Environmental Science and Pollution Research

LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study

--Manuscript Draft--

Manuscript Number:	
Full Title:	LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study
Article Type:	Research Article
Keywords:	LCA; Life cycle assessment; Spatial differentiation; Tomatoes; ReCiPe2016
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Funding Information:	Interreg V-A Greece-Italy / IR2MA: "Large Scale Irrigation Management Tools for Sustainable Water Management in Rural Areas and Protection of Receiving Aquatic Ecosystems" (5003280) — Dr Andi Mehmeti
Abstract:	Albanian grown tomatoes have been more export-oriented, with a rising interest for communicating environmental information using a life cycle assessment (LCA) approach. Meanwhile, spatial differentiation and inclusion of new impact categories are at the forefront of agriculture-related LCA research. In this context, ReCiPe 2016, most recent impact model covering 21 output indicators (6 spatially differentiated) was used to generate a full-fledged LCA of greenhouse tomatoes in a typical Albanian farm. Assessment per 1 ha of cropped land produced 18 midpoint indicators and 3 endpoint indicators and distinguished foreground (on-farm) and background (off-farm) systems. Most important midpoint categories for study area identified from foreground-background analysis were global warming (3109.85 kg CO2-eq), stratospheric ozone depletion (0.0298 kg CFC11-eq), particulate matter formation (10.47 kg PM2.5-eq), human health and ecosystem ozone formation (17.67 and 38.5 kg NOx-eq), water consumption (5060.6 m3), and terrestrial acidification (53 kg SO2-eq). The foreground is the most impacting system for damages to human health (caused by particulate matter formation, water consumption, and global warming) and ecosystem quality (caused by terrestrial acidification and ecosystem damage ozone formation). The background system (production of raw materials) has a major impact on 10 midpoint impact categories. The impacts primarily originated from nitrogen-based fertilizer emissions and diesel fuel with the origin of the impact from nitrous oxide (N2O), ammonia volatilization (NH3), nitrous oxides (N2O), nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOCs). Water consumption was dominated by irrigation water use. A sensitivity analysis indicated that nutrient emission factor

	model, spatial differentiation, or energy source generate different results and outlooks about the relevance of different processes, impact categories, and overall LCA performance. Site-dependent characterization of environmental impact resulted in variation from 6.1% to 77.1% compared to site-generic characterization, highlighting the importance of a multi-impact and spatial approach to increase the discriminating power of LCA.
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Cover letter

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Cover letter

01/04/2019
Editorial Department of Environmental Science and Pollution Research
Springer Berlin Heidelberg

Dear Esteemed Editor-in-Chief,

I am submitting a manuscript for consideration of publication in the Journal of Environmental Science and Pollution Research. The manuscript is entitled "**LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study**".

This work is among ***very few agriculture-related studies*** and the ***first LCA on tomato production*** considering 21 impact categories and including spatial differentiation in life cycle assessment (LCA). The work contributes to a better understanding of the environmental impact of tomato production from a regional perspective and will help LCA practitioners working with the agricultural sector, in cross-checking/verifying the robustness of the studies. The main aspects considered to be the novelty of this article are:

a) The first time the estimation of the eco-profile using a life cycle analysis and interpretation of LCA results using eighteen midpoint indicators (problem-oriented) and three endpoint indicators (damage-oriented). The work includes new impact categories not addressed in previous LCA studies (e.g. human health ozone formation, ecosystems ozone formation, water footprint, etc.) and novel impact pathways such as i) Impacts of water use on human health, terrestrial ecosystems, and freshwater ecosystems; ii) iii) Impacts of climate change on freshwater ecosystems; impacts of tropospheric ozone formation on terrestrial ecosystems. The work enhances accuracy in quantifying life cycle impacts on human health, ecosystem services, and natural resources.

b) Differently, from generic assessments present in literature, this is the first study to use spatially differentiated characterization factors for several impact categories (fine particulate matter formation, photochemical ozone formation, acidification, freshwater eutrophication, and water use). Such practical application will give fresh input to the scientific literature about the sense and nonsense of site-dependent impact assessment in LCA.

c) The analysis of tradeoffs between and/or aggregation across impact categories and the implications of midpoint versus endpoint indicators using a midpoint to endpoint analysis. The work identifies which are the most relevant to human health and ecosystem quality.

All of the authors declare that they have all participated in the design, execution, and analysis of the paper and that they have approved the final version. Additionally, there are no conflicts of interest in connection with this paper, and the material described is not under publication or consideration for publication elsewhere.

Note: This work ***was previously accepted*** *with minor revisions on 30/03/2019 at Journal of Energy, Ecology, and Environment (Springer), submission ID: EEAE-D-18-00094R2 and entitled "Generic and spatially differentiated life-cycle environmental impacts of tomato greenhouse production: An Albanian case study".*

The manuscript was withdrawn from authors with the consent of Journal Editorial Office production coordinator Pravin Selvakumar and Editor-in-Chief Bin Chen because the journal is not assigned with an impact factor and our co-author which is a Ph.D. student it is requested obligatory each year to submit one first-author research paper for peer-review and publication to a journal with impact factor prior to passing to next year or defending her dissertation. We slightly modified the title and performed another language and technical revision of the article.

We look forward to hearing from you in due course,

Thank you very much for your consideration.

Yours Sincerely,

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Highlights
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Highlights

- First multi-impact LCA study covering 18 midpoint and 3 endpoint indicators.
- Country-specific characterization factors were used to estimate life cycle impacts.
- Fertilizers and fossil fuel-based energy dominated the life cycle impacts.
- LCA results are strongly dependent on methodological decisions.
- Spatial differentiation generates different LCA results and outlooks.

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LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: An Albanian case study

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Abstract

Albanian grown tomatoes have been more export-oriented, with a rising interest for communicating environmental information using a life cycle assessment (LCA) approach. Meanwhile, spatial differentiation and inclusion of new impact categories are at the forefront of agriculture-related LCA research. In this context, ReCiPe 2016, most recent impact model covering 21 output indicators (6 spatially differentiated) was used to generate a full-fledged LCA of greenhouse tomatoes in a typical Albanian farm. Assessment per 1 ha of cropped land produced 18 midpoint indicators and 3 endpoint indicators and distinguished foreground (on-farm) and background (off-farm) systems. Most important midpoint categories for study area identified from foreground-background analysis were global warming (3109.85 kg CO_2-eq), stratospheric ozone depletion (0.0298 kg CFC11-eq), particulate matter formation (10.47 kg PM2.5-eq), human health and ecosystem ozone formation (17.67 and 38.5 kg NO_x-eq), water consumption (5060.6 m^3), and terrestrial acidification (53 kg SO_2-eq). The foreground is the most impacting system for damages to human health (caused by particulate matter formation, water consumption, and global warming) and ecosystem quality (caused by terrestrial acidification and ecosystem damage ozone formation). The background system (production of raw materials) has a major impact on 10 midpoint impact categories. The impacts primarily originated from nitrogen-based fertilizer emissions and diesel fuel with the origin of the impact from nitrous oxide (N_2O), ammonia volatilization (NH_3), nitrous oxides (N_2O), nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOCs). Water consumption was dominated by irrigation water use. A sensitivity analysis indicated that nutrient emission factor model, spatial differentiation, or energy source generate different results and outlooks about the relevance of different processes, impact categories, and overall LCA performance. Site-dependent characterization of environmental impact resulted in variation from 6.1% to 77.1% compared to site-generic characterization, highlighting the importance of a multi-impact and spatial approach to increase the discriminating power of LCA.

Keywords: LCA; Life cycle assessment; Spatial differentiation; Tomatoes; ReCiPe2016;

1. Introduction

Albanian grown agricultural products have been more export-oriented focusing on the development of greenhouse technology for horticulture and high-value crops. Typical greenhouse-grown tomatoes are the fastest-growing export products marking a rise of 40% from 2012 to 2017 (INSTAT 2018) thus giving a new impetus to the agricultural economy. Withal, greenhouse horticulture is a resource-intensive system, and trends towards expansion and intensification indicate the need for greater use of agricultural inputs, which in turn leads to adverse environmental impacts (Todorović et al. 2018). These issues could become overwhelmingly pressing for the Southern Mediterranean countries with a highly climate-sensitive agriculture sector and one of the hot spots in terms of water scarcity, which could increase in the future due to climate change (Daccache et al. 2014; Saadi et al. 2015). Climate projections for Albania indicate a decrease of 28% in the annual availability of water for the agricultural sector by 2050 (World Bank 2011). This will likely intensify the problems of water scarcity and land degradation, and affect negatively the sustainability of agricultural production (Todorovic 2016). Current deficient surface water supply infrastructure and increasing water demand by other sectors will drive groundwater use which is commonly associated with intensive water and energy inputs (Lal 2004; Martin-Gorriz et al. 2014), and environmental footprints of water and energy resources (Levidow et al. 2014; Pradeleix et al. 2015; Mehmeti et al. 2016). Excessive fertilization is also a common agricultural practice considered a critical input affecting the overall sustainability of greenhouse vegetable production (Hao et al. 2009; Liang et al. 2014).

With increasing attention to sustainability issues of crop production systems, life cycle thinking and related decision support tools have continued to thrive in contemporary agricultural research for management and decision-making across economic, environmental and social dimensions (De Luca et al. 2015). Life cycle assessment (LCA) is a systemic tool greatly used to understand and report the full environmental impacts of horticultural crop production systems (Ingram and Thomas Fernandez 2012). Life cycle thinking and life cycle assessment are particularly relevant for addressing sustainability problems and crucial to provide support for better integration of environmental sustainability with decision-making (Sala et al. 2015, 2017). As a result, a rapidly expanding interest in LCA and environmental impacts of tomatoes, from the open field (Jones et al. 2012; Page et al. 2012; Ntinas et al. 2017) to greenhouse production systems (Del Borghi et al. 2014; Payen et al. 2015; Bosona and Gebresenbet 2018) have been documented. Up to date, research has been mainly focused predominantly on site-generic factors and non-spatial insights for emissions which together with other factors can make big differences to the LCA results (Notarnicola et al. 2017). Regional characterization of environmental impacts with midpoint and endpoint modeling is a priority so that a more realistic and balanced picture of agricultural practices can be presented (Antón et al. 2014). In this context, using a novel, environmental multi-impact life cycle assessment method (ReCiPe 2016) we generated a spatialized LCA and environmental profile evaluation of solar greenhouse-grown tomatoes on a typical Albanian farm by incorporating spatial differentiation information in the life cycle impact assessment. This research makes several contributions to the current literature. First, we represent the first agriculture oriented LCA study and documented evidence for the environmental performance of crop products in Albania from a systemic and holistic perspective. This is of crucial importance for export products to advance in knowledge, build awareness, interpret the results and explore the improvement options for the future. Next, it advances insight in the additional LCA information by considering spatially differentiated information to grasp the local particularities of crop production for following specific impact indicators (Huijbregts et al. 2017b): fine particulate matter formation, photochemical ozone formation, acidification, freshwater eutrophication, and water use. The country-level implementation will give fresh input from such practical application and improve the current agricultural LCA studies since environmental impacts are highly influenced by technology and geographical location (Dias et al. 2017; Mutel et al. 2018). Only one study (Antón et al. 2014) has previously investigated the effect of spatial differentiation in the inventory and impact assessment model. From spatially differentiated assessments important information can be derived in order to improve product sustainability (Thies et al. 2019). Finally, it broadens the scope of indicators covered by contemporary LCAs by combining a long list of midpoint indicators (problem-oriented, 18 indicators) to three areas of protection, i.e. human health, ecosystem quality, and resource scarcity. Harmonized midpoint-endpoint interpretation of LCA results better communicates trade-offs, thus, connecting transparent and comparable information (Todorović et al. 2018). The results are expected to be of interest to local growers and export managers, agricultural researchers and LCA practitioners with the aim to address the following key research questions:

1. What life cycle environmental impacts and their causes (emissions and resource use) can be identified for greenhouse tomato production in Albania?
2. What are the most relevant midpoints/endpoints impact categories and trade-offs between category indicators?
3. How spatial differentiation and the inclusion of site-dependent characterization factor influences environmental impacts?

2. Assessment framework and methodological approach

The overall impact assessment framework used in this work is based on the general framework of the LCA methodology and involves the following steps (ISO 14045 2012): goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and life cycle interpretation and scenario analysis (Figure 1). First, the LCA methodology is introduced, including the system model to be assessed (Curran 2017), developed life cycle inventory (quantification of inputs and outputs) associated with the system under study (Sala et al. 2016) and characterization of the impacts using a spatially explicit life cycle impact assessment method with broad range of environmental impacts under the three areas of protection of human health, natural environment, and natural resources (Huijbregts et al. 2017b). The impact assessment is carried out in three phases: classification of emissions into one or more impact categories both with global and spatially differentiated characterization factors, midpoint characterization (emissions weighted to represent their contribution to each midpoint category) and endpoint characterization (aggregating impact categories into areas of protection).

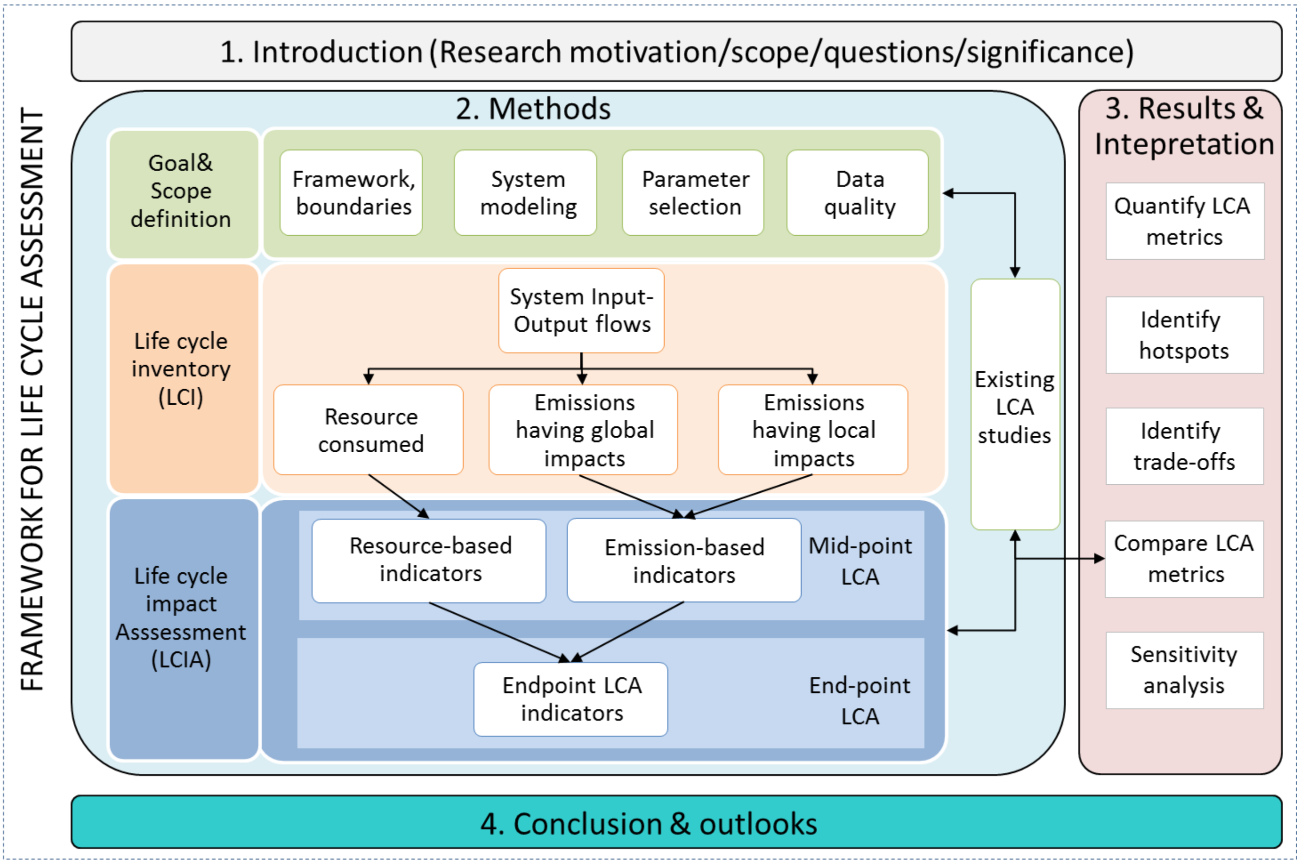

Figure 1. Stepwise assessment framework applied for the LCA of tomato production.

Interpretation phase combines and discusses the results from the case study evaluation using a hotspots' analysis where the most relevant impact categories, processes, and elementary flows are identified and a sensitivity analysis is conducted. To complement the LCA analysis a literature review of the past LCA studies is carried out to understand how

LCA has been applied in practice, to grasp the key variation in results and revealing the key facts and key figures of such studies. Results are presented and discussed by highlighting both strengths and limitations and further compared with other LCA studies. Finally, the formulation of conclusions and recommendations is performed, according to the goal and scope of the study.

2.1 LCA study set-up

The system model (system boundaries, functional unit, processes, and system LCA parameters), methodological assumptions, life cycle impact assessment model and indicators are described in the next sections.

2.1.1LCA: Goal and scope

The goal of the study is baseline understanding of the magnitude, sources and their impacts and to compare relative contributions from each process in greenhouse tomato production in Lushnja district, Southwest of Albania (Figure 2). Administratively, the command area is 4466 ha stretching in sixteen villages and is part of Lushnja District (40.9420° N, 19.6996° E), one of the largest and most developed agricultural areas in Albania (Guri et al. 2015). Taking advantage of the typical Mediterranean climate with mild winters and favorable solar energy regime (more than 1700 kWh/m^2/year and 2500 hours of the sunshine) greenhouse horticulture oriented to the exportation represent an important component of the agricultural economy. According to official statistics (INSTAT 2018) the cultivated areas with vegetables in greenhouses augmented by 59% in four years (from 804 ha in 2013 to 1278 ha in 2017), whereas the number of solar greenhouses with plastic cover increased by 61% (from 896 to 1443 units).

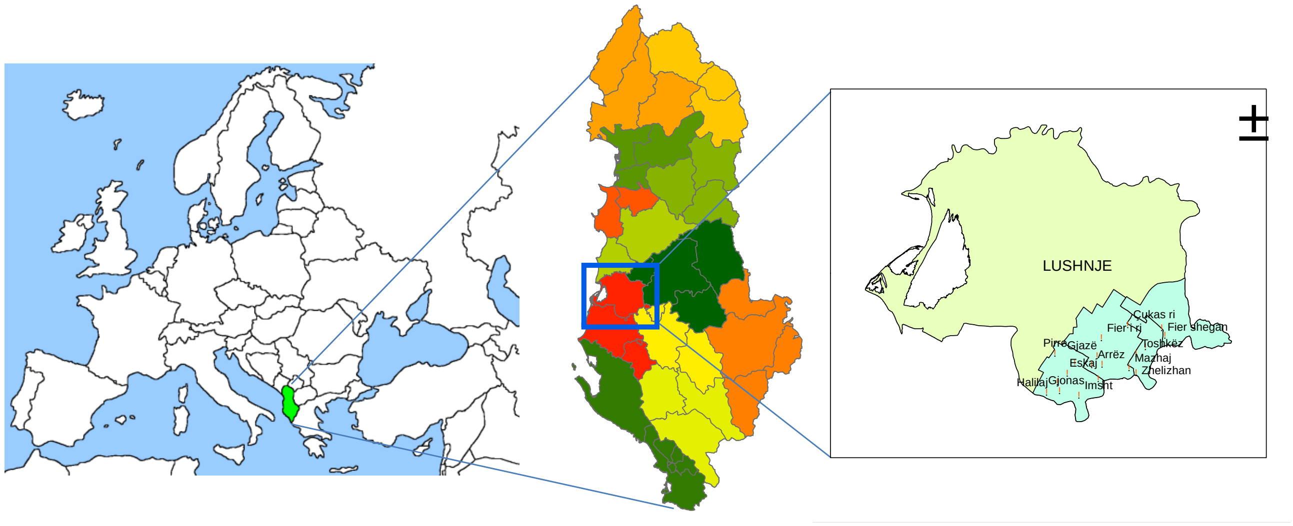

Figure 2. Map of Albania and the location of the study area.

The scope of this study is tomato cultivation from cradle-to-farm-gate approach including production, transport, and use of all on-farm inputs (Figure 3) required to produce the functional unit: 1 ha of cropped tomatoes over one cropping season.

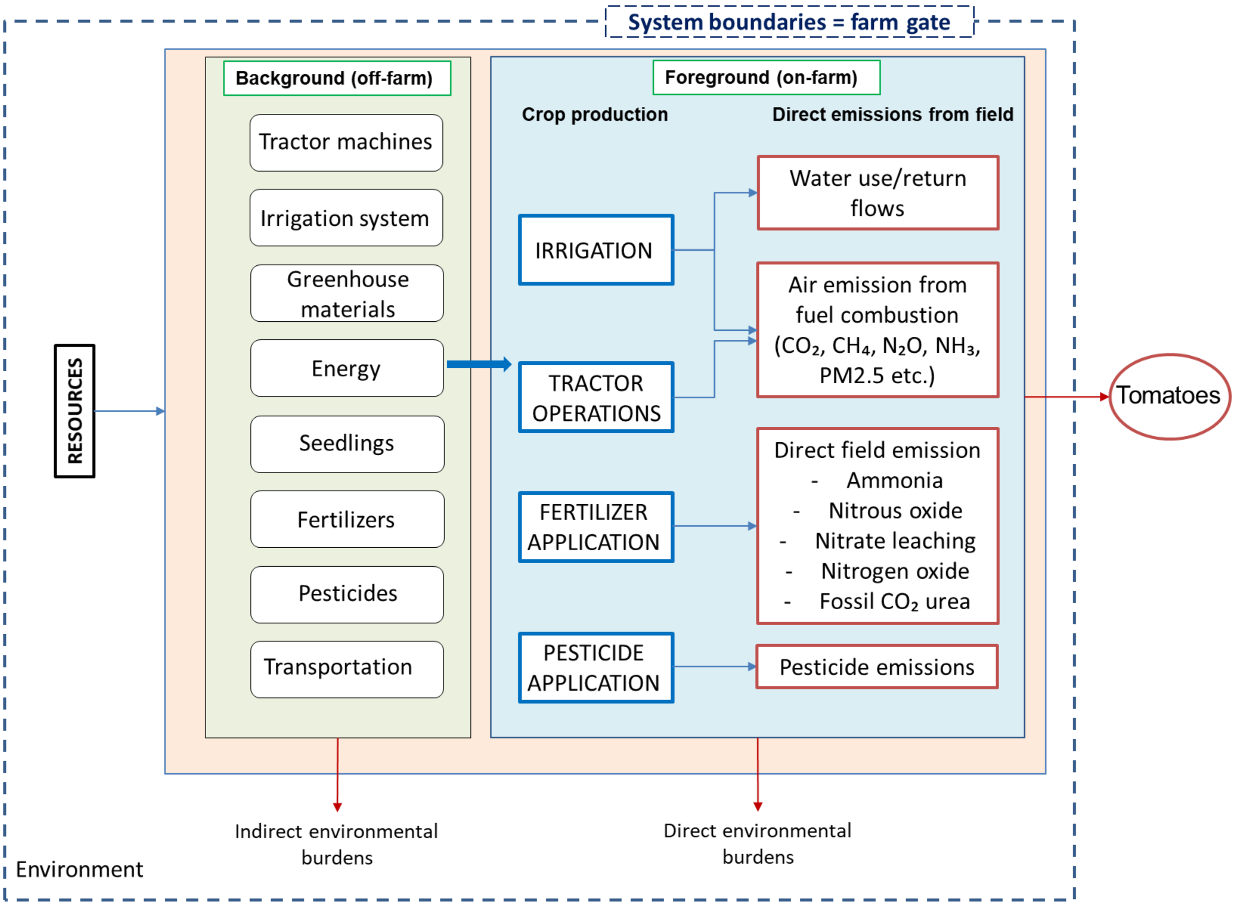

Figure 3. LCA scope and system boundaries for a cradle-to-farm-gate LCA of tomato production.

Within the system boundaries, the following processes and inputs were included: the production of seedlings, greenhouse structure, irrigation and agricultural (tractor) equipment, agrochemical (fertilizers and pesticides) and energy requirement for irrigation and field operations. The production system was divided into the foreground (on-farm) and background (off-farm) sub-systems for deriving the process inventories and the impact assessment using an attributional modeling approach.

2.1.2Life Cycle Inventory (LCI) and product model

Primary input data (farms, type of machinery or irrigation system, energy, water, materials and product at farm gate) representing typical farm practices in the study area were collected through field surveys (Canaj, 2016). Table 1 lists the main primary data on inputs for the full production phase of greenhouse-grown tomatoes using soil system. Final life cycle inventory data including material use, energy consumption, and emissions from crop production and system processes were quantified using AusAgLCI methodology (Grant et al. 2014). Foreground ‘inventory flows’ included irrigation (water use), land use flows for “occupation”, air emissions due to combustion of fossil fuels by the tractor and irrigation engines, direct field emission from fertilizer and pesticide use. The greenhouses are irrigated with groundwater and diesel-powered pumps with an average net irrigation requirement of 4000 m^3/ha and overall efficiency of the water supply of about 80%. The water pumping is carried out with a total dynamic head of 50 m (2.65 bars of pressure for drip including pressure losses and 2.35 bars for lifting). The standard pump energy calculations (Rothausen and Conway 2011) were used to determine energy use considering pump efficiency of 80% (for electric motors) and 40% for diesel pumps, and motor efficiency of 66% (Grant et al. 2014). Water-related impacts were based on water consumption (amount of water that the watershed of origin is losing) reported merely as a product of irrigation withdrawal multiplied by the country water requirement ratio, i.e. the ratio between the amount of water consumed and the amount of extracted water for agricultural purposes (Huijbregts et al. 2017a). The irrigation system includes a multi-year use drip irrigation system where impacts were evaluated according to the amount of material requested to cover one hectare of the irrigated flat field (ALCAS 2017).

Table 1. Primary input data of greenhouse tomato production in Lushnja district, Albania.

Name	Amount	Unit
Product flows		
Tomato, harvested, at farm gate/ALB	95	ton/ha
Input processes		
Seedling		
Seedling, for transplant, at farm/RER U	30000	p/ha
Irrigation		
Water, groundwater, unspecified, 50 m total pumping head/ALB	5000	m^3/ha
Electricity, mix ALB adapted, irrigation/ALB	1290.3	kWh/ha
Diesel burned in building machine, irrigation/ALB	212.5	kg/ha
Drip irrigation system, production, per ha/RER U	1	ha
Drawing of pipes, steel/RER U	0.03	kg/ha
Extrusion, plastic pipes/RER U	27.79	kg/ha
Polyethylene, HDPE, granulate, at plant/RER U	11.50	kg/ha
Polyethylene, LDPE, granulate, at plant/RER U	14.52	kg/ha
Polypropylene, PP, at factory gate/RER U	0.39	kg/ha
Polyvinylidenchloride, granulate, at plant/RER U	1.38	kg/ha
Steel, converter, low-alloyed, at plant/RER U	0.025	kg/ha
Fertilizer & Pesticides		
Urea, at regional storehouse /RER U	290	kg/ha
Phosphorus, Single Superphosphate/RER U	180	kg/ha
Potassium Sulfate, at regional storehouse/RER U	200	kg/ha
Pesticide unspecified, at regional storehouse/RER U	5	kg a.i/ha
Tractor Processes		
Diesel fuel, field operations (no irrigation)	65	kg/ha
Time to process 1 ha	11	hour/ha
Tractor, module production	4.23	kg/ha
Tractor weight	3600	kg
Tractor lifetime	7000	hours
Greenhouse structure		
Steel, low-alloyed, at plant/RER U	25.6	kg/ha
Aluminum, primary, at plant/RER U	1.03	kg/ha
Polyethylene, LDPE, granulate, at plant/RER U	6.5	kg/ha
Transport		
Transport, freight, rail/RER U	200	t/km
Transport, lorry 3.5-16t, fleet average/RER U	200	t/km
Transport, barge/RER U	200	t/km
Land occupation		
Occupation, annual crop, greenhouse	1	ha

Agricultural machinery included tractor and implements for greenhouse operations. Fuel consumption for miscellaneous farm activities was sourced directly from farmers while the amount of machinery (tractor, production, per kg) required for these activities was calculated over the expected lifetime of the tractor and implement in agricultural processes. Emissions due to agricultural operations from tractor and irrigation engines (Table 2) were estimated as a product of the mass of fuel consumed and fuel combustion airborne emission factors (Nemecek and Kagi 2007).

Table 2. Calculated field emissions from nitrogen fertilizer and fuel combustion.

Output	Amount	Unit
Nitrogen fertilizer emissions		
Ammonia Volatilization (NH_3)	16.19	kg NH_3/ha
Direct N_2O emissions from fertilizer application N_2O (dir, F)	1.89	kg N_2O/ha
Soil direct NOx emissions (dir, F)	0.40	kg N_2O/ha
Indirect N_2O emissions via atmospheric deposition of N volatilized N_2O (ATD)	0.21	kg N_2O/ha
Indirect N_2O emissions via leaching and runoff from fertilizer application N_2O (L, F)	0.47	kg N_2O/ha
CO_2 urea-based application	209.44	kg CO_2/ha
Nitrate (NO_3) leaching	175.9	kg NO_3/ha
Phosphorus (phosphates), to groundwater	1.198	kg PO_4^{3-}/ha
Fuel combustion emissions		
Ammonia (NH_3)	0.01	kg/ha
Particulate matter (PM < 2.5 um)	1.30	kg/ha
Carbon dioxide (CO_2)	865.80	kg/ha
Dinitrogen monoxide (N_2O)	0.03	kg/ha
Methane (CH_4)	0.04	kg/ha
Carbon monoxide (CO)	2.25	kg/ha
Nitrous oxide (NOx)	12.49	kg/ha
Non-methane volatile organic compounds (NMVOC)	0.75	kg/ha
Sulphur dioxide (SO_2)	0.28	kg/ha
Cadmium	2.78E-06	kg/ha
Chromium	1.39E-05	kg/ha
Copper	4.72E-04	kg/ha
Nickel	1.94E-05	kg/ha
Zinc	2.78E-04	kg/ha
Selenium	2.78E-06	kg/ha
Benzo[a]anthracene	2.22E-05	kg/ha
Benzo[k]fluoranthene	1.39E-05	kg/ha
Chrysene	5.55E-05	kg/ha
Dibenzo[a]anthracene	2.78E-06	kg/ha
Fluoranthene	1.25E-04	kg/ha
Phenanthene	6.94E-04	kg/ha

Urea (46% N), single superphosphate, and potassium sulfate are the most common fertilizer used. Soil direct (nitrification/denitrification) and indirect (leaching and runoff and atmospheric deposition) nitrous oxide (N_2O), ammonia (NH_3) volatilization, and nitrate leaching (NO_3) were computed using IPCC TIER1 approach for all nitrogen sources (Table 2). The emission factors and other constant used to model atmospheric emissions from fertilizers were: i) emission factor for direct soil emissions = 0.01 kg N_2O-N/kg N input; ii)

Fraction of synthetic fertilizer emitted as NOx + NH_3 = 0.1 kg NH_3-N+NO_x-N/kg synthetic applied; iii) N deposition emission factor = 0.01 kg N_2O-N/kg NH_3-N+NO_x-N emitted; iv) Fraction of nitrogen input to soils that is lost through leaching and runoff = 0.1 kg N/kg fertilizer; v) Emission factor for leached N = 0.75 kg N leaching or runoff / kg N applied.

Carbon dioxide (CO_2) from urea fertilization and NO_x emissions were estimated based on Nemecek and Kagi (2007) while the field pesticide emissions by applying default Ecoinvent® inventories. The greenhouse structure was modeled as a generic data set representing the typical structure of a greenhouse (Hendricks 2012). The inputs for greenhouse structure in terms of steel, plastics, concrete were normalized according to their lifetime (steel 20 years, aluminum 20 years, and plastic 3.5 years). All farm inputs were assumed to have a transport distance of 200 km.

2.1.3Life cycle impact assessment (LCIA) model and indicators

The life-cycle impact assessment (LCIA) methodology used in the study is the LCA-ReCiPe2016 (v.1.1) using midpoint and endpoint modeling (Hierarchist perspective). The ReCiPe2016 life cycle impact assessment method (Huijbregts et al. 2017b) calculated eighteen (18) midpoint indicators and three (3) endpoint indicators (Table 3).

A damage indicator result is the quantified contribution of each midpoint category where each midpoint category is allocated to one or more damage categories. Spatially differentiated information is used for six impact categories (Table 3), while for other categories the impact assessment is carried out on European/global level. A Microsoft Excel spreadsheet model with data from SimaPro 8.3 software and Ecoinvent® v. 3 as the database was used for the calculations of life cycle impacts. Environmental impacts of the foreground system are calculated from the global and country-specific midpoint and endpoint characterization factors (Supplementary material, Table A1) retrieved from Huijbregts et al. (2017a). The impact assessment is complemented with background datasets derived from Ecoinvent® including emissions/impacts resulting from the production and manufacturing of farm inputs (fuel, fertilizers, pesticides, machinery, infrastructures, pumping and piping system) using processes from the Europe region.

Table 3. The relation between midpoint and endpoint categories in the ReCiPe 2016 method, including country-specific impact categories.

Midpoint impact category	Endpoint impact category			Available Country-specific impacts
	Damage to Human health	Damage to Ecosystems	Damage to Resource availability	
Global warming	+	+		
Stratospheric ozone depletion	+			
Ionizing radiation	+			
Human health ozone formation	+			+
Fine particulate matter formation	+			+
Ecosystem Ozone Formation		+		+
Terrestrial acidification		+		+
Freshwater eutrophication		+		+
Marine eutrophication		+		
Terrestrial ecotoxicity		+		
Freshwater ecotoxicity		+		
Marine ecotoxicity		+		
Human carcinogenic toxicity	+			
Human non-carcinogenic toxicity	+			
Land use		+		
Mineral resource scarcity			+	
Fossil resource scarcity			+	
Water consumption	+	+		+

3. Results and discussion

The key steps in interpreting the results of this LCA study include: i) Cradle-to-farm-gate life cycle impact assessment (LCIA) metrics using a foreground-background system analysis and comparison with literature; ii) Identification and interpretation of midpoint-endpoint analysis and identification of most relevant contributions (processes and elementary flows); iii) Sensitivity analysis; iv) Conclusions, limitations, and recommendations.

3.1 Life cycle impact scores on midpoint and endpoint level

The cradle to farm gate LCA-based results and the contribution of the background and foreground processes into the system for tomato cultivation in a solar greenhouse in Albania is shown in Table 4. A detailed analysis for each process is available in the supplementary information. The impact indicator results per functional unit (hectare of land cropped) were: global warming potential of 3109.85 kg CO_2-eq, water consumption potential of 5060.6 m^3, terrestrial acidification potential of 53 kg SO_2-eq, and freshwater eutrophication of 0.48 kg P-eq. Resource depletion impact categories of fossil and mineral resource scarcity were estimated 754 kg oil-eq/ha and 13.78 kg Cu-eq/ha, respectively. Toxicity-related impacts ranged from 67.1 to 37875 kg 1.4-DCB-eq/ha for freshwater ecotoxicity potential and human non-carcinogenic toxicity potential, respectively.

Table 4. Life cycle impact scores of greenhouse tomato production at midpoint and endpoint level (ReCiPe 2016, Hierarchist - H).

Characterization factor	Unit	LCIA System 1 ha	LCIA Foreground 1 ha	LCIA Background 1 ha
Midpoint impact categories				
Global warming	kg CO_2-eq	3109.85	1851.7	1258.15
Stratospheric ozone depletion	kg CFC11-eq	0.0298	0.0286	0.0012
Ionizing radiation	kBq Co-60-eq	169.9	-	169.9
Human health ozone formation	kg NOx-eq	17.67	14.47	3.19
Fine particulate matter formation	kg PM2.5-eq	10.47	8.46	2.01
Ecosystem Ozone Formation	kg NOx-eq	38.5	35.17	3.32
Terrestrial acidification	kg SO_2-eq	53	45.8	7.2
Freshwater eutrophication	kg P-eq	0.48	0.05	0.44
Marine eutrophication	kg N-eq	190.06	11.80	178.3
Terrestrial ecotoxicity	kg 1.4-DCB-eq	891.38	890.2	1.14
Freshwater ecotoxicity	kg 1.4-DCB-eq	63.44	25.62	37.82
Marine ecotoxicity	kg 1.4-DCB-eq	67.1	11.9	55.1
Human carcinogenic toxicity	kg 1.4-DCB-eq	85.38	0.53	84.9
Human non-carcinogenic toxicity	kg 1.4-DCB-eq	38476	433	38043
Land use	m^2a crop-eq	7324.43	7300	24.43
Mineral resource scarcity	kg Cu-eq	14.4	-	14.38
Fossil resource scarcity	kg oil-eq	754	-	754
Water consumption	m^3 consumed	5060.6	2500	2560.6
Endpoint impact categories				
Human Health	DALY	0.03007	0.013	0.0171
Ecosystem Quality	Species × year	0.001035	0.000994	0.000041
Resource Availability	USD2013	300.33	-	300.33

The scores endpoint categories were 0.03007 DALY/ha for damage on human health (loss of disability-adjusted life years), 0.001035 Species × year/ha for damage to ecosystems (loss of species density) and 300.33 USD2013/ha damage to resource availability (surplus cost potential). Foreground-Background system analysis (Table 4) allowed determining the relative importance of the activities conducted in the foreground system to the relative contribution of the background subsystem. The studied system was characterized by relevant contribution of the foreground processes to global warming (59.5%), stratospheric ozone depletion (96%), human and ecosystem ozone formation potential (81.9% and 91.4%), terrestrial acidification (86.4%), terrestrial ecotoxicity potential (99%), land use (99.7%), freshwater consumption (49.4%). On the endpoint level, induced 43.2% of damages to human health and 96 % of ecosystem quality. Background contribution from resource production processes included high environmental impact for ionizing radiation potential, toxicity-related impacts, fossil, and mineral resource scarcity. Moreover, the background contribution dominated damages to resource availability.

3.1.1 Comparison of LCIA results with other studies

Table 5 presents the main LCA studies of tomato cultivation and processing in diverse regions across the globe including current preferences for the functional unit, system boundaries, impact assessment methodology, and their LCIA results. Studies primarily use a mass-based functional unit, e.g., 1 kg or 1 ton at the farm gate. The environmental performance is usually assessed in a cradle to farm-gate LCA approach i.e., covering all the activities from the extraction of raw materials to field operations up to the farm gate. More than half of the studies are of European origin. The impacts are quantified with generic models adopting an attributional approach, for instance, the determination of burdens associated with tomatoes life cycle and its sub-systems (Curran 2017). CML method is the most widely used for assessing environmental impacts using global midpoint impact indicators (except for acidification and photo-oxidant formation based on average European values) to generate LCA performance (ILCD 2010). Hence, global warming, acidification, and eutrophication are the most popular metrics used. Water has received little attention, and only a few articles (Dias et al. 2017; Hogberg 2010; Payen et al. 2015) used water consumption as an additional indicator. Endpoint or damage-oriented assessment is rarely considered.

Table 5. Life cycle impact scores of tomato production among LCA studies according to their functional unit.

Authors	FU	System boundaries	LCIA method	Location	GWP	ODP	AP	EP	FETP	TETP	METP	WCP	HH	EQ	RA
This study	1 ha (1 ton)	X-to-farm gate;	ReCiPe 2016	Albania	3109.8 (32.73)	0.0298 (3.14E-04)	53 (0.557)	0.48 (0.005)	63.44 (0.667)	891.38 (9.38)	67.1 (0.706)	5060.6 (53.3)	0,03007 (0,00032)	0,001035 (1,09E-05)	300,3 (3.16)
Almeida et al. (2014)	1 kg	X-to-market;	IPCC 2007	Italy	2.28	-	-	-	-	-	-	1.226	-	-	-
Bojacá et al. (2014)	1 ton	X-to-farm gate;	CML 2001	Colombia	32	-	0.529	0.407	0.12	37.6	-	-	-	-	-
Bosona and Gebresenbet (2018)	1 ton	X-to-market;	ReCiPe 2008	Sweden	547.13	-	-	-	-	-	-	-	-	-	-
Boulard et al. (2011)	1 kg	X-to-farm gate;	CML 2001	France	2.02	4.3E-08	0.034	0.137	-	-	-	-	-	-	-
Cellura et al. (2012)	1 ton	X-to-grave;	CML 2001	Italy	897.1	4.1E-04	5.1	1.8				84.3			
Del Borghi et al. (2014)	1 kg	X-to-factory gate;	CML 2001	Italy	0.3733 - 0.5932	-	0.0006 - 0.0009	0.0014-0.0022	-	-	-	41.82 - 65.51	-	-	-
Dias et al. (2017)	1 kg	X-to-farm gate;	TRACI 2.1	Canada	3.2	5.9E-07	6.6E-03	2.6E-03	-	-	-	-	-	-	-
He et al. (2016)	1 ton	X-to-market;	CML/IPCC	China	207 - 260	-	5.92 - 5.94		-	-	136.5 - 177.4	59.04 - 60.06	-	-	-
Khoshnevisan et al. (2014)	1 ton + 1 ha	X-to-farm gate;	CML 2 baseline	Iran	129.39	2.00E-05	0.37	0.03	5.81	17,497	-	-	-	-	-
Martínez-Blanco et al. (2011)	1 ton	X-to-farm gate;	CML2001	Spain	152.6	1.38E-05	0.938	0.348	-	-	-	-	-	-	-
Ntinas et al. (2017)	1 kg + 1 m^2	X-to-farm gate;	IPCC 2006	Greece + Germany	400 - 10100	-	-		-	-	-	-	-	-	-
Page et al. (2012)	1 kg	X-to-farm gate;	IPCC 2006	Australia	430 - 1860	-	-	-	-	-	-	4.97 - 52.7	9.04E-06	2.69E-05	-
Payen et al. (2015)	1 kg	X-to-market;	ReCiPe 2008	Morocco	0.546	-	0.0032	0.000168	0.00312	0.00288	0.211	0.297	5,00E-07	3.9E-09	1
Pérez Neira et al. (2018)	1 kg	X-to-regional center	IPCC 2006	Spain	0.39	-	-	-	-	-	-	-	-	-	-
Pérez Neira et al. (2018)	1 ton	X-to-farm gate;	CML 2001	Spain	250	-	1	0.49	-	-	-	-	-	-	-
Torrellas et al. (2012)	1 ton + 1 ha	X-to-farm gate;	CML-IA baseline	Iran	65.82	9.24E-06	0.39	0.032	4.1	17.34E03	-	-	-	-	-

Abbreviations: GH – Greenhouse; OF – Open Field; X – Cradle; GWP – Global warming potential; ODP – Ozone depletion potential; AP – Acidification potential; EP – Eutrophication; FETP – Fresh-water aquatic ecotoxicity potential; TETP – Terrestrial ecotoxicity potential; WCP – Water consumption potential; HH – Human health; EQ – Ecosystem quality; RA – resources availability.

The LCIA impacts per unit of crop production in our study can be arithmetically calculated (Table 4) considering an average crop yield performance of 95 ton/ha. The results obtained allow the comparison with the results from other LCA studies. The cross-comparison shows that our results share several similarities and differences with earlier studies, although it is important to note that also that the variation in results among studies is great. Variability in food LCA is related to seasonality, choice of agricultural management practices (e.g. heated or unheated systems) and crop yield achieved (Notarnicola et al. 2017). This variability is further enhanced by data sets and modeling choices (data input and system boundaries, time perspective, allocation, etc.), modeling of environmental impacts, impact assessment method/s (the philosophies and perspectives behind them) and reporting format (Todorovic et al. 2016; Ave et al. 2018).

3.2 Implications of midpoint versus endpoint indicators

A novel contribution of the ReCiPe 2016 model is the integration of the multiple midpoints to one or more damage categories (damage to human health, ecosystems and resource availability) to provide to identify most impactful midpoints and their relative importance (Figure 4). Such detailed analysis represents a better and more practical understanding of the LCIA results (especially for an inexperienced with LCA) since a large number of midpoint indicators is very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning (Huijbregts et al. 2017b). It provides the possibility to analyze the tradeoffs and aggregate the consequences of different midpoint impacts (Zelm 2010). For damage to human health (Figure 5), the system major impacts originated from particulate matter formation (40%), human non-carcinogenic toxicity (29.2%), water consumption (20%) and global warming (9.6%). For damage to ecosystems, terrestrial acidification and ecosystem ozone formation were the two major impact indicators with 70.1 and 18.8% share, respectively. A minor impact originated from land use (6.3%) and water consumption (3.9%). Particulate matter formation potential is primarily linked with the emissions of secondary PM2.5 aerosols (SO_2, NH_3, and NO_x), global warming potential with any of greenhouse gases (mainly CO_2, CH_4, and N_2O), land use because of occupation of a certain area of land during a certain time and transformation of a certain area of land while water impacts with water consumption.

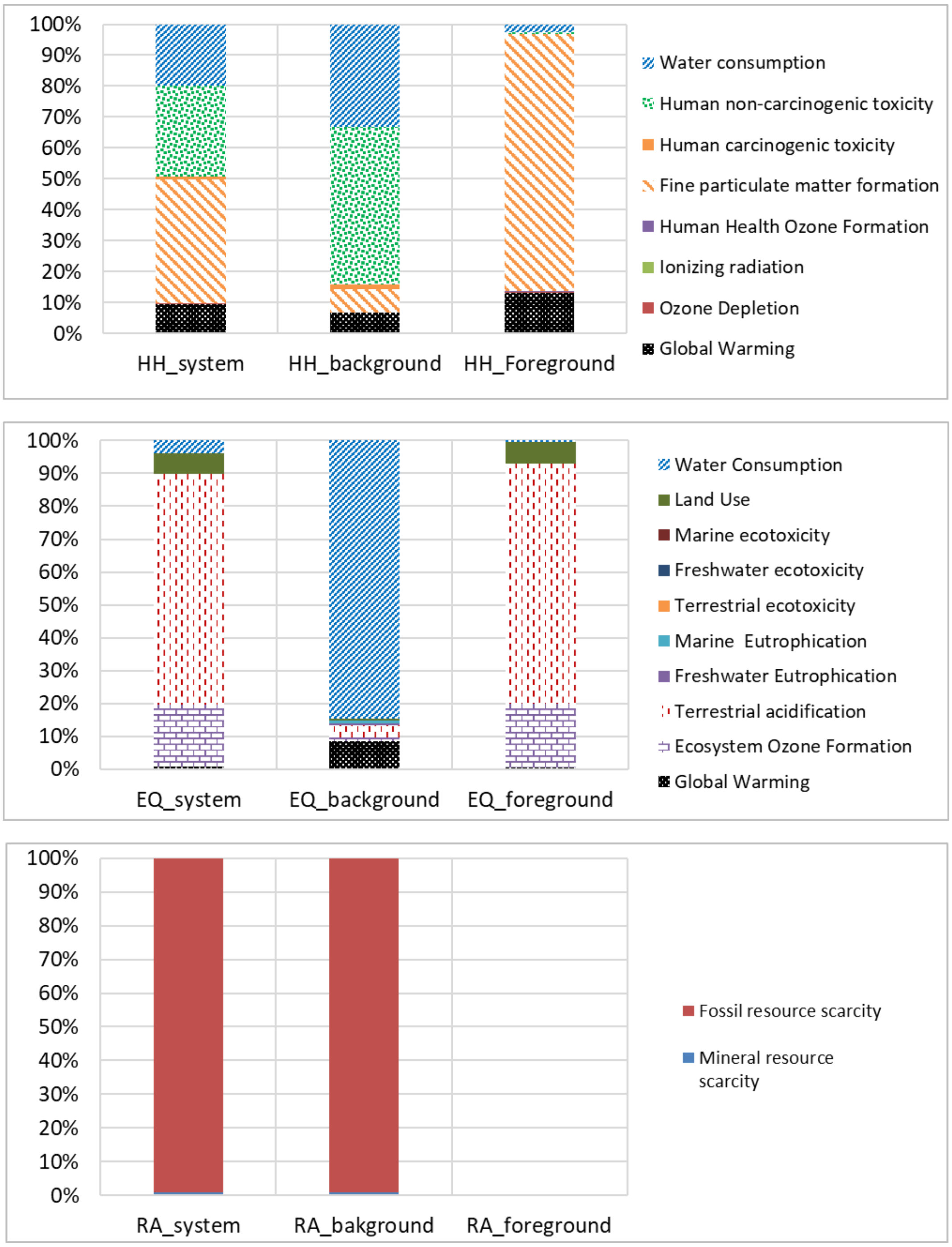

Figure 4. The relative contribution of the different midpoint impact category indicators to human health (HH), ecosystem quality (EQ), and resource availability (RA).

The result of the midpoint to endpoint analysis underlines the relative importance of the importance of differentiating between foreground and background systems since different environmental impact categories may be largest in either the foreground or the background systems. The foreground processes were found important for total damage to human health and less relevant for total damage to human health. Water consumption presented high potential environmental impact in the background system since foreground impacts of water consumption are low since the impacts for Albania consider the good water conditions of the country. The damage to resource availability shows the predominance of the background system and fossil resource scarcity which is strictly linked to fossil fuel use.

3.2.1 Process/Input/Elementary flow contribution analysis

Contribution analyses of cradle-to-farm gate impact assessment identified different processes (Figure 5) and elementary flows (Figure 6) with the major contribution to an impact category. The chemical fertilizers and fossil fuel energy used in irrigation processes and tractor operations were identified as the main contributors to environmental impacts (Figure 5). These basic findings are consistent with the other LCA studies in unheated greenhouse confirming the main factors contributing to environmental impacts include energy for irrigation, greenhouse infrastructure, and fertilizer emissions (Torrellas et al. 2012; Bojacá et al. 2014; Del Borghi et al. 2014; Manfredi and Vignali 2014). For systems with lower pumping demand and no heating requirements, agrochemicals become an increasingly dominant factor for the environmental footprint (Jones et al. 2012). Otherwise, energy used by the heating system had significant effects on the environmental burdens (Boulard et al. 2011; Khoshnevisan et al. 2014; Ntinas et al. 2017; Zarei et al. 2018; Bosona and Gebresenbet 2018).

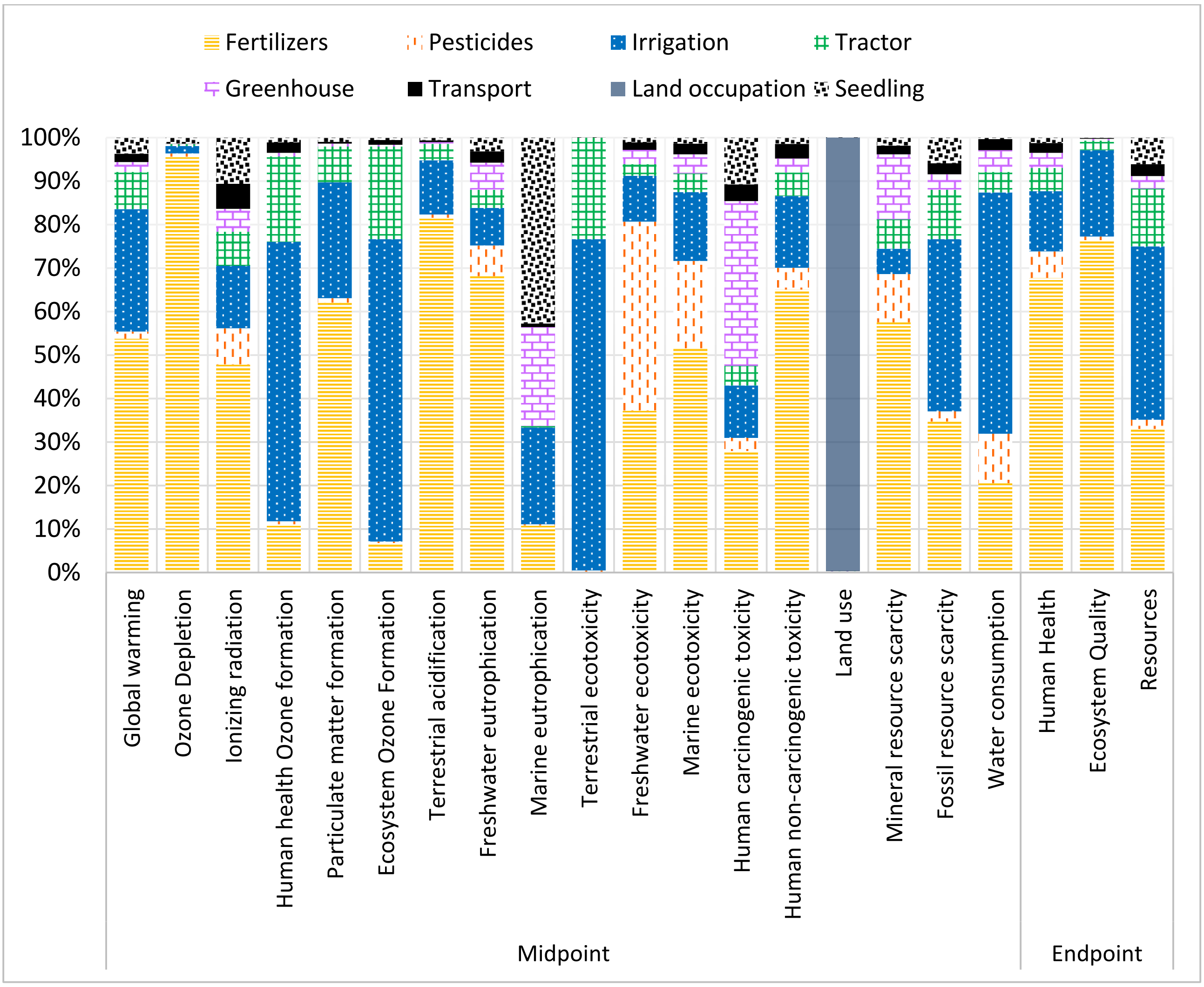

Figure 5. Contribution (%) of processes in the unheated tomato production systems.

In this study, at the midpoint level, the combined impact of field emissions and fertilizer manufacture accounted on average for 40% of the burdens (Figure 5). At endpoint level, accounted between 31 and 71.6% in three impact indicators. The source of these field emissions was nitrogen-based fertilizer (Figure 6) contributing significantly to the overall impacts in global warming (31%), ozone depletion (94.7%), particulate matter formation (50.8%), terrestrial acidification (73.4%), and subsequently to human health (36.2%) and ecosystem quality (69.9%). Fertilizer-derived N_2O induced 24.6% of global warming and was the single most important ozone-depleting emission. About 6.7% of global warming was caused by CO_2 emissions from urea consumption. Ammonia (NH_3) volatilization was the key source of particulate matter formation (50%), terrestrial acidification (73%), and human health (33%), and ecosystem quality (70%). Leaching of different nitrogen and phosphorus species contributed to some extent to marine and freshwater eutrophication with 6.2 and 9.8% share, respectively. In the background system, the production of N-fertilizers (urea) was responsible for most of the environmental impact categories.

The contribution of fertilizers to multiple cradle-to-farm-gate impacts in other studies varies depending on the category. It represented 32% of global warming and 51% of eutrophication (Torrellas et al., 2012); 28, 35 and 22% for abiotic depletion, acidification and eutrophication (Bojacá et al. 2014); more than 20% to the impact categories of acidification, eutrophication, and global warming (Khoshnevisan et al., 2014); 60% of acidification and eutrophication impacts (Payen et al., 2015); 30.05% (He et al. 2016) and 41% (Garofalo et al., 2017) to global warming**.** Ammonia and nitrate emissions were important in acidification and eutrophication (He et al. 2016; Payen et al. 2015). Pesticide impacts (production + application) were relevant for freshwater ecotoxicity 43.5%, marine ecotoxicity 20%, and mineral resources 11% and water consumption 11.4%. In other studies, pesticides accounted between 0.80 and 2.1 % (Torrellas et al. 2012), 0.15 and 25% (Bojacá et al. 2014), less than 1% (Khoshnevisan et al. 2014), and up 96% of terrestrial ecotoxicity (Payen et al. 2015).

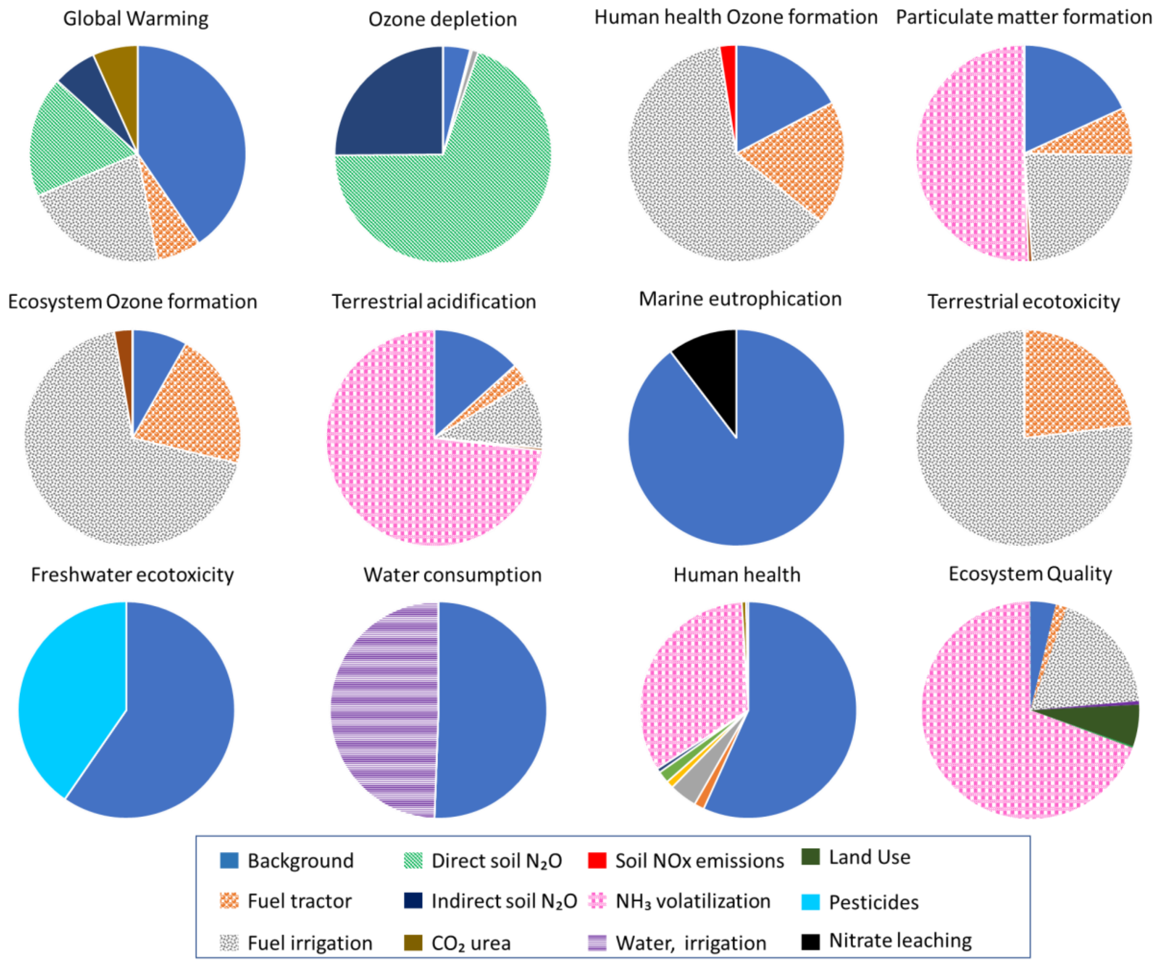

Figure 6. Processes and elementary flows cumulatively contributing to most relevant midpoint and endpoint impacts.

Irrigation processes (irrigation water + infrastructure + energy) were relatively a large contributor to specific midpoint impact categories. It represented 28.1% of global warming; 64.2% of human damage ozone formation; 69.5% of ecosystem damage ozone formation; 76.2% of terrestrial eco-toxicity; 39.6% of fossil fuel scarcity; and 55.4% of water consumption. To endpoint, impact categories contributed with 13.9% on human health, 18.7% on ecosystem quality and 43.5% resource availability. The main contributor to the water consumption potential was the direct water consumption in irrigation (49.4%), while energy used to power irrigation dominated other impact categories (Figure 6). Earlier studies have shown that the irrigation water use accounted for 45% (Almeida et al. 2014), 65% (Dias et al. 2017) and 94% (Payen et al. 2015) of the freshwater deprivation over the entire tomato life cycle. Diesel consumption was the main source of fossil resource scarcity while direct air emissions from combustion of fuel in watering and field operations resulted in high impacts in global warming (predominantly CO_2), ozone formation including human health and terrestrial ecosystem (NO_x and NMVOC emissions) and terrestrial eco-toxicity (heavy metals, particularly zinc). Irrigation infrastructure (production phase of the driplines and pump) had slight environmental impacts representing a noticeable impact only to marine eutrophication (+21%), freshwater eco-toxicity (+7%), marine eco-toxicity (9%), and human carcinogenic toxicity (+10.8%). Polyethylene and synthetic rubber give the most significant contribution to these categories.

The limited use of machinery resulted in minor environmental impacts for tractor processes (tractor and fuel production and tractor use emissions) with a contribution between 3 and 23% (Figure 6). The results lead to the similar conclusion with Bojacá et al. (2014) reporting that machinery has marginal contributions to most impact categories and only the burdens for abiotic and eutrophication potential was relevant with shares of 17 and 21%, respectively. On contrary, Zarei et al. (2018) reported that diesel fuel used in field operations was relevant for many impact categories with a contribution from 22.9% (abiotic depletion) to 87.5% (ozone layer depletion).

Regarding greenhouse management, the impacts occurred only in the background system, as there is no heating system (only natural ventilation). Greenhouse structure represented 22.7% of marine eutrophication; 37.9% of human carcinogenic toxicity; and 15% of mineral resource scarcity (Figure 6). The steel used to build the greenhouse infrastructure, and the polyethylene cover were the main burdens for the greenhouse structure. In other studies structure accounted between 34.9 to 47.8%, 30 to 48% of the contributions across selected impact categories (Torrellas et al. 2012), 39% for terrestrial ecotoxicity and 98% for ozone depletion (Bojacá et al. 2014) and up to 69% of impacts (Payen et al. 2015).

The transportation of farm inputs had negligible environmental impacts across all categories with a contribution of less than 6%. Bojacá et al. (2014) found that the impact for the transport of cultivation inputs was on average 3.2% while Manfredi and Vignali (2014) estimated between 4 to 7%. The results confirm that within cradle-to-farm gate approach, transportation of farm inputs has a negligible effect, however, with the expansion of system boundaries on a cradle-to-market approach transportation might lead to substantial energy depletion (He et al. 2016) and relevant contribution to global warming, terrestrial acidification, and eutrophication with more than 38% impact (Payen et al. 2015).

3.3 Sensitivity analysis of LCA model parameters

Finally, a sensitivity analysis was carried out on some of the most important input parameters (Table 6) which drive most of the uncertainty in the results in order is to assess the reliability of the results and conclusions. Firstly, we studied the sensitivity of global characterization versus country-level characterization factors for impact categories presented in Table 3. Secondly, a sensitivity for flow and nutrient modeling by using lower emission factors (Table 11.3, IPCC 2006) than the average. Thirdly, we studied the sensitivity of LCA results to the type of power source required for pumping (from diesel to electricity from the grid and gravity-based irrigation systems) since LCA profile, and ranking of alternatives depend crucially on the source used to produce electricity (Tyson et al. 2012).

One of the discussions on the adopted impact assessment method includes the evaluation and estimation of characterization factors which highly affect the results of the LCIA phase (Zampori et al. 2016). The assessment at the midpoint level with country-level characterization factors resulted in higher LCA impacts with about 8.2% for human health ozone formation, 17% for particulate matter formation, 57.3% for ecosystem ozone formation, 17.2% for terrestrial acidification and 5.9% for water consumption in respect to generic characterization factors. On the contrary, it resulted in 71.8% fewer freshwater eutrophication impacts. At the endpoint level, 12.1% and 77.1% human health and ecosystem quality impacts were calculated with respect to generic characterization factors.

Table 6. The sensitivity of each indicator to different LCA model parameters.

Impact category	Unit	Baseline Spatial LCA	Generic LCA	Fertilizer-model	Electricity-irrigation	Gravity-irrigation
Midpoint impact categories						
Global warming	kg CO$_2$-eq	3109.8	3109.8	2487.7	2480.6	2314.1
Stratospheric ozone depletion	kg CFC11-eq	0.0298	0.0298	0.0068	0.0295	0.0294
Ionizing radiation	kBq Co-60-eq	169.9	169.9	169.9	254.4	151.0
Human health ozone formation	kg NOx-eq	17.67	16.2	17.3	6.7	6.5
Fine particulate matter formation	kg PM2.5-eq	10.47	8.7	6.7	7.9	7.7
Ecosystem Ozone Formation	kg NOx-eq	38.5	16.4	37.7	12.2	11.9
Terrestrial acidification	kg SO$_2$-eq	53	43.9	25.7	47.2	46.6
Freshwater eutrophication	kg P-eq	0.48	0.83	0.48	0.60	0.45
Marine eutrophication	kg N-eq	190.06	190.06	182.2	192	188.9
Terrestrial ecotoxicity	kg 1.4-DCB-eq	891.38	891.38	891.4	212.4	212.3
Freshwater ecotoxicity	kg 1.4-DCB-eq	63.44	63.44	63.4	66.3	61.5
Marine ecotoxicity	kg 1.4-DCB-eq	67.1	67.1	67.1	69.7	62.9
Human carcinogenic toxicity	kg 1.4-DCB-eq	85.38	85.38	85.4	89.9	78.2
Human non-carcinogenic toxicity	kg 1.4-DCB-eq	38,476	38,476	38476.1	41162.2	36278.9
Land use	m^{2}a crop-eq	7324.43	7324.43	7324.4	7324.3	7323.3
Mineral resource scarcity	kg Cu-eq	14.4	14.4	14.4	14.5	13.6
Fossil resource scarcity	kg oil-eq	754	754	754.0	542.2	501.6
Water consumption	m^3	5060.6	4760.6	5060.6	14306	4819.4
Endpoint impact categories						
Human Health	DALY	0.03007	0.0264	0.02042	0.04993	0.02745
Ecosystem Quality	Species × year	0.001035	0.00024	0.00038	0.00098	0.00085
Resource Availability	USD2013	300.3	300.3	300.3	196.4	188.1

The sensitivity for nutrient emission factors indicates notable differences in impact categories of global warming (-25%), stratospheric ozone depletion (-335%), fine particulate matter formation (-55%), terrestrial acidification (-106%), human health (-47%), and ecosystem quality (-175%). These indicators were greatly affected by field emissions of nitrous oxide (N$_2$O), nitrogen oxide (NO$_X$) and ammonia (NH$_3$). The energy used for irrigation also influence the estimated LCIA results to some extent. Shifting to electrically powered pumping shows a substantial increase in terms of ionizing radiation (+50%), freshwater eutrophication (+24%), water consumption potential (+183%) and human health (+66%). The water consumption impacts were mainly related to upstream impacts with energy mix for electricity production in Albania which is mainly based on hydropower. Ecotoxicity indicators show a small increase of up to 7%. On the other hand, it is obvious that the electricity-powered irrigation is more environmentally friendly for global warming potential (-20%), human health ozone formation potential (-62%), ecosystem ozone formation potential

(-68%), fine particulate matter formation (-24%), terrestrial acidification (-76%) and fossil resource scarcity (-28%). For energy-related impact categories, there is a great potential to largely improve their performance by using a gravity-based irrigation system since LCA impacts from the energy needed for abstraction (pumping) and water application and other structures (pumps, filters) are eliminated.

It should be noted that differences of the impact-assessment numerical results indicate a difference of processes and their degree of contribution to the impact categories, the relative importance of the activities conducted in the foreground system to the relative contribution of the background subsystem, the relevance of the different midpoint impact categories and their contribution to damage impact categories. The contribution analysis of midpoints to human health and ecosystem quality shows that most impactful midpoints remain the same although across scenarios their magnitude of the impact is different (Figure 7). The contribution of particulate matter formation to human health damage decreased from 40% to 14%, while water consumption increased from 20 to 40% between generic and spatially differentiated impact scores. For damage to ecosystem quality, the effect from ecosystem ozone formation and terrestrial acidification decreased from 19 to 6% and 70 to 36%, respectively. Consequently, land use becomes the dominant midpoint indicator when generic modeling is used. This is mainly because of trade-offs between categories, where an increase in impact scores for some categories is compensated by a decrease in others. This underlines the importance of regional considerations in LCA calculations which will increase the possibility of making correct conclusions and sub-optimizations.

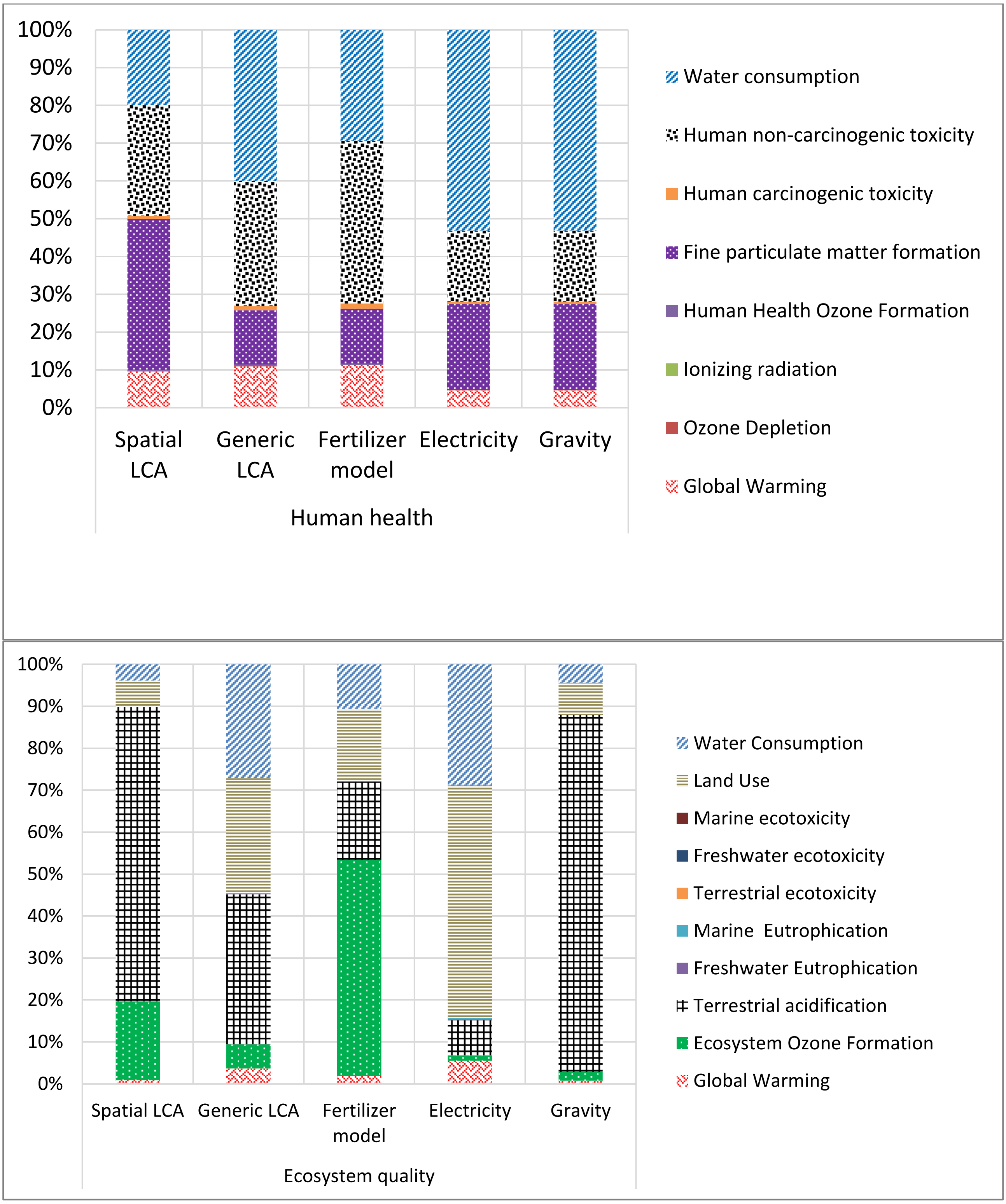

Figure 7. The contribution of midpoint indicators to human health and ecosystem quality for scenarios addressed in the sensitivity analysis.

4. Conclusions

In this study we performed a full-fledged life cycle impact assessment to shed light on the cradle-farm gate environmental impacts of unheated greenhouse tomato production in a typical farm in Albania, so far lacking in the scientific literature. The assessment evaluated the magnitude and significance of the potential environmental impacts, investigated which inputs or processes cause the highest impact, and included spatial differentiation for some impact categories not typically addressed in LCA studies. This first analysis shows that fertilization and irrigation are the most crucial management practices in terms of environmental impacts to reduce associated nutrient and fuel emissions and water use for irrigation. The practices will directly affect global warming, stratospheric ozone depletion, human and ecosystem ozone formation potential, terrestrial acidification, and freshwater consumption and associated impacts to areas of protection (human health, ecosystem quality, and resource availability). The extended analysis between foreground (on-farm) and background (off-farm) sub-systems identified that the foreground is the most impacting system for damages to human health (caused by particulate matter formation, water consumption, and global warming) and ecosystem quality (caused by terrestrial acidification and ecosystem damage ozone formation). The background system (production of raw materials) has a major impact on 10 midpoint impact categories and one endpoint category (resources). Our sensitivity analysis indicated that LCA impacts of tomatoes can be strongly influenced by some model parameters/scenarios such as spatial differentiation, nutrient emission factor model, or energy mix generating different results and outlooks about the relevance of different processes, impact categories, and overall LCA performance. Practical application of spatial differentiation in the evaluation of some impact categories revealed important differences (from 6.1% to 77.1%) for local or regional scale, thus, increasing the reliability and validity of overall LCA results toward more realistic environmental assessment of local agricultural practices. This implies that with regards to impact assessment, the use of site-generic characterization factors data can lead to results that do not reflect the impacts accordingly (i.e. the magnitude of impacts, the most relevant midpoint categories and their relevance on endpoint level). Clearly, more site-specific data about cropping practices and emission factors combined with spatial differentiation and harmonized midpoint-endpoint analysis will increase the discriminating power of LCA.

Agriculture is the most important sector in Albania and holistic sustainability models and metrics can play a key role in sustainability in agricultural systems. Our study and LCA model will be used as a springboard to start to itemize and quantify the environmental impacts of crops and a basis to extend current life cycle thinking to incorporate social and economic issues for a comprehensive accounting of sustainability performance of tomato and crop production.

Acknowledgments

This research was made possible by a research grant from Mediterranean Agronomic Institute of Bari (CIHEAM- Bari) in the framework of project IR$_2$MA – Large Scale Irrigation Management Tools for Sustainable Water Management in Rural Areas and Protection of Receiving Aquatic Ecosystems (www.irrigation-management.eu) funded by the European Union Cooperation Program INTERREG Greece-Italy 2014-2020. We gratefully acknowledge the support of the funding agency and the Mediterranean Agronomic Institute of Bari (CIHEAM- Bari).

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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List of Figures

Figure 1

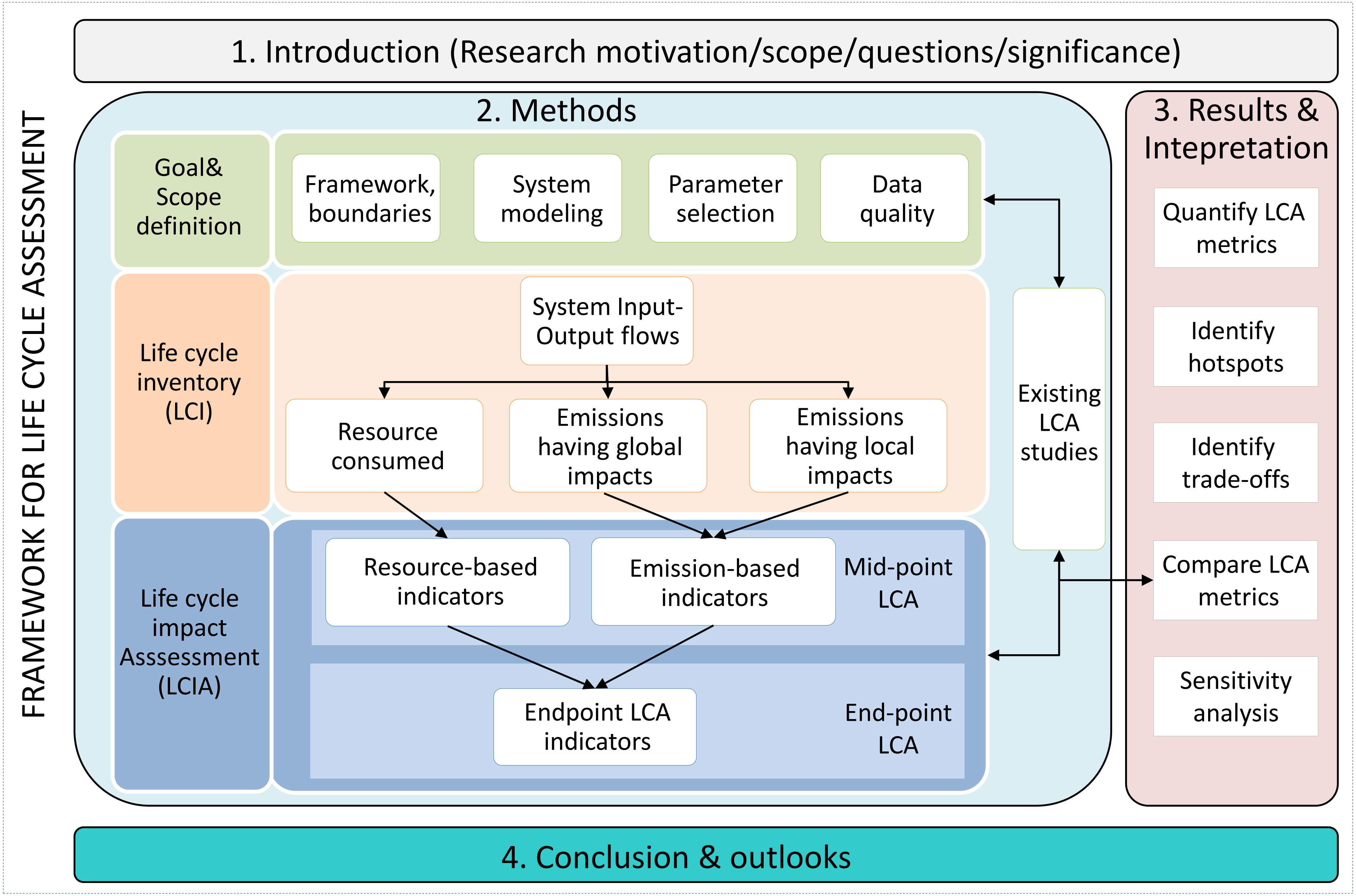
FRAMEWORK FOR LIFE CYCLE ASSESSMENT
1. Introduction (Research motivation/scope/questions/significance)
2. Methods
Goal& Scope definition
Framework, boundaries
System modeling
Parameter selection
Data quality
Life cycle inventory (LCI)
System Input-Output flows
Resource consumed
Emissions having global impacts
Emissions having local impacts
Life cycle impact Asssessment (LCIA)
Resource-based indicators
Emission-based indicators
Mid-point LCA
Endpoint LCA indicators
End-point LCA
Existing LCA studies
3. Results & Intepretation
Quantify LCA metrics
Identify hotspots
Identify trade-offs
Compare LCA metrics
Sensitivity analysis
4. Conclusion & outlooks

Figure 2

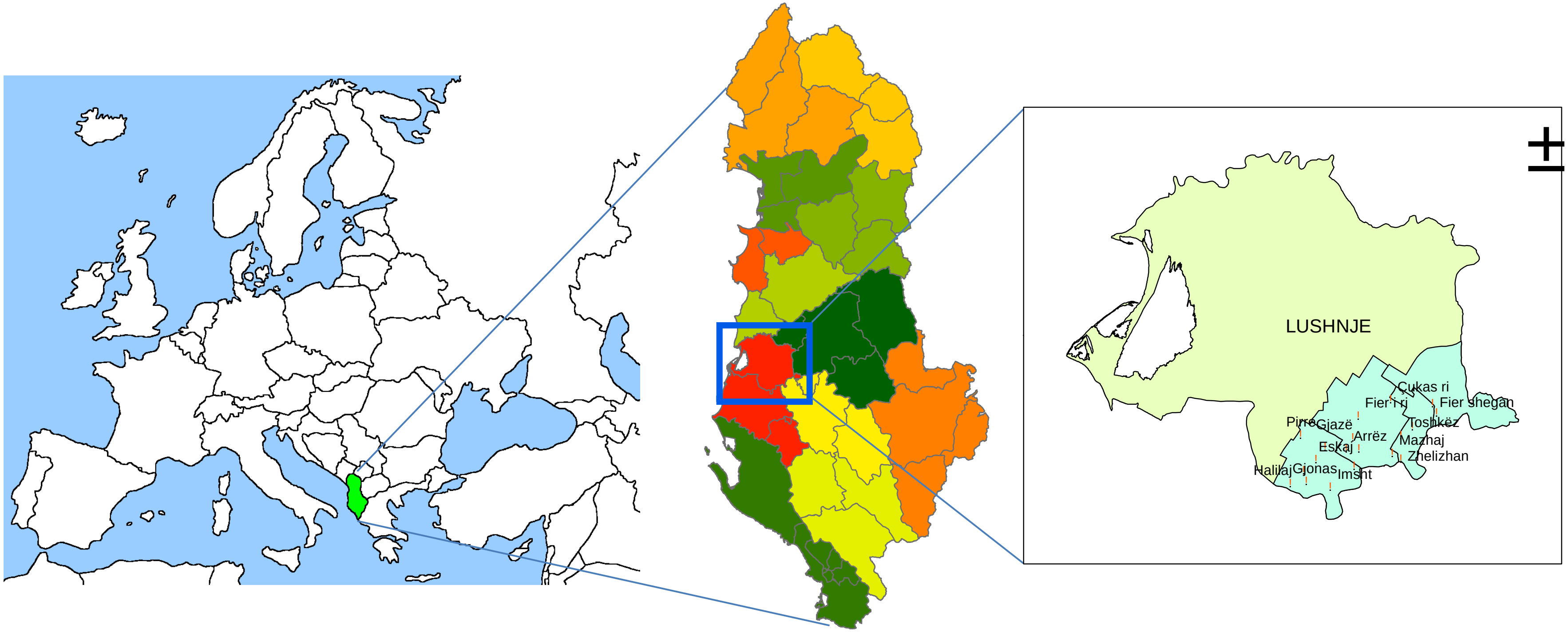
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Figure 3

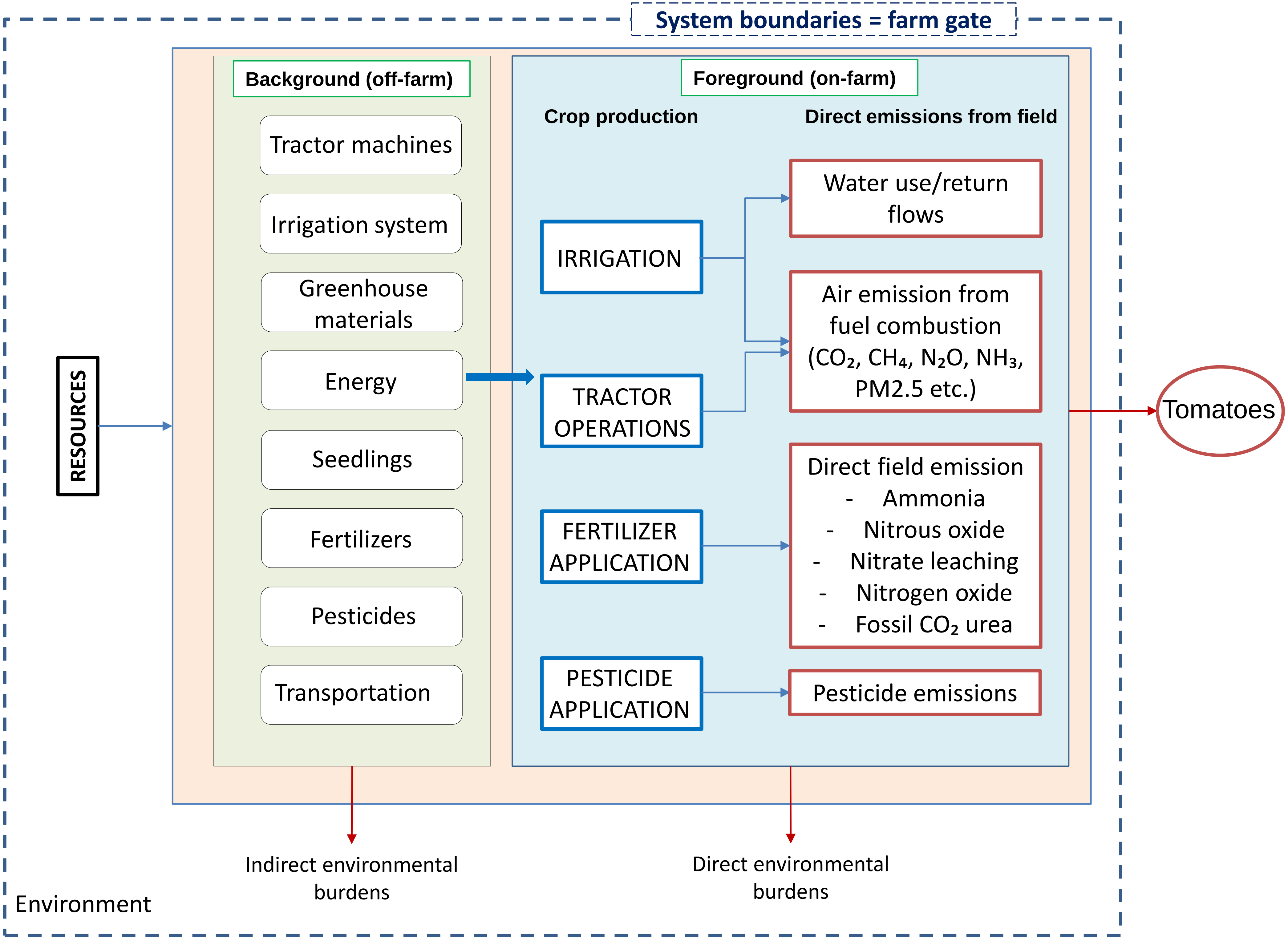
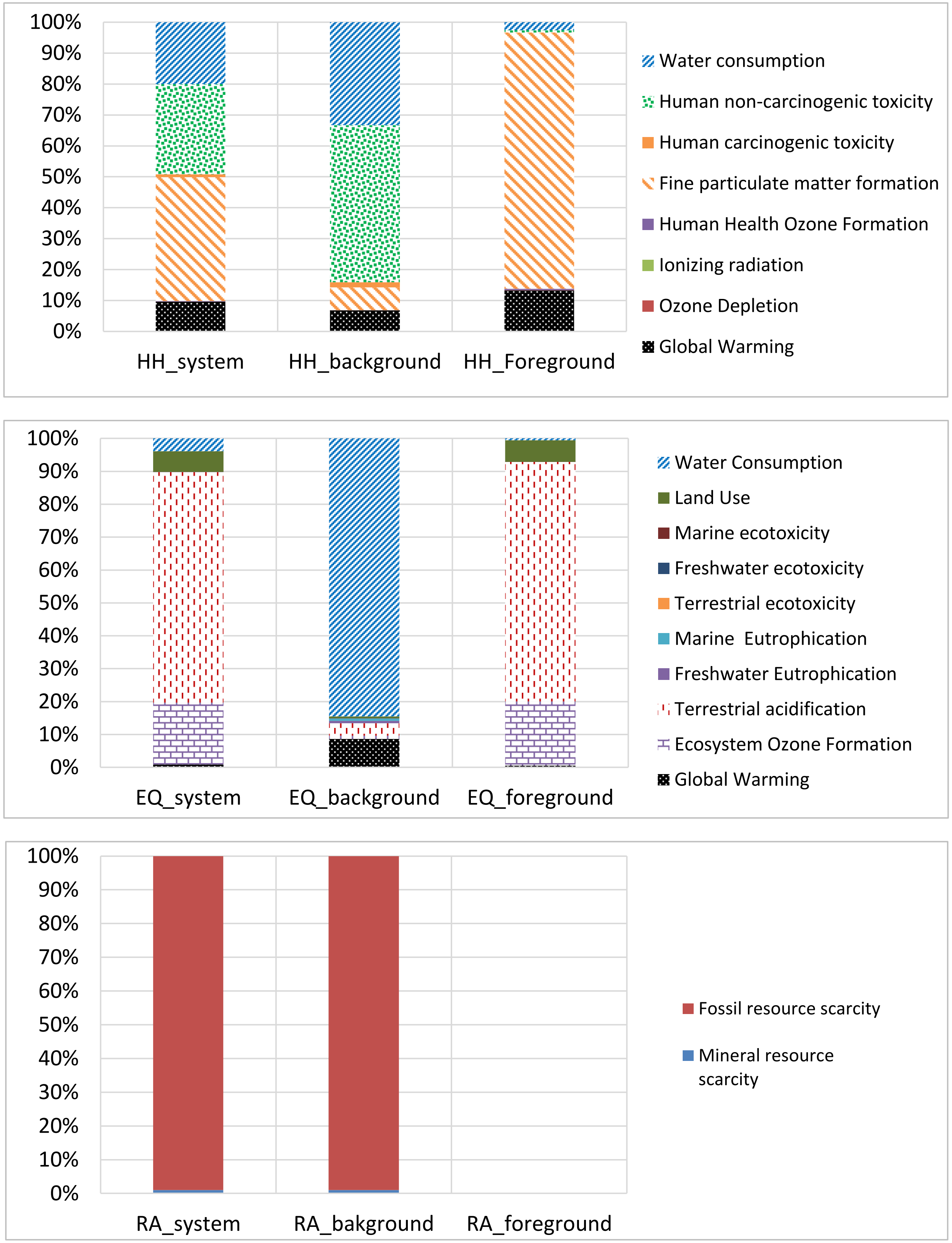

System boundaries = farm gate
Background (off-farm)
Tractor machines
Irrigation system
Greenhouse materials
Energy
Seedlings
Fertilizers
Pesticides
Transportation
Foreground (on-farm)
Crop production
Direct emissions from field
IRRIGATION
TRACTOR OPERATIONS
FERTILIZER APPLICATION
PESTICIDE APPLICATION
Water use/return flows
Air emission from fuel combustion (CO_2, CH_4, N_2O, NH_3, PM2.5 etc.)
Direct field emission
- Ammonia
- Nitrous oxide
- Nitrate leaching
- Nitrogen oxide
- Fossil CO_2 urea
Pesticide emissions
RESOURCES
Tomatoes
Indirect environmental burdens
Direct environmental burdens
Environment

Figure 4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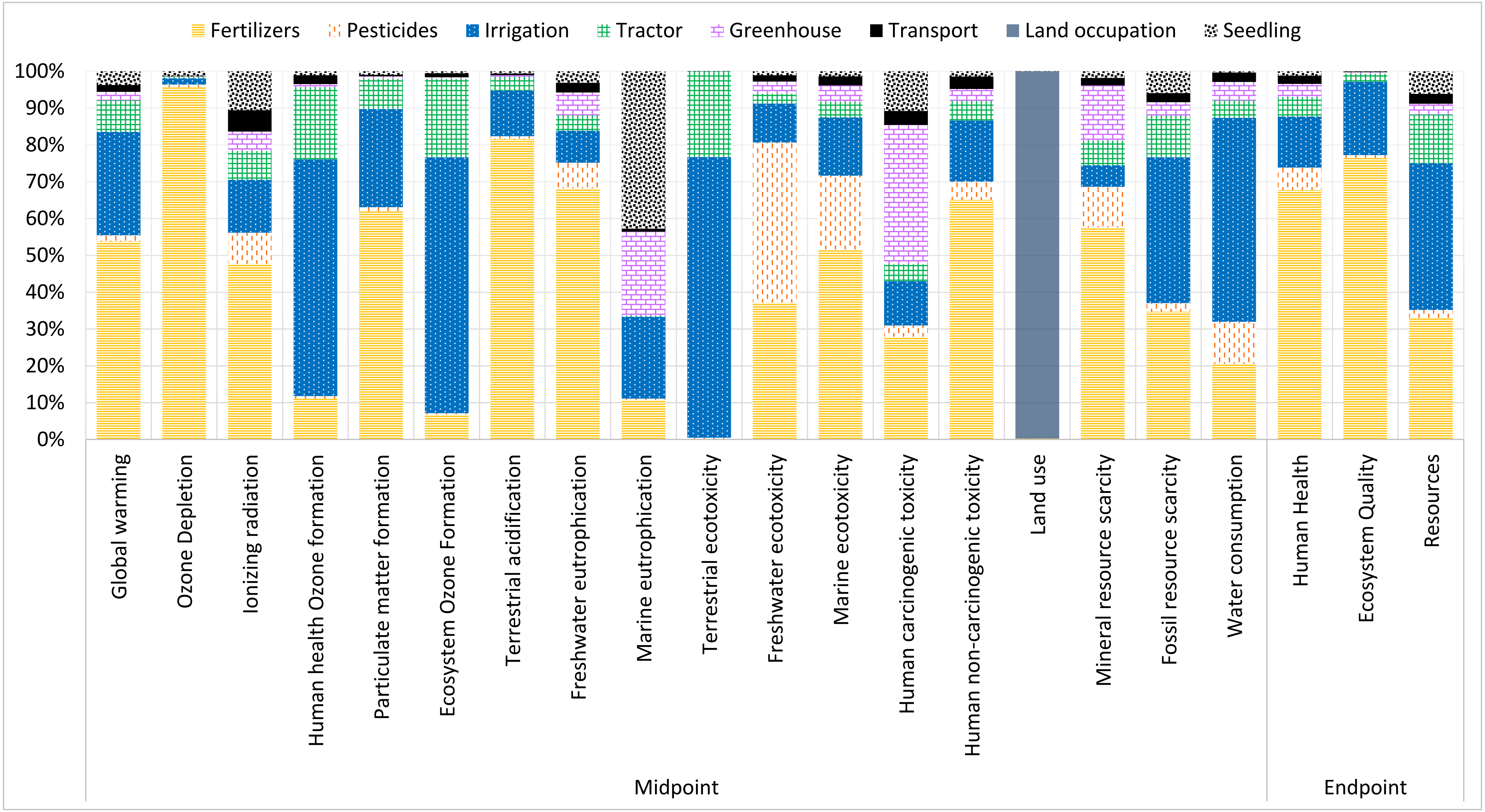
HH_system
HH_background
HH_Foreground
Water consumption
Human non-carcinogenic toxicity
Human carcinogenic toxicity
Fine particulate matter formation
Human Health Ozone Formation
Ionizing radiation
Ozone Depletion
Global Warming
EQ_system
EQ_background
EQ_foreground
Water Consumption
Land Use
Marine ecotoxicity
Freshwater ecotoxicity
Terrestrial ecotoxicity
Marine Eutrophication
Freshwater Eutrophication
Terrestrial acidification
Ecosystem Ozone Formation
Global Warming
RA_system
RA_bakground
RA_foreground
Fossil resource scarcity
Mineral resource scarcity

Figure 5



Fertilizers
Pesticides
Irrigation
Tractor
Greenhouse
Transport
Land occupation
Seedling
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Global warming
Ozone Depletion
Ionizing radiation
Human health Ozone formation
Particulate matter formation
Ecosystem Ozone Formation
Terrestrial acidification
Freshwater eutrophication
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcinogenic toxicity
Human non-carcinogenic toxicity
Land use
Mineral resource scarcity
Fossil resource scarcity
Water consumption
Human Health
Ecosystem Quality
Resources
Midpoint
Endpoint

Figure 6

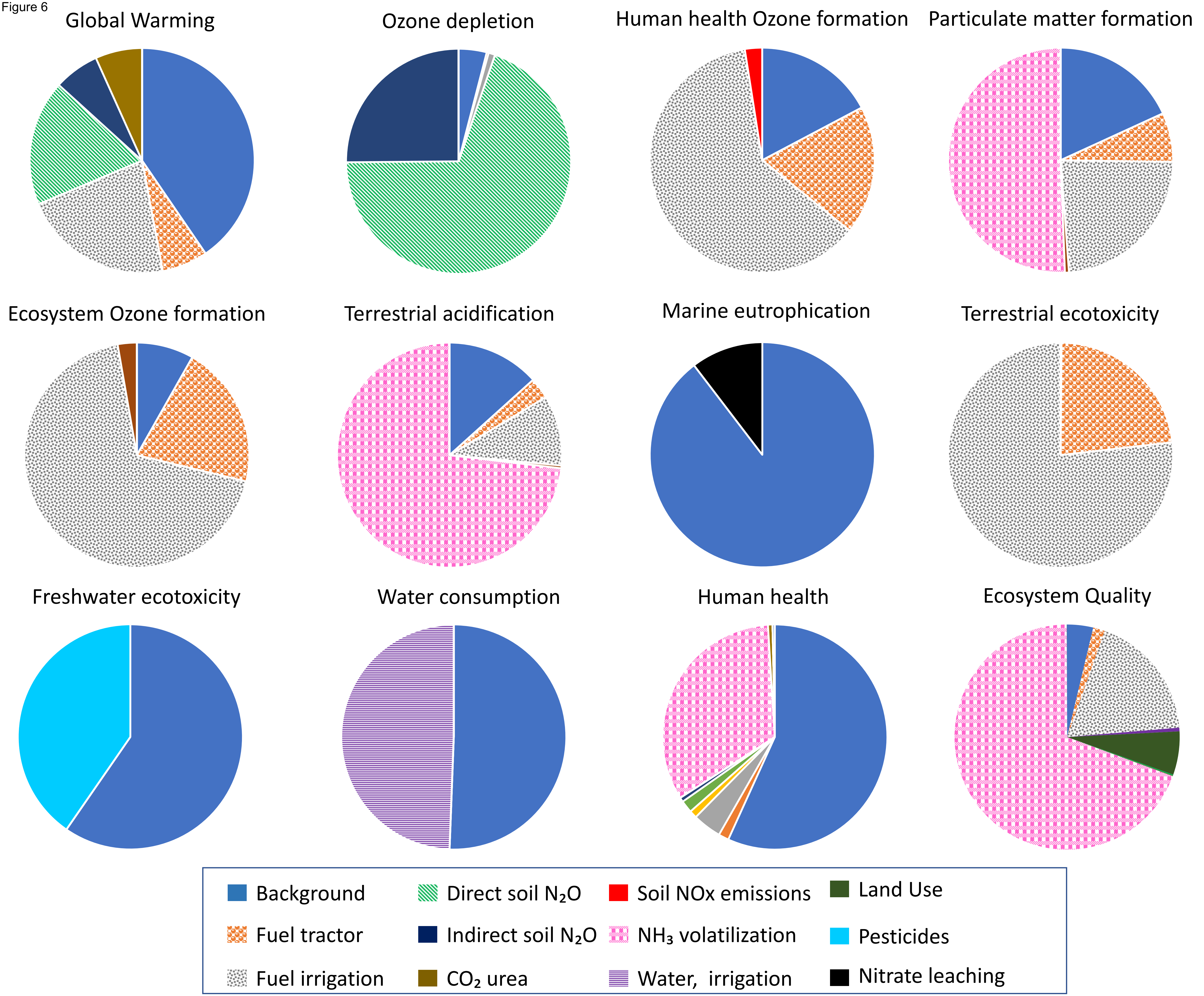
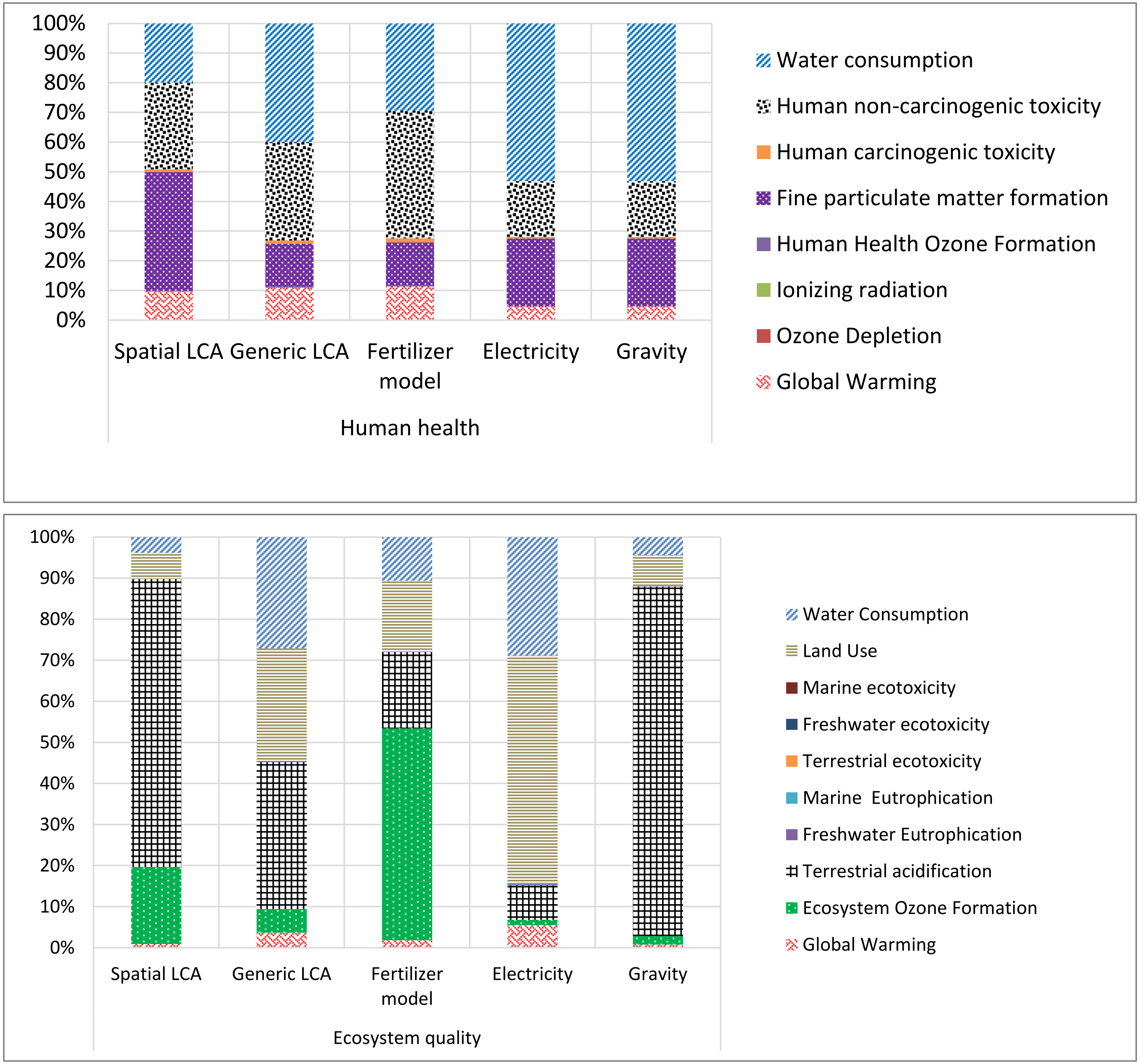

Global Warming
Ozone depletion
Human health Ozone formation
Particulate matter formation
Ecosystem Ozone formation
Terrestrial acidification
Marine eutrophication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Water consumption
Human health
Ecosystem Quality
Background
Fuel tractor
Fuel irrigation
Direct soil N_2O
Indirect soil N_2O
CO_2 urea
Soil NOx emissions
NH_3 volatilization
Water, irrigation
Land Use
Pesticides
Nitrate leaching

Figure 7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Spatial LCA
Generic LCA
Fertilizer model
Electricity
Gravity
Human health
Water consumption
Human non-carcinogenic toxicity
Human carcinogenic toxicity
Fine particulate matter formation
Human Health Ozone Formation
Ionizing radiation
Ozone Depletion
Global Warming
100%
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Spatial LCA
Generic LCA
Fertilizer model
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Terrestrial acidification
Ecosystem Ozone Formation
Global Warming

List of Tables

Table 1. Primary input data of greenhouse tomato production in Lushnja district, Albania.

Name	Amount	Unit
Product flows		
Tomato, harvested, at farm gate/ALB	95	ton/ha
Input processes		
Seedling		
Seedling, for transplant, at farm/RER U	30000	p/ha
Irrigation		
Water, groundwater, unspecified, 50 m total pumping head/ALB	5000	m3/ha
Electricity, mix ALB adapted, irrigation/ALB	1290.3	kWh/ha
Diesel burned in building machine, irrigation/ALB	212.5	kg/ha
Drip irrigation system, production, per ha/RER U	1	ha
Drawing of pipes, steel/RER U	0,03	kg/ha
Extrusion, plastic pipes/RER U	0.03	kg/ha
Polyethylene, HDPE, granulate, at plant/RER U	27.79	kg/ha
Polyethylene, LDPE, granulate, at plant/RER U	11.50	kg/ha
Polypropylene, PP, at factory gate/RER U	14.52	kg/ha
Polyvinylidenchloride, granulate, at plant/RER U	0.39	kg/ha
Steel, converter, low-alloyed, at plant/RER U	1.38	kg/ha
Fertilizer & Pesticides		
Urea, at regional storehouse /RER U	290	kg/ha
Phosphorus, Single Superphosphate/RER U	180	kg/ha
Potassium Sulfate, at regional storehouse/RER U	200	kg/ha
Pesticide unspecified, at regional storehouse/RER U	5	kg a.i/ha
Tractor Processes		
Diesel fuel, field operations (no irrigation)	65	kg/ha
Time to process 1 ha	11	hour/ha
Tractor, module production	4.23	kg/ha
Tractor weight	3600	kg
Tractor lifetime	7000	hours
Greenhouse structure		
Steel, low-alloyed, at plant/RER U	25.6	kg/ha
Aluminum, primary, at plant/RER U	1.03	kg/ha
Polyethylene, LDPE, granulate, at plant/RER U	6.5	kg/ha
Transport		
Transport, freight, rail/RER U	200	t/km
Transport, lorry 3.5-16t, fleet average/RER U	200	t/km
Transport, barge/RER U	200	t/km
Land occupation		
Occupation, annual crop, greenhouse	1	ha

Table 2

Table 2. Calculated field emissions from nitrogen fertilizer and fuel combustion.

Output	Amount	Unit
Nitrogen fertilizer emissions		
Ammonia Volatilization (NH_3)	16.19	kg NH_3/ha
Direct N_2O emissions from fertilizer application N_2O (dir, F)	1.89	kg N_2O/ha
Soil direct NOx emissions (dir, F)	0.40	kg N_2O/ha
Indirect N_2O emissions via atmospheric deposition of N volatilized N_2O (ATD)	0.21	kg N_2O/ha
Indirect N_2O emissions via leaching and runoff from fertilizer application N_2O (L, F)	0.47	kg N_2O/ha
CO_2 urea-based application	209.44	kg CO_2/ha
Nitrate (NO_3) leaching	175.9	kg NO_3/ha
Phosphorus (phosphates), to groundwater	1.198	kg PO_4^{3-}/ha
Fuel combustion emissions		
Ammonia (NH_3)	0.01	kg/ha
Particulate matter (PM < 2.5 um)	1.30	kg/ha
Carbon dioxide (CO_2)	865.80	kg/ha
Dinitrogen monoxide (N_2O)	0.03	kg/ha
Methane (CH_4)	0.04	kg/ha
Carbon monoxide (CO)	2.25	kg/ha
Nitrous oxide (NOx)	12.49	kg/ha
Non-methane volatile organic compounds (NMVOC)	0.75	kg/ha
Sulphur dioxide (SO_2)	0.28	kg/ha
Cadmium	2.78E-06	kg/ha
Chromium	1.39E-05	kg/ha
Copper	4.72E-04	kg/ha
Nickel	1.94E-05	kg/ha
Zinc	2.78E-04	kg/ha
Selenium	2.78E-06	kg/ha
Benzo[a]anthracene	2.22E-05	kg/ha
Benzo[k]fluoranthene	1.39E-05	kg/ha
Chrysene	5.55E-05	kg/ha
Dibenzo[a]anthracene	2.78E-06	kg/ha
Fluoranthene	1.25E-04	kg/ha
Phenanthene	6.94E-04	kg/ha

Table 3

Table 3. The relation between midpoint and endpoint categories in the ReCiPe 2016 method, including country-specific impact categories.

Midpoint impact category	Endpoint impact category			Available Country-specific impacts
	Damage to Human health	Damage to Ecosystems	Damage to Resource availability	
Global warming	+	+		
Stratospheric ozone depletion	+			
Ionizing radiation	+			
Human health ozone formation	+			+
Fine particulate matter formation	+			+
Ecosystem Ozone Formation		+		+
Terrestrial acidification		+		+
Freshwater eutrophication		+		+
Marine eutrophication		+		
Terrestrial ecotoxicity		+		
Freshwater ecotoxicity		+		
Marine ecotoxicity		+		
Human carcinogenic toxicity	+			
Human non-carcinogenic toxicity	+			
Land use		+		
Mineral resource scarcity			+	
Fossil resource scarcity			+	
Water consumption	+	+		+

Table 4

Table 4. Life cycle impact scores of greenhouse tomato production at midpoint and endpoint level (ReCiPe 2016, Hierarchist - H).

Characterization factor	Unit	LCIA System 1 ha	LCIA Foreground 1 ha	LCIA Background 1 ha
Midpoint impact categories				
Global warming	kg CO_2-eq	3109.8	1851.7	1258.1
Stratospheric ozone depletion	kg CFC11-eq	0.0298	0.0286	0.0012
Ionizing radiation	kBq Co-60-eq	169.9	-	169.9
Human health ozone formation	kg NOx-eq	17.67	14.47	3.19
Fine particulate matter formation	kg PM2.5-eq	10.47	8.46	2.01
Ecosystem Ozone Formation	kg NOx-eq	38.5	35.17	3.32
Terrestrial acidification	kg SO_2-eq	53	45.8	7.2
Freshwater eutrophication	kg P-eq	0.48	0.05	0.44
Marine eutrophication	kg N-eq	190.06	11.80	178.3
Terrestrial ecotoxicity	kg 1.4-DCB-eq	891.38	890.2	1.14
Freshwater ecotoxicity	kg 1.4-DCB-eq	63.44	25.62	37.82
Marine ecotoxicity	kg 1.4-DCB-eq	67.1	11.9	55.1
Human carcinogenic toxicity	kg 1.4-DCB-eq	85.38	0.53	84.9
Human non-carcinogenic toxicity	kg 1.4-DCB-eq	38476	433	38043
Land use	m^2a crop-eq	7324.43	7300	24.43
Mineral resource scarcity	kg Cu-eq	14.4	-	14.38
Fossil resource scarcity	kg oil-eq	754	-	754
Water consumption	m^3 consumed	5060.6	2500	2560.6
Endpoint impact categories				
Human Health	DALY	0.03007	0.013	0.0171
Ecosystem Quality	Species × year	0.001035	0.000994	0.000041
Resource Availability	USD2013	300.3	-	300.3

Table 5

Table 5. Life cycle impact scores of tomato production among LCA studies according to their functional unit.

Authors	FU	System boundaries	LCIA method	Location	GWP	ODP	AP	EP	FETP	TETP	METP	WCP	HH	EQ	RA
This study	1 ha (1 ton)	X-to-farm gate;	ReCiPe 2016	Albania	3109.8 (32.73)	0.0298 (3.14E-04)	53 (0.557)	0.48 (0.005)	63.44 (0.667)	891.38 (9.38)	67.1 (0.706)	5060.6 (53.3)	0,03007 (0,00032)	0,001035 (1,09E-05)	300,3 (3.16)
Almeida et al. (2014)	1 kg	X-to-market;	IPCC 2007	Italy	2.28	-	-	-	-	-	-	1.226	-	-	-
Bojacá et al. (2014)	1 ton	X-to-farm gate;	CML 2001	Colombia	32	-	0.529	0.407	0.12	37.6	-	-	-	-	-
Bosona and Gebresenbet (2018)	1 ton	X-to-market;	ReCiPe 2008	Sweden	547.13	-	-	-	-	-	-	-	-	-	-
Boulard et al. (2011)	1 kg	X-to-farm gate;	CML 2001	France	2.02	4.3E-08	0.034	0.137	-	-	-	-	-	-	-
Cellura et al. (2012)	1 ton	X-to-grave;	CML 2001	Italy	897.1	4.1E-04	5.1	1.8				84.3			
Del Borghi et al. (2014)	1 kg	X-to-factory gate;	CML 2001	Italy	0.3733 - 0.5932	-	0.0006 - 0.0009	0.0014-0.0022	-	-	-	41.82 - 65.51	-	-	-
Dias et al. (2017)	1 kg	X-to-farm gate;	TRACI 2.1	Canada	3.2	5.9E-07	6.6E-03	2.6E-03	-	-	-	-	-	-	-
He et al. (2016)	1 ton	X-to-market;	CML/IPCC	China	207 - 260	-	5.92 - 5.94		-	-	136.5 - 177.4	59.04 - 60.06	-	-	-
Khoshnevisan et al. (2014)	1 ton + 1 ha	X-to-farm gate;	CML 2 baseline	Iran	129.39	2.00E-05	0.37	0.03	5.81	17,497	-	-	-	-	-
Martínez-Blanco et al. (2011)	1 ton	X-to-farm gate;	CML2001	Spain	152.6	1.38E-05	0.938	0.348	-	-	-	-	-	-	-
Ntinas et al. (2017)	1 kg + 1 m^2	X-to-farm gate;	IPCC 2006	Greece + Germany	400 - 10100	-	-		-	-	-	-	-	-	-
Page et al. (2012)	1 kg	X-to-farm gate;	IPCC 2006	Australia	430 - 1860	-	-	-	-	-	-	4.97 - 52.7	9.04E-06	2.69E-05	-
Payen et al. (2015)	1 kg	X-to-market;	ReCiPe 2008	Morocco	0.546	-	0.0032	0.000168	0.00312	0.00288	0.211	0.297	5,00E-07	3.9E-09	1
Pérez Neira et al. (2018)	1 kg	X-to-regional center	IPCC 2006	Spain	0.39	-	-	-	-	-	-	-	-	-	-
Pérez Neira et al. (2018)	1 ton	X-to-farm gate;	CML 2001	Spain	250	-	1	0.49	-	-	-	-	-	-	-
Torrellas et al. (2012)	1 ton + 1 ha	X-to-farm gate;	CML-IA baseline	Iran	65.82	9.24E-06	0.39	0.032	4.1	17.34E03	-	-	-	-	-

Abbreviations: GH – Greenhouse; OF – Open Field; X – Cradle; GWP – Global warming potential; ODP – Ozone depletion potential; AP – Acidification potential; EP – Eutrophication; FETP – Fresh-water aquatic ecotoxicity potential; TETP – Terrestrial ecotoxicity potential; WCP – Water consumption potential; HH – Human health; EQ – Ecosystem quality; RA – resources availabiliity,

Table 6

Table 6. The sensitivity of each indicator to different LCA model parameters.

Impact category	Unit	Baseline Spatial LCA	Generic LCA	Fertilizer-model	Electricity-irrigation	Gravity-irrigation
Midpoint impact categories						
Global warming	kg CO_2-eq	3109.8	3109.8	2487.7	2480.6	2314.1
Stratospheric ozone depletion	kg CFC11-eq	0.0298	0.0298	0.0068	0.0295	0.0294
Ionizing radiation	kBq Co-60-eq	169.9	169.9	169.9	254.4	151
Human health ozone formation	kg NOx-eq	17.67	16.2	17.3	6.7	6.1
Fine particulate matter formation	kg PM2.5-eq	10.47	8.7	6.7	7.9	6.3
Ecosystem Ozone Formation	kg NOx-eq	38.5	16.4	37.7	12.2	6.2
Terrestrial acidification	kg SO_2-eq	53	43.9	25.7	47.2	39.1
Freshwater eutrophication	kg P-eq	0.48	0.83	0.48	0.60	0.8
Marine eutrophication	kg N-eq	190.06	190.06	182.2	192	188.9
Terrestrial ecotoxicity	kg 1.4-DCB-eq	891.38	891.38	891.4	212.4	212.3
Freshwater ecotoxicity	kg 1.4-DCB-eq	63.44	63.44	63.4	66.3	61.5
Marine ecotoxicity	kg 1.4-DCB-eq	67.1	67.1	67.1	69.7	62.9
Human carcinogenic toxicity	kg 1.4-DCB-eq	85.38	85.38	85.4	89.9	78.2
Human non-carcinogenic toxicity	kg 1.4-DCB-eq	38,476	38,476	38476.1	41162.2	36278.9
Land use	m^2a crop-eq	7324.43	7324.43	7324.4	7324.3	7323.3
Mineral resource scarcity	kg Cu-eq	14.4	14.4	14.4	14.5	13.6
Fossil resource scarcity	kg oil-eq	754	754	754.0	542.2	501.6
Water consumption	m^3	5060.6	4760.6	5060.6	14306	4519.4
Endpoint impact categories						
Human Health	DALY	0.03007	0.0264	0.02042	0.04993	0.02420
Ecosystem Quality	Species × year	0.001035	0.00024	0.00038	0.00098	0.00021
Resource Availability	USD2013	300.3	300.3	300.3	196.4	188.1

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