMPACT version of USEtox parameterized for Thai environmental conditions (e.g., landscape, temperature, population, and food consumption) provided by Mankong et al. (2022). In addition, the species richness parameter is only available in the LC-IMPACT version of USEtox, where it has been adjusted for Thailand by applying the values from Indochina as shown in the ESM2, Section S10. Thai-specific characterization factors of chemicals considered in this study are shown in ESM2, Section S6. More details on the derivation of impact scores based on BAU and developed scenarios can be found in ESM2, Sections S3, S4, S5, S7, and S8. Some limitations and recommendations related to quantifying the impacts of toxic substance emissions are provided in ESM1.

3.5. Sensitivity analysis

Sensitivity analysis is performed to check the robustness of results and their sensitivity to variable parameters in LCA (Wei et al., 2015). The important input parameters considered in this study are pesticides, fertilizers, and diesel (i.e., used in machinery) applied in major crop production systems in Thailand. The minimum and maximum applied amounts of pesticides/fertilizers/diesel in each crop system based on regions and sugarcane harvesting practices are used for sensitivity testing as detailed in ESM1, Table S1. A method of testing how the LCA results change when varying (increasing or decreasing) input parameters by 10 % is applied when regional data is not available. The potential toxicity impacts on human health and ecosystem quality of modified input materials are quantified and demonstrated in ESM2, Section S9. BAU potential ecotoxicity impacts per defined FU in Thailand are compared based on LC-IMPACT version of USEtox and the formal USEtox model in upstream, field, and downstream emissions (ESM2, Sections S3, S4, and S5). Two major inventory modelling approaches in LCA are typically referred to as attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA). These models have been used in responding to different research questions (Ekvall, 2019). To meet all aspects of the agricultural LCA study, ALCA should also be applied to quantify upstream emissions-related impacts in BAU and different action plan scenarios. The background data based on ecoinvent processes of all input materials are identified and shown in ESM2, Section S9.

4. Results and discussion

4.1. Business-as-usual impacts

This study aims to assess the impacts of Thailand's major crop production systems on human health and ecosystem quality caused by toxic substance emissions according to where and how much they occur along the life cycle as shown in Figs. 2 and 3.

The BAU results indicate that total human toxicity impacts (Fig. 2) per one-tonne production of rice are 0.124 DALY or 1.5 months of average individual human lifetime loss, while it is 0.00064, 0.002, 0.00028 DALY or 6, 17, 2 h of average individual human lifetime loss from cassava, sugarcane, and oil palm production, respectively. Fig. 3 shows that one tonne of rice, cassava, sugarcane, and oil palm production causes ecotoxicity impacts of 147, 32, 15, and 54 million PDF m^3 d. Table 2 and Fig. S2 (in ESM1) further demonstrate the life cycle toxicity impacts caused by upstream and field/downstream emissions which allow us to identify the main contributors to the source emissions.

4.1.1. Upstream emission-related impacts

Table 2 and Fig. S2 (in ESM1) demonstrate that the supply chain activities related to the fertilizers and fuel (i.e., diesel in rice, cassava, sugarcane, and gasoline in oil palm) are identified as the major contributors to upstream emission-related human toxicity and ecotoxicity impacts. Fertilizer production including the supply chain of nutrients such as N, P, K, and associated transport can release several toxic substances (e.g., Cr, As, Pb) as shown in the ecoinvent database. Therefore, the contribution of upstream activities of fertilizers to the total human toxicity and ecotoxicity impact is determined as 34 to 35 % for rice, 68 to 69 % for cassava, 51 to 52 % for sugarcane, and 79 % for oil palm. Based on the inventories of oil palm production, 12 kg of K_2O fertilizer is used to produce a tonne of fresh fruit bunch, which is 3 to 17 times higher than in other crop production. Thus, the supply chain activities of K_2O fertilizer are identified as the main contributor to human toxicity (47 %) and ecotoxicity (49 %) impacts in oil palm production. In addition, fuel supply chain activities have the highest contribution to the human toxicity and ecotoxicity impacts in rice (diesel: 43 to 45 %), cassava (diesel: 23 to 24 %), sugarcane (diesel: 38 to 41 %), and oil palm (gasoline: 8 to 9 %). According to the foreground data, an average of 15 L of

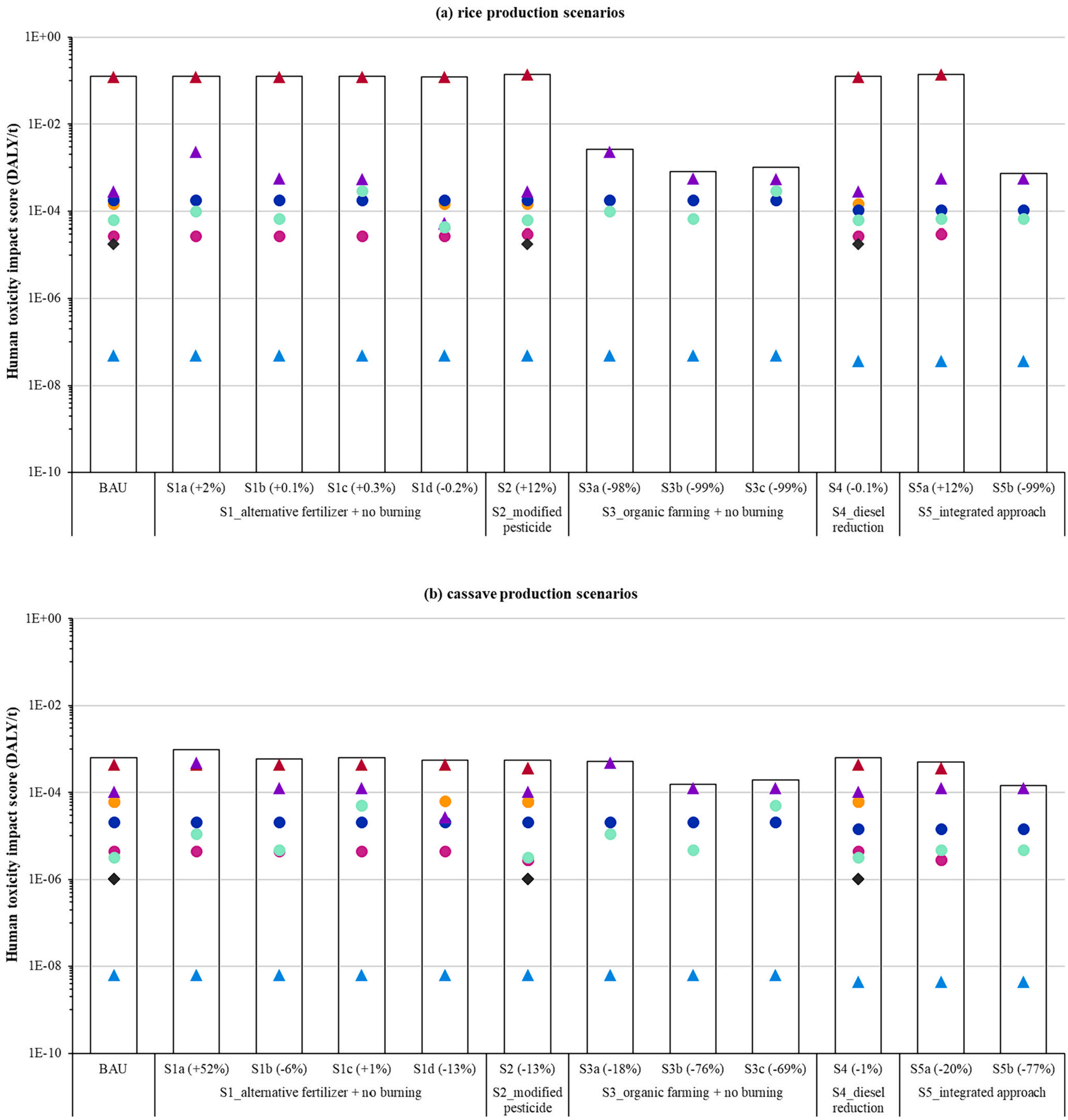

Fig. 2. Action plan scenarios compared to business-as-usual (% change, (+) increase or (−) decrease) of total human toxicity impact scores of one-tonne production of (a) rice, (b) cassava, (c) sugarcane, and (d) oil palm in Thailand with the contribution of upstream (●, U), field (▲, F), and downstream (◆, D) emission-related impacts. U-Other processes include U-Manure, U-Soil amendment, U-Gasoline, U-Ethanol, U-LPG, U-Natural gas, and U-Electricity. F-Other processes include F-Diesel used in machinery, F-Gasoline used in machinery, and F-Diesel used in transport. More details on impact scores based on business-as-usual and action plan scenarios of each process contribution are illustrated in ESM2, Section S8.

diesel is used in agricultural machinery per one tonne of paddy rice, compared to an average of 0.2 to 2.1 L for other major crops. Based on the ecoinvent database, the contribution of some emitted toxic substances from diesel production such as As, Cr, Hg, Ba, and Zn to human toxicity is determined as 29, 17, 14, 9, and 8 %, respectively, while the contribution to ecotoxicity is determined for Al, Ba, and Sr as 94, 3, and 2 %, respectively.

4.1.2. *Field and downstream emission-related impacts*

Table 2 and Fig. S2 (in ESM1) demonstrate that on-farm emissions of pesticides and heavy metals are crucial contributors to the total human toxicity and ecotoxicity impacts.

On-farm pesticide emissions show a high impact contribution to the human toxicity impacts for rice (100 %), cassava (81 %), sugarcane (100 %), and oil palm (32 %). Pesticides used in these crops are mainly distributed to agricultural soil (47 to 93 %) and field crops (19 to 47 %).

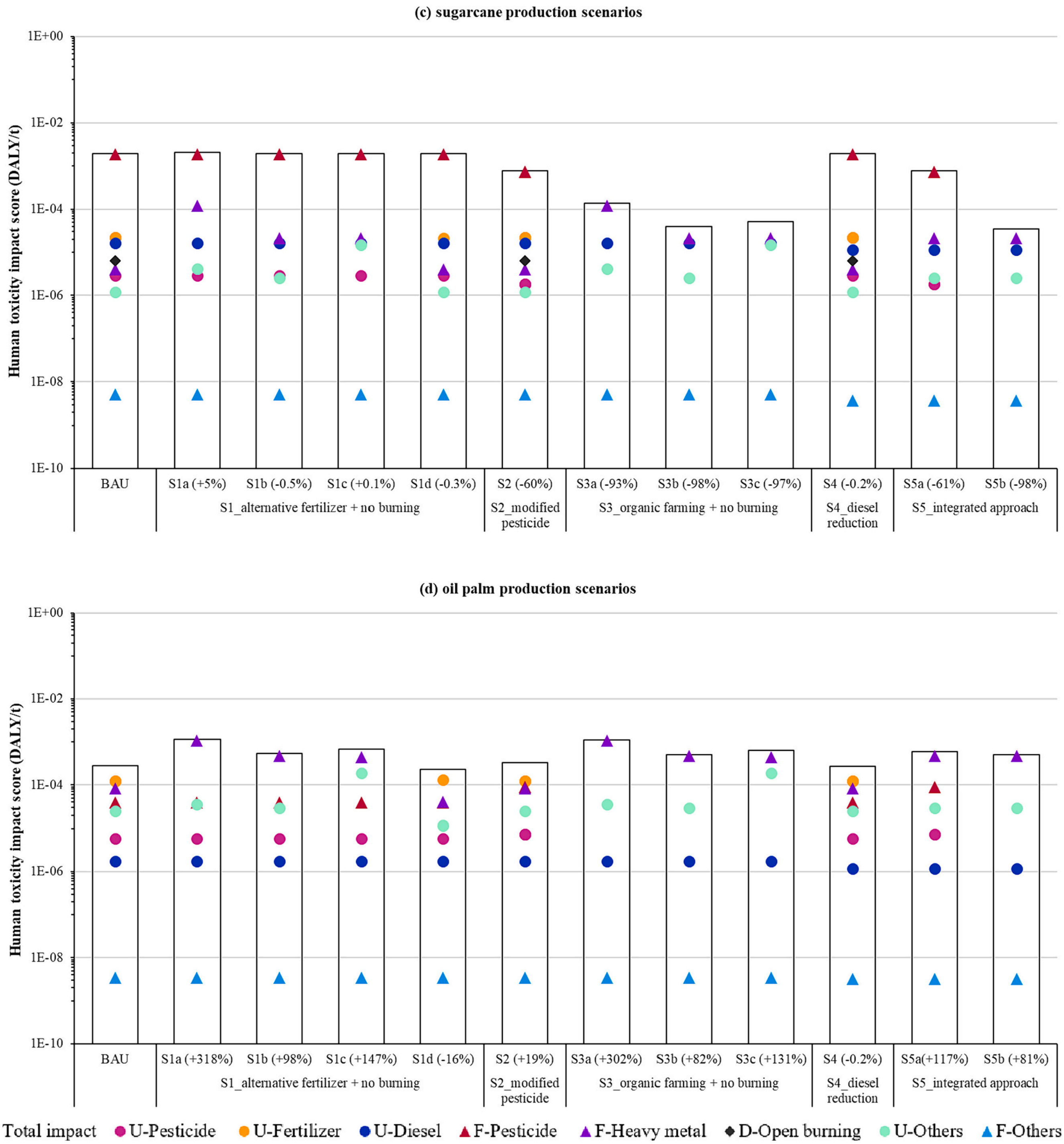

Fig. 2. (*continued*).

Consumption of pesticide residues in treated crops is the main pesticide exposure pathway for the general human population (Fantke and Jolliet, 2016). Based on the collected data, a total pesticide active ingredient of 2 kg is applied per one tonne of harvested rice which is 5 to 7 times higher than in other crops, resulting in the highest human toxicity impacts. Pesticides with high contribution to human toxicity impacts are Butachlor (51 %) and Glyphosate-isopropylammonium (36 %) in rice, 2,4-D dimethyl ammonium (97 %) in cassava, Ametryn (99 %) in sugarcane, and Glyphosate-isopropylammonium (91 %) in oil palm. These are the top ten herbicides used in Thailand annually (NABC, 2021). The results indicate that heavy metals emitted from fertilizer and manure application at farms are also the main contributors to cassava (19 %) and oil palm (68 %) cultivation. Based on the inventories, due to using fewer pesticides and high fertilizer/manure in cassava and oil palm production, heavy metal emissions become the major contributors to human toxicity impacts. The main heavy metals that contribute to human toxicity impacts of cassava and oil palm production are Zn (56 to 75 %) mainly sourced from manure and Cd (18 to 33 %) mainly sourced from chemical fertilizers. Animal feed contamination with heavy metals such as Cd and Pb has been reported which comes from feed processing and on-farm pollution. These metals (e.g., Cu, Zn, and Fe) are used as supplements for growth promotion and antimicrobial purposes (Dai et al., 2016; Zhang et al., 2012).

For ecotoxicity impacts, the results show that heavy metals released

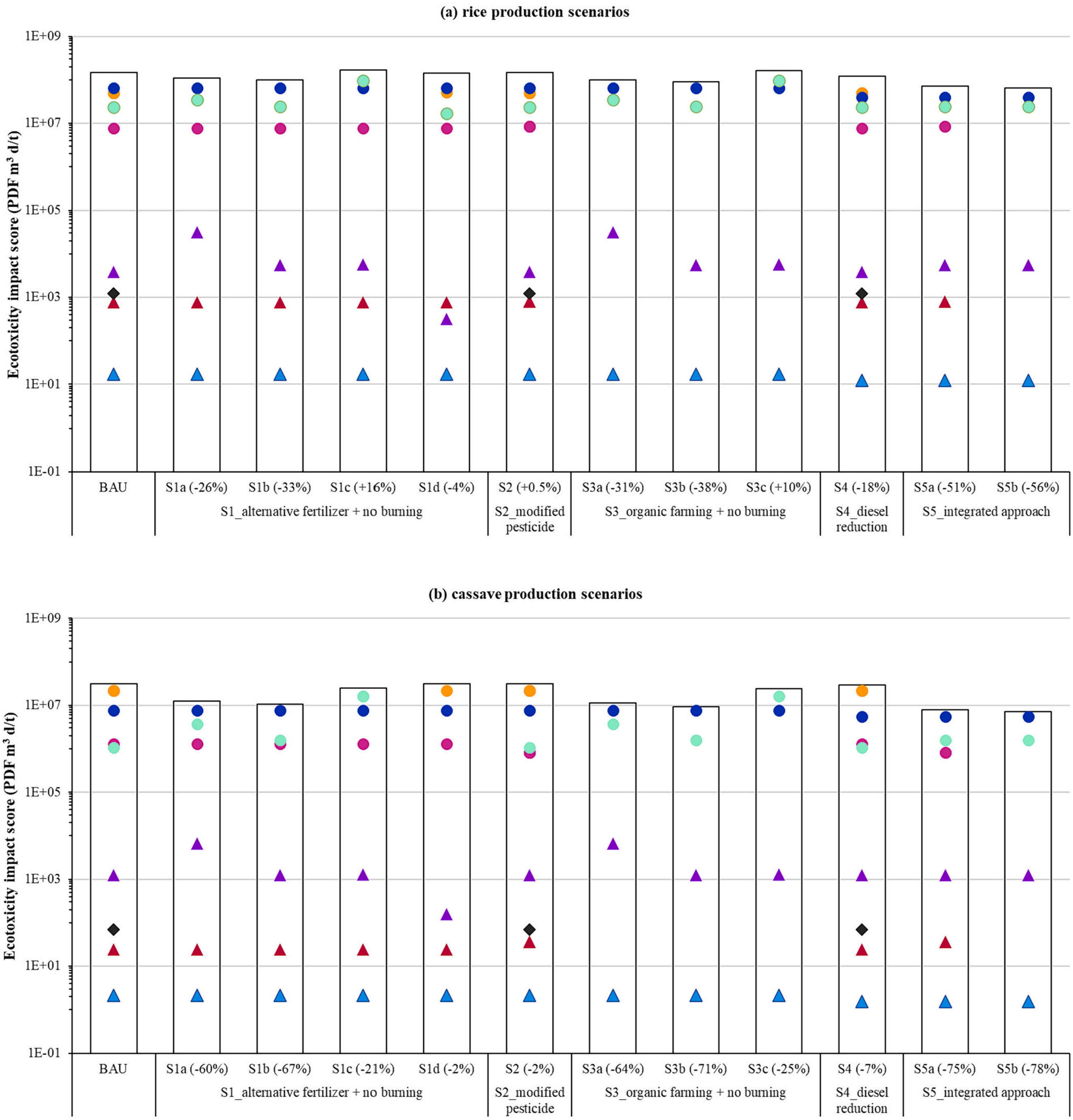

Fig. 3. Action plan scenarios compared to business-as-usual (% change, (+) increase or (−) decrease) of total ecotoxicity impact scores of one-tonne production of (a) rice, (b) cassava, (c) sugarcane, and (d) oil palm in Thailand with the contribution of upstream (●, U), field (▲, F), and downstream (◆, D) emission-related impacts. U-Other processes include U-Manure, U-Soil amendment, U-Gasoline, U-Ethanol, U-LPG, U-Natural gas, and U-Electricity. F-Other processes include F-Diesel used in machinery, F-Gasoline used in machinery, and F-Diesel used in transport. More details on impact scores based on business-as-usual and action plan scenarios of each process contribution are illustrated in ESM2, Section S8.

from fertilizers and manure applications are major contributors to rice (83 %), cassava (98 %), and oil palm (98 %) cultivation. Rice cultivation requires the highest fertilizers (i.e., 30 kg applied) and manure (i.e., 162 kg applied) for one tonne of production. This may explain why heavy metal emissions in rice production systems dominate the ecotoxicity impacts. The main heavy metals that contribute to ecotoxicity impacts in rice, cassava, and oil palm cultivation are Zn (63 to 66 %) and Cu (20 to 30 %). High Zn emissions to freshwater and agricultural soil in these crop production systems (0.003 to 0.1 kg/t of crop) combined with high Thai-specific CFs (ranging from 0.003 to 20,648 PDF m^3 d/kg emitted) yield high ecotoxicity impact scores. Pesticide on-farm emissions are also the main contributors to ecotoxicity impacts with the contribution of 17 % and 87 % in rice and sugarcane cultivation. In rice cultivation, predominant pesticides are Acetochlor (55 %), Atrazine (21 %), and Alachlor (15 %), while in sugarcane, it is Ametryn (85 %) and Atrazine (15 %). The main contributing pesticides (i.e., Alachlor, Atrazine, and Ametryn) currently used in Thailand are in fact banned in Europe based on EU regulation number 649/2012 (European Parliament, 2023).

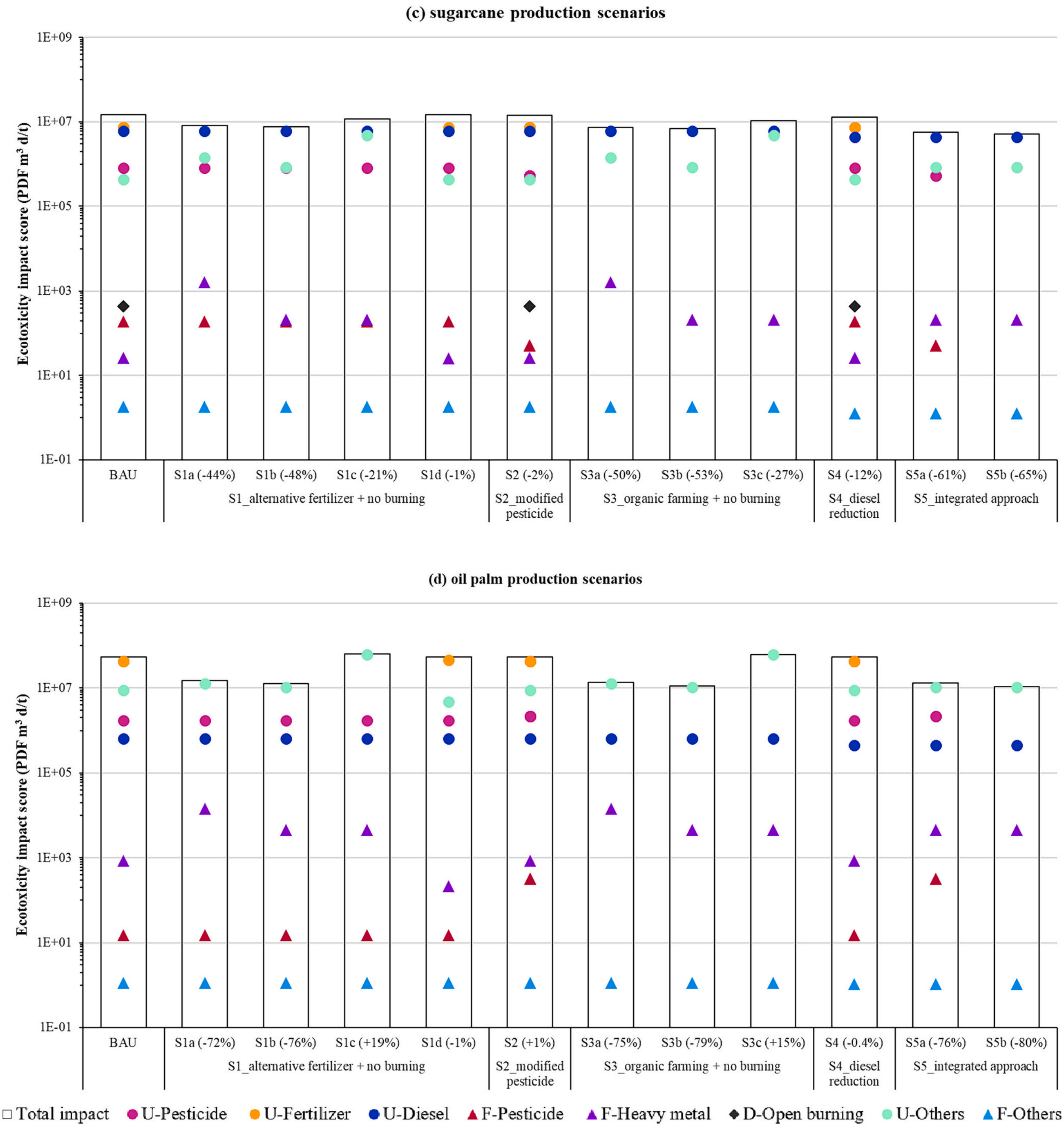

Fig. 3. (*continued*).

For downstream emission-related impacts (Table 2), the main toxic substances released from crop residue burning (i.e., rice straw, cassava rhizome, and sugarcane trash) that contribute to human toxicity are Hg (42 %), Cd (37 %), and Benzo[*a*]pyrene (11 %), and Cd (92 %) for ecotoxicity.

4.1.3. Overall emission-related impacts and damage costs

Figs. 2, 3, and Table 2 show the contribution of all involved inputs to the total toxicity impacts considering upstream, field, and downstream emissions. The BAU results in Table 2 indicate that emissions coming from upstream (i.e., supply chain activities related to the required agricultural inputs) mostly dominate the total ecotoxicity impacts by 100 %, and are mainly caused by fertilizers and fuel production. The contribution of total upstream emissions to total ecotoxicity impacts of major crop production systems is 4 to 5 orders of magnitude higher than field emissions (see also the impact scores in ESM2, Section S7). Meanwhile, the contribution of upstream emissions to total human toxicity impacts is determined as 0.3 % for rice, 14 % for cassava, 2.2 % for sugarcane, and 56 % for oil palm due to fertilizer production. On the other hand, the contribution of field emissions (on-farm operations) to total human toxicity impacts is determined as 44 to 100 % mainly caused by pesticide and heavy metal emissions. Furthermore, downstream emissions show a slight contribution (0.2 to 0.3 %) to total human toxicity impacts.

Table 2
Main process and toxic substance contribution (% share) to human health (a) and ecosystem quality (b) impacts based on different emission sources for one tonne of major crop production in Thailand.

Emission source	Main process/substance contribution (%) per emission source			
	Rice	Cassava	Sugarcane	Oil palm
a) Human health impacts[a]				
U-Pesticide	6.7 %	4.9 %	6.9 %	3.8 %
U-Fertilizer	35.2 %	68.8 %	51.9 %	79.0 %
	Urea (52), N (27), P_2O_5 (14), K_2O (7)	N (54), K_2O (30), P_2O_5 (16)	N (69), P_2O_5 (15), K_2O (15), Urea (1)	K_2O (47), N (40), P_2O_5 (12)
U-Manure	4.8 %	3.6 %	0.0 %	8.5 %
U-Soil amendment	n/a	n/a	n/a	−0.3 %
U-Diesel	42.8 %	22.7 %	38.4 %	1.1 %
	As (29), Cr (17), Hg (14), Ba (9), Zn (8)	As (29), Cr (17), Hg (14), Ba (9), Zn (8)	As (29), Cr (17), Hg (14), Ba (9), Zn (8)	
U-Gasoline	10.6 %	n/a	2.5 %	7.7 %
	As (31), Cr (14), Hg (12), Pb (7), Ba (7), Cd (6)			
U-Ethanol	n/a	n/a	n/a	0.0 %
U-LPG	n/a	n/a	n/a	0.1 %
U-Natural gas	n/a	n/a	n/a	0.0 %
U-Electricity	n/a	n/a	0.3 %	0.0 %
F-Pesticide	99.8 %	80.7 %	99.8 %	32.2 %
	Butachlor (51), Glyphosate-isopropylammonium (36), Alachlor (10)	2,4-D dimethyl ammonium (97)	Ametryn (99)	Glyphosate-isopropylammonium (90), Chlorpyrifos (10)
F-Heavy metal	0.2 %	19.3 %	0.2 %	67.8 %
		Zn (75 %), Cd (18), Pb (4)		Zn (56), Cd (33), Pb (6)
F-Diesel combustion from machinery	0.0 %	0.0 %	0.0 %	0.0 %
F-Gasoline combustion from machinery	0.0 %	n/a	0.0 %	0.0 %
F-Diesel combustion from transport	0.0 %	n/a		0.0 %
D-Open burning[b]	100 %	100 %	100 %	n/a
	Hg (42), Cd (37), Benzo[*a*]pyrene (11)	Hg (42), Cd (37), Benzo[*a*]pyrene (11)	Hg (42), Cd (37), Benzo[*a*]pyrene (11)	
	Process contribution (%) per total impacts			
Upstream (U)	0.3 %	14.3 %	2.2 %	56.1 %
Field (F)	99.7 %	85.6 %	97.5 %	43.9 %
Downstream (D)	0.0 %	0.2 %	0.3 %	n/a
b) Ecotoxicity impacts[a]				
U-Pesticide	5.3 %	4.1 %	5.4 %	3.2 %
U-Fertilizer	34.0 %	68.2 %	50.8 %	78.9 %
	Urea (52), N (27), P_2O_5 (13), K_2O (7)	N (54), K_2O (31), P_2O_5 (15)	N (69), K_2O (16), P_2O_5 (14), Urea (1)	K_2O (49), N (40), P_2O_5 (11)
U-Manure	4.4 %	3.3 %	0.0 %	7.9 %
U-Soil amendment	n/a	n/a	n/a	0.2 %
U-Diesel	44.9 %	24.3 %	40.8 %	1.2 %
	Al (94), Ba (3), Sr (2)	Al (94), Ba (3), Sr (2)	Al (94), Ba (3), Sr (2)	
U-Gasoline	11.4 %	n/a	2.8 %	8.5 %
	Al (96), Ba (3), Sr (2)			
U-Ethanol	n/a	n/a	n/a	0.0 %
U-LPG	n/a	n/a	n/a	0.1 %
U-Natural gas	n/a	n/a	n/a	0.0 %
U-Electricity	n/a	n/a	0.2 %	0.0 %
F-Pesticide	16.5 %	1.9 %	87.0 %	1.8 %
	Acetochlor (55), Atrazine (21), Alachlor (15)		Ametryn (85), Atrazine (15)	
F-Heavy metal	83.1 %	97.9 %	12.2 %	98.1 %
	Zn (63), Cu (30), Cr (4)	Zn (66), Cu (25), Cd (5)	Cd (37), Cr (30), Zn (26)	Zn (63), Cu (20), Cd (10)
F-Diesel combustion from machinery	0.3 %	0.2 %	0.8 %	0.0 %
F-Gasoline combustion from machinery	0.0 %	n/a	0.0 %	0.1 %
F-Diesel combustion from transport	0.0 %	n/a		0.0 %
D-Open burning[b]	100 %	100 %	100 %	n/a
	Cd (92)	Cd (92)	Cd (92)	
	Process contribution (%) per total impacts			
Upstream (U)	100.0 %	100.0 %	100.0 %	100.0 %
Field (F)	0.0 %	0.0 %	0.0 %	0.0 %
Downstream (D)	0.0 %	0.0 %	0.0 %	n/a

n/a means that the process does not apply in a particular crop system.
More details on the main process and toxic substance contributors are presented in the ESM2, Section S3 (upstream), S4 (field), and S5 (downstream).
[a] The main substance contributors are identified when the process shows ≥10 % of impact contribution.

[b] Only on-farm burning of generated crop residues is taken into account.

To have a comprehensive view of potential national-level impacts, the damage costs of major crop production on human health and ecosystem quality are quantified as shown in Fig. 4. In 2019, 31, 31, 129, and 16 million tonnes of rice, cassava, sugarcane, and oil palm, respectively, were produced in Thailand on a plantation area of 15.9 million ha (OAE, 2023). As a result, the total human health and ecosystem quality impacts of major crop systems in Thailand in 2019 were 4.1 × 10^6 DALY (i.e., around 56 thousand statistical human lives when considering human life expectancy in 2019 of 73.4 years (WHO, 2023)) and 8.4 × 10^{15} PDF m^3 d. More details on the derivation of damage costs are shown in ESM2, Section S7. Based on the major crop production in Thailand in 2019 and the monetary factors projected by Mankong et al. (2022), the damage costs related to four major crops produced per crop year are 2453 billion Thai Baht (THB) for human health and 1224 billion THB for ecosystem quality. Rice production shows the highest contribution to total human health (93 %) and ecosystem quality (55 %) damage costs compared with other major crop production. Pesticide application is identified as the main contributor to the total human health damage costs, with the contribution of 99 %. Fertilizer and diesel production are the main contributors to ecosystem quality damage costs, accounting for 47 % and 37 % of the contribution to the total costs respectively. Mankong et al. (2022) reported the pesticide damage costs (external costs) on human health and ecosystem quality as 7188 and 3.01 million THB/crop-year for nine crops in Thailand (i.e., rice cultivation with a dry direct-seeded system and with a pre-germinated direct-seeded system (83 % share of rice cultivation), vegetables, and fruit trees). Fantke et al. (2012) quantified the health impacts and related damage costs of pesticides used in Europe in 2003 accounting for 1960 DALY corresponding to annual damage costs of 78.4 million Euro (EUR) or approximately 3 billion THB (1 EUR ≈ 38 THB). Pimentel (2005) estimated the environmental and social costs of pesticides used in the United States, which were determined as 1.1 billion USD per year for public health (around 39 billion THB, 1 USD ≈ 34.4 THB) and 3.1 billion USD per year for the loss of ecosystem species (around 107 billion THB, 1 USD ≈ 34.4 THB). Based on the previous studies on pesticide damage costs, the relevant cost on human health and ecosystem quality for the four major crops in Thailand in crop year 2019 is high. However, in this study, we consider not only pesticides but also various toxic substances from upstream, field, and downstream emissions in terms of their impacts and associated damage costs. In particular, Thailand's large-scale major crop production systems result in high overall toxicity impacts and associated damage costs per crop year.

4.2. Action plan scenarios compared to business-as-usual

Five alternative scenarios divided into 11 sub-scenarios are developed and applied in major crop production systems in Thailand to mitigate the life cycle of human and ecosystem health impacts. The developed scenarios according to Thailand's action plans are subjected to conventional and organic farming. Figs. 2 and 3 illustrate the total human toxicity and ecotoxicity impacts of action plan scenarios compared to BAU (% change) with process contribution of upstream, field, and downstream emissions. The results indicate that the impacts and contributions can vary across different major crop production systems.

Scenario S1 aims to identify the manure/fertilizer types lowest impacts on human health and ecosystem quality compared to BAU. The results show that substituting organic fertilizers (crop residues + manure) for chemical fertilizers significantly reduces the ecotoxicity impacts with the exception of poultry manure used in rice and oil palm. The application of swine manure (i.e., scenario S1b_R + swine) along

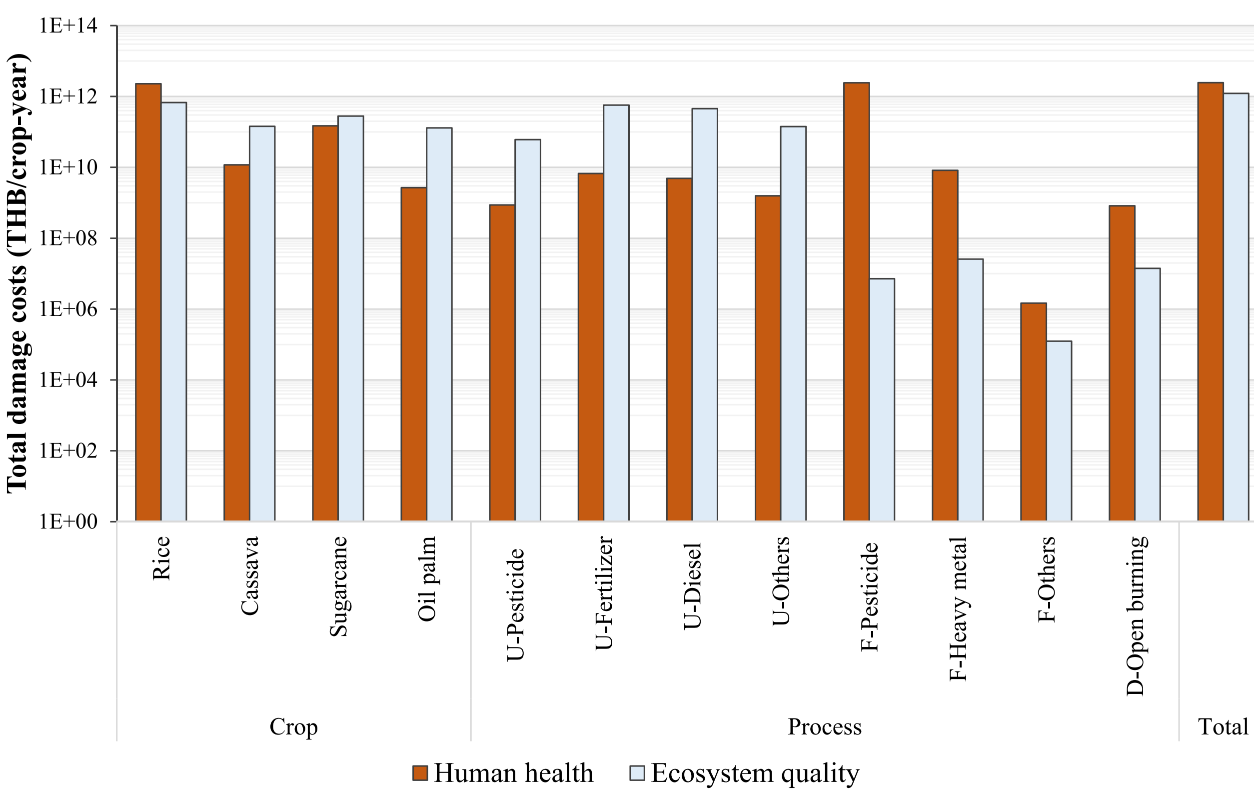

Fig. 4. Total damage costs to human health and ecosystem quality of major crop production (tonne) in Thailand in crop year 2019 illustrated by crop, process (U: upstream, F: field, and D: downstream), and total. U-Other processes include U-Manure, U-Soil amendment, U-Gasoline, U-Ethanol, U-LPG, U-Natural gas, and U-Electricity. F-Other processes include F-Diesel used in machinery, F-Gasoline used in machinery, and F-Diesel used in transport.

with crop residues has the highest potential to reduce the ecotoxicity impacts of rice (33 %), cassava (67 %), sugarcane (48 %), and oil palm (76 %), while it has limited potential to mitigate the human toxicity impacts of cassava (6 %) and sugarcane (0.5 %) production. However, it shows an increase in human toxicity impacts from the production of rice (0.1 %) and oil palm (98 %). Similarly, the application of cattle manure in all major crops significantly reduces the ecotoxicity impacts by 26 to 72 %. However, this manure can increase the human toxicity impacts by 2 to 318 %. High poultry manure used in scenario S1c_R + poultry (i.e., 28 to 515 kg per tonne of crop) is identified as an additional contributor to human toxicity (ranging from 0.1 to 147 %) in all crop production systems and to ecotoxicity in rice (16 %) and oil palm (19 %) production. Poultry manure application on farms releases heavy metals (e.g., Zn, Cd, Cu) resulting in human toxicity impacts. The supply chain activities of poultry manure also release various toxic substances causing additional human toxicity (e.g., Cr, As, Pb, Ni, Cd) and ecotoxicity (e.g., Al) impacts. Meanwhile, using crop residues with chemical fertilizers instead of manure in scenario S1d_R + chemicals shows impact mitigation from 0.2 to 16 % for human toxicity and 1 to 4 % for ecotoxicity.

In scenario S2, pesticide application doses in major crops are adjusted to meet the Good Agricultural Practices (GAP). The banned pesticides are compensated based on the same pesticide target pests and modes of action. Since pesticide application on farms is the main contributor to field emission-related human toxicity impacts, modified pesticides affect the high variability of impacts. There is a small influence on ecotoxicity impacts (ranging from −2 to +1 %). Scenario S2_modified pesticide effectively mitigates human toxicity impacts in cassava (13 %) and sugarcane (60 %) production. Substituting Glyphosate-isopropylammonium for Paraquat dichloride in cassava and sugarcane according to guidelines, reduces the total pesticide application doses by 32 % and 46 %, respectively. Meanwhile, total pesticide application doses in rice and oil palm production systems are increased by 8 % and 69 %. This is a reason for increasing the human toxicity impacts in rice and oil palm production at 12 % and 19 %. Glyphosate-isopropylammonium, the predominant pesticide that contributes to field emission-related human toxicity impacts in oil palm systems is thus shared with Captan (26 %) due to the increased dose from 0.00003 to 0.12 kg applied per tonne of crop. Moreover, substituting Carbosulfan for Chlorpyrifos in oil palm results in an increased dose from 0.0011 to 0.04 kg applied per tonne of crop. The modified oil palm system-related human toxicity impacts are thus caused by Carbosulfan at 20 %. For rice production systems, the application dose of Glyphosate-isopropylammonium is adjusted from 0.21 to 0.353 kg applied per tonne of crop. Glyphosate-isopropylammonium with the contribution of 53 % therefore becomes the main contributor instead of Butachlor for field emission-related human toxicity impacts in rice production.

In scenario S3 as organic farming, crop residues are used as organic fertilizers to avoid crop burning. All chemical fertilizers and synthetic pesticides as the main contributors to human toxicity and ecotoxicity impacts are excluded from the crop production systems. Different manure is used instead of chemical fertilizers and current integrated techniques are defined to manage the pests in the specific system. The results therefore show that this scenario significantly mitigates human toxicity in rice, cassava, and sugarcane production (ranging from 18 to 99 %), but it leads to an increase in the impacts in oil palm production (ranging from 82 to 302 %). The results indicate that applying swine manure combined with no pesticides in organic farming (i.e., scenario S3b_R + swine + no pesticide) results in the highest reduction in human toxicity impacts, ranging from 76 to 99 % in all crops except for oil palm and for ecotoxicity from 38 to 79 % in all crops. This scenario is highly effective, achieving almost 100 % reduction in human toxicity impacts in rice and sugarcane production, due to the significant impacts caused by pesticide use. However, the heavy metal emissions from manure application become the predominant contributors instead of pesticides in related human toxicity impacts in all crop production. The high amount of each manure required to meet the main nutrient K requirement in the BAU system of oil palm results in high heavy metal emissions related to human toxicity impacts. Similarly, even after excluding chemical fertilizers and pesticides from the crop systems, the ecotoxicity impacts can still be high due to the supply chain activities of diesel, manure, and gasoline.

Scenario S4 (S4_diesel reduction) aims to investigate the impact of reducing diesel used in machinery. The results show that replacing 30 % of diesel with biodiesel has a limited potential to reduce the total impacts ranging from 0.1 to 1 % for human toxicity and 0.4 to 18 % for ecotoxicity. Diesel is identified as the main contributor to ecotoxicity impacts in rice production. Therefore, the reduction of diesel used in rice results shows the highest ecotoxicity impact mitigation of 18 % followed by sugarcane (12 %), cassava (7 %), and oil palm (0.4 %). This scenario is not effective in oil palm production due to the use of gasoline as the main fuel type.

Based on the results, an integrated approach is required to relieve the human toxicity and ecotoxicity impact potential in major crop production in Thailand. Therefore, Scenario S1b_R + swine, S2_modified pesticide, and S4_diesel reduction are selected for use in conventional farming (i.e., scenario S5a_conventional farming). Scenario S3b_R + swine + no pesticide and S4_diesel reduction are selected for use in organic farming (i.e., scenario S5b_organic farming). Swine manure is identified as having the most effective input in mitigating ecotoxicity impacts in all major crop production compared with other manure/fertilizers investigated in scenarios S1 and S3. Swine manure combined with no pesticides also has a high potential for human toxicity impact mitigation in rice, cassava, and sugarcane production evaluated by scenario S3. Although the scenario S2_modified pesticide is not effective in rice and oil palm production (i.e., impact increased by 0.5 to 19 %), this scenario should be included in the integrated approach scenario to promote the GAP and to manage the banned pesticides. The results show that scenario S5a_conventional farming effectively mitigates impacts in cassava and sugarcane production, ranging from 20 to 61 % for human toxicity and 61 to 75 % for ecotoxicity. This scenario is also effective in reducing ecotoxicity by 51 % and 76 % in the production of rice and oil palm, but it is unable to minimize the human toxicity impacts (i.e., impact increased by 12 % and 117 %). Meanwhile, scenario S5b_organic farming demonstrates the greatest performance for ecotoxicity impact reduction ranging from 56 to 80 % in all major crop production. This scenario is also effective in reducing human toxicity impacts in the production of rice (99 %), cassava (77 %), and sugarcane (98 %), but not in oil palm production.

4.3. Sensitivity analysis results

The changes in outputs per change in input are measured and presented in percent change (ESM2, Section S9). The results show a wide range of percent change, ranging from −100 % to +3525 % when applying minimum and maximum amounts of key input materials used in each crop system based on region and practice in sensitivity analysis as illustrated in ESM2, Section S9. This analysis demonstrates that the impacts rely on key input values proportionally, suggesting that accurate data is important in maintaining the accuracy of total impacts. The interpretation of the results should rely on the specific data collected in a particular year and the scope of the study. However, sensitivity analysis with varying amounts of input parameters (i.e., minimum and maximum, and ± 10 %) in this study refers to the fluctuation of input materials required in crop cultivation systems in practice.

However, the results show a limitation in using minimum inputs and the variation of emission fractions for sensitivity analysis in LCA. Some pesticides are excluded from the sensitivity analysis due to no application data (by regions or harvesting practices) as well as the varied pesticide emission fractions causing disproportionate sensitivity results. In addition, Fig. S3 in ESM1 shows that the upstream emission-related ecotoxicity impacts derived from LC-IMPACT version of USEtox are higher than those derived from USEtox consensus model at 2 to 3 orders of magnitude for all process contributions. Based on the results, considering ecotoxicity impacts on marine and terrestrial (soil) species in LC-IMPACT is crucial. Similarly, field emission-related ecotoxicity impacts, LC-IMPACT version of USEtox provides impact scores higher than USEtox at 1 to 2 orders of magnitude for all process contributions except for field pesticide and heavy metal emissions. Impacts from heavy metal emissions based on LC-IMPACT version of USEtox are the same or higher than those from USEtox at 1 order of magnitude. Meanwhile, pesticide application impacts based on the LC-IMPACT version of USEtox are the same or lower than those from USEtox at 1 order of magnitude. In LC-IMPACT version of USEtox, the species richness factor is adjusted for Thailand by applying the value of Indochina. As a result, the species richness of freshwater species in Thailand is 0.09, default USEtox uses 0.12. The reduction of species richness decreases the ecotoxicity impacts of pesticide and heavy metal emissions which are the main contributors to the field ecotoxicity impacts.

Table S3 in ESM 1 shows that there are no significant differences in upstream emission-related total toxicity impacts of major crop production derived from ALCA and CLCA. When focusing on each material production, the largest difference in toxicity impacts associated with upstream emissions from these two models is observed by only 1 order of magnitude. However, the results show the differences in positive and negative impacts found in borax and ethanol production. The details of borax and ethanol production modelled based on ALCA and CLCA available in the ecoinvent process are examined. The same resources and sources of materials are considered in the two models for borax and ethanol production. The major difference in the ALCA and CLCA modelling is from the share of electricity and heat used in borax and ethanol production. These two models have been developed based on different concepts with different purposes for supporting decisions. ALCA assesses a share of global environmental significant flows in and out of a product life cycle based on specific or market average supplier data and treats co-product allocation by applying allocation factors. CLCA quantifies the global environmental impact due to a change in demand for a product/service based on marginal data on suppliers, and avoids co-product allocation by system expansion or substitution (UNEP-SETAC, 2011). These definitions/applications therefore indicate that ALCA and CLCA are used depending on the goal of the study in line with responses to different questions. CLCA is used in this study to support the decision addressing the implications of the Thai action plans in relation to increase in demand of agricultural products.

Table S4 in ESM 1 shows the percent change (increase or decrease) of action plan scenarios compared to BAU when applying different modelling approaches (ALCA and CLCA) to quantify upstream emission-related total toxicity impacts. The results indicate that ALCA and CLCA result in variations in the percent changes of action plan scenarios compared to BAU. However, the trend of impact mitigation based on different action plan scenarios is the same although different upstream emissions models are applied. This indicates the robustness of results since they are not significantly influenced by the modelling approaches.

4.4. Policy implications

Based on the overall action plan scenario results, some scenarios can be suggested to improve the major crop production systems in terms of minimizing human and ecosystem health impacts and related damage costs. The integrated approaches under conventional and organic farming are possible to apply in the major crop production systems in line with Thailand's action plans number 1 to 4 (see the plans in ESM1, Table S2).

The integrated approach under conventional farming may serve as an overall guide. This scenario incorporates multiple methods such as using crop residues as organic fertilizers instead of chemical fertilizers to avoid residue burning, applying swine manure to meet nutrient requirements, applying modified pesticides to meet GAP and to manage the banned pesticides, and reducing diesel used in agricultural machinery. Similarly, the integrated approach under organic farming shows a high impact mitigation on human toxicity and ecotoxicity in all major crop systems except for human toxicity in oil palm. This scenario involves multiple methods comparable with the integrated approach under conventional farms without pesticide use. However, for implementing this approach at the national level, some concerns remain and further improvements are needed, which include 1) the availability of crop residues used as organic fertilizers varied annually, 2) the limitation on the availability and utilization of swine manure in Thailand, 3) effective pesticide management (only conventional farms), and 4) increasing the use of renewable energy used instead of diesel (>30 %). In conventional farming, simply adjusting pesticides to compensate for the banned pesticides according to the same pesticide target pests and modes of action can cause an increase in human toxicity impacts as seen in the rice and oil palm systems. Suitable pesticide substitution in specific crop production systems is required. Using high amounts of manure (containing heavy metals) can cause an increase in human toxicity impacts as can be seen in the oil palm system. The suitable source and amount of organic fertilizer used in specific crop production systems should be investigated. In organic farming, although the use of manure is recommended for soil amendment and nutrient improvement (Sae Lim, 2016), manure causes heavy metal emissions into crop production systems. As a result, heavy metal emissions are identified as the main contributors to the total human toxicity impacts in organic crop systems. There is a need to find and evaluate the alternatives and appropriate sources of organic fertilizers (e.g., green manure) to use in specific crop production systems. Particularly, the Notification of the Department of Agriculture on Organic Fertilizer Criteria 2014 (DOA, 2014) should specify the maximum allowable levels of heavy metal contaminants in different manure. Furthermore, the use of diesel has become the main contributor along with the release of heavy metals from manure. It is therefore necessary to promote the use of renewable energy instead of fossil fuels (e.g., diesel and gasoline).

5. Conclusions

Our results illustrate that one-tonne production of rice, cassava, sugarcane, and oil palm in Thailand causes total human toxicity impacts of 1.5 months, and 6, 17, and 2 h of average individual human lifetime loss, respectively. One tonne of rice, cassava, sugarcane, and oil palm production causes total ecotoxicity impacts of 147, 32, 15, and 54 million PDF m^3 d. Field emissions represent the majority of total human health impacts (44 to 100 %), mainly caused by on-farm pesticide (14 to 99 %) and heavy metal (0.2 to 30 %) emissions. Upstream emissions dominate the ecotoxicity impacts (100 %), mainly caused by supply chain operations of fertilizer (34 to 79 %) and fuel (diesel: 24 to 45 % in rice, cassava, and sugarcane; gasoline: 9 % in oil palm) production. At the national level, four major crops under Thailand's production in 2019 caused total impact scores of 4.1×10^6 DALY or around 56 thousand statistical human lives for human toxicity and 8.4×10^{15} PDF m^3 d for ecotoxicity. As a result, total damage costs associated with human health and ecosystem quality are 2453 and 1224 billion THB. Furthermore, besides field pesticide and heavy metal emissions, the results show that because LC-IMPACT includes additional ecotoxicity impacts of chemicals on marine and terrestrial (soil) species, the obtained impacts are 1 to 3 orders of magnitude higher than those derived from USEtox.

Considering the action plan scenario results, the integrated approach under conventional and organic farming is effective in mitigating the impacts of major crop production systems in Thailand. The integrated approach incorporates multiple methods such as using crop residues as organic fertilizers instead of chemical fertilizers to avoid residue burning, applying swine manure to meet nutrient requirements, applying modified pesticides to meet GAP and to manage the banned pesticides (only conventional farms), and increasing the use of biofuel instead of diesel used in agricultural machinery. In conventional farming, the integrated approach effectively mitigates impacts in cassava and sugarcane production, ranging from 20 to 61 % for human toxicity and 61 to 75 % for ecotoxicity. This scenario is also effective in reducing ecotoxicity by 51 % and 76 % in the production of rice and oil palm, but it is unable to minimize the human toxicity impacts (i.e., impact increased by 12 % and 117 %). In organic farming, the integrated approach is highly effective in all major crops except for oil palm production, mitigating 77 to 99 % for human toxicity and 56 to 78 % for ecotoxicity.

In summary, our results illustrate the need for considering all on-farm operations, supply chain activities, and crop residue burning emissions, and using country-specific CFs which is crucial and helps increase the accuracy and reliability of results. The toxicity impacts of crop production can be partly mitigated by integrated approaches including mainly using crop residues and swine manure, using pesticides as advised, and using biofuel in agricultural machinery. The proposed approaches can be adapted also to other production systems and regions, to facilitate a national-level strategic decision support for policy makers toward more sustainable agricultural production in Thailand and beyond.

Supplementary material

Supplementary data included in this article are Electronic Supplementary Material-1 (ESM1) and Electronic Supplementary Material-2 (ESM2), Sections S1 to S10 can be found online at https://doi.org/10.5281/zenodo.10003828.

CRediT authorship contribution statement

Phatchari Mankong: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft and revision. **Peter Fantke:** Methodology, Supervision, Formal analysis, Writing - review and editing. **Agneta Ghose:** Methodology, Supervision, Writing - review and editing. **Farshad Soheilifard:** Methodology, Writing - review and editing. **Susan Anyango Oginah:** Methodology. **Tanapon Phenrat:** Supervision, Writing - review and editing. **Jitti Mungkalasiri:** Supervision. **Shabbir H. Gheewala:** Conceptualization, Methodology, Supervision, Writing - review and editing. **Trakarn Prapaspongsa:** Conceptualization, Methodology, Supervision, Writing - review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data generated or analyzed during this study are included in this published article and its supplementary information files.

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